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PREDGOVOR

Stalni porast potrošnje energije, usprkos njenim ograničenim izvorima, uz sve veću prijetnju za okoliš, glavni su problemi 21. stoljeća koji nude brojne znanstvene izazove. Energetska učinkovitost, „zelena“ i obnovljiva energija te „čiste“ proizvodne tehnologije globalne su teme za istraživanja kao i trajni zadaci za inženjere i znanstvenike. Napredne energetske tehnologije u funkciji korištenja konvencionalnih i obnovljivih oblika energije moraju se kontinuirano razvijati, što zahtijeva velike napore istraživača i financijska ulaganja. Iako se primjena obnovljivih izvora energije stalno povećava, s postojećim stanjem ne možemo još biti zadovoljni jer su potencijalne mogućnosti znatno veće. Velike mogućnosti stoje pred stručnjacima i znanstvenicima na tome području i od njih se očekuju nova optimalna rješenja. Radovi prezentirani na ovome znanstvenom skupu prikaz su dijela rezultata takvih istraživanja, a također i različitih primjera iz praktičnih iskustava.
Međunarodni kongres **Energija i okoliš 2012** je 23. po redu tradicionalni skup znanstvenika i stručnjaka iz područja energetike i zaštite okoliša koji se svake druge godine okupljaju u Opatiji, što se ovdje s ponosom može istaknuti. Glavne tematske cjeline ovogodišnjega skupa su sljedeće: Učinkovito korištenje energije u industriji, Učinkovito korištenje energije u stambenim objektima, Učinkovito korištenje energije u prometu, Rješenja za učinkovitu pretvorbu energije, Rješenja za smanjenje utjecaja na okoliš iz različitih energetskih i industrijskih procesa te Rješenja za smanjenje klimatskih promjena. Radovi su podijeljeni prema tematskim cjelinama te su predstavljeni u pripadnim tehničkim sekcijama.
Ovaj znanstveni skup je međunarodni. Na njemu sudjeluju predstavnici iz osam zemalja, čime se u otvaraju mogućnosti dobre suradnje na području energetike i zaštite okoliša. Zbornik sadrži ukupno 26 radova visoke znanstvene i stručne razine, koji daju uvid u neka najnovija dostignuća iz područja obnovljivih izvora energije, zaštite okoliša i održiva razvoja.
Od učesnika Kongresa se očekuje da će pružiti pomoć te dati doprinos u tehničkome ali i administrativnome rješavanju brojnih problema iz područja energetike, zaštite okoliša i održiva razvoja. Učesnici iz zemlje i inozemstva omogućuju razmjenu ideja, rezultata istraživanja i praktičnih iskustava bitnih za razvoj i primjenu novih tehnologija. Želja i cilj je da ovaj skup doprinese promidžbi korištenja obnovljivih izvora energije u komercijalne svrhe kao i održivom pristupu korištenja postojećih konvencionalnih izvora energije uz maksimalno poštivanje principa i primjenu najnovije tehnologije zaštite okoliša.
Usprkos tome što se općenito gledano, do sada, postigao veliki napredak u smanjenju utjecaja na okoliš u odnosu na proizvodnju/potrošnju energije, još uvijek na tome području ima neiskorištenih mogućnosti za daljnja poboljšanja na kojima treba poraditi. Dodatni napori trebaju biti usmjereni na povećanje učinkovitosti u procesima proizvodnje i korištenja energije jer će u protivnome željeni cilj za postizanje održive energetske budućnosti teško biti ostvaren.
Poticati istraživanja i razvoj u području naprednih energetskih tehnologija, uključujući obnovljive izvore energije, energetsku učinkovitost, tehnologiju „zelenoga“ korištenja fosilnih goriva kroz nacionalnu i međunarodnu suradnju, generalni su ciljevi ovoga znanstvenog skupa. Organizator očekuje da će u tome dati barem mali doprinos.

Za Organizacijski odbor
Prof. dr. sc. Zmagoslav Prelec

Rijeka, rujan 2012.

FOREWORD

The continuous growing of energy demand, despite its limited sources with growing environmental concerns, are the major challenge of 21^{st} century, offering numerous scientific opportunities. The energy efficiency, "green" and renewable energy as "clean" production technologies are global themes for the investigation and continuous tasks for engineers and scientists. Advanced technologies for the use of conventional and renewable energy sources have to be developed continuously, what require significant research efforts and growing financial funds. Despite of growing use of renewable energy, there is not yet a reason to be satisfied with the existing conditions because of potential possibilities which are still to be utilised. The papers presented on this scientific meeting are the presentation of a part of results of such investigations as of various examples and practical experiences, too.

The Congress **Energy and the environment 2012** is 23^{rd} traditional assembly of scientists and experts in the field of energy and environmental protection, who meet biannually in Opatija, what is worthy to be emphasised with the proud. The main topics are following: Efficient use of energy in industry, Efficient use of energy in buildings, Efficient use of energy in traffic, Solutions for efficient energy conversion, Solutions for decreasing of environmental impacts in various energy process and Solutions for climate changes decreasing. The papers are divided according mentioned thematic fields and presented in corresponding technical sessions.

This scientific meeting is international. The participation of representatives from eight countries opens possibilities for a wide collaboration in the field of efficient energy use and environment protection. Totally 26 papers are introduced into the Proceedings, which have the enviable scientific and professional value giving an insight into new achievements in fields of the use of renewable energy, environment protection and sustainable development.

The Congress participants are expected to give a contribution to sustainable solutions for many technical and environmental issues in the field of energy. The participants from country and abroad will facilitate exchanges of ideas, research results and practical experiences relevant for the development and implementation of new technologies. Besides, the wish and the aim of Organising Committee is to contribute the commercial use of renewable energy sources as the sustainable energy policies with the maximum introduction and use of the newest technology of the environment protection engineering.

Despite of the fact that a great global progress is achieved in reducing energy – related environmental impacts to this date, there are still a lot work to be done and possibilities to be used. Additional efforts are required to be made for energy efficiency improvements in production processes and use of energy or the desired goal to achieve the sustainable energy future could be elusive.

The promotion of the increased research and development in the field of advanced technology, including renewable energy sources, energy efficiency, technology of "green" use of fossil fuel through both national and international collaboration are general aims of this scientific meeting. The Organising Board express his hope that this goal will be obtained at least partially.

For Organising Committee
Prof. D. Sc. Zmagoslav Prelec

Rijeka, rujan 2012.

SADRŽAJ - CONTENTS

UČINKOVITO KORIŠTENJE ENERGIJE/
RJEŠENJA ZA SMANJENJE UTJECAJA NA OKOLIŠ

EFFICIENT USE OF ENERGY/
SOLUTIONS FOR REDUCING ENVIRONMENTAL IMPACT

UČINKOVITO KORIŠTENJE ENERGIJE U PROMETU
EFFICIENT USE OF ENERGY IN TRANSPORT

UČINKOVITO KORIŠTENJE ENERGIJE/
RJEŠENJA ZA SMANJENJE UTJECAJA NA OKOLIŠ

EFFICIENT USE OF ENERGY/
SOLUTIONS FOR REDUCING ENVIRONMENTAL IMPACT

ENERGY EFFICIENCY AND ITS IMPLICATIONS IN INDUSTRY

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Abstract: *Through its National Action Plan of Energy Efficiency 2008-2016 the Republic of Croatia plans energetic savings of 0,47 Mtoe/5,47 TWh in construction, transportation and small industries. Regarded as ratio useful output/energetic input, energy efficiency frequently implies wrong conclusions so decision makers in energy sector rely on complementary indicators like thermal efficiency and specific energetic consumption (SEC), mostly used in industry. Though increase of energy efficiency represents one of the most important strategic goals for developed countries, it cannot be analysed independently of other developing goals. Avoiding possible negative effects the energy efficiency has over the investment cycles can be achieved through aligned functioning of all subjects of national energetic and economic sector.*

Key words: Republic of Croatia, energy efficiency, industry, SEC, negative rebound effects

1. INTRODUCTION

The majority of developing countries are facing today serious problems in energy sector, with no exception for the Republic of Croatia. The core problem in energy deficit can be detected in excessive usage of traditional energy resources which, in most countries, comprise up to 90% of the national energy demand. While the energy consumption per capita is to be considered as one of the basic indicators of high life standard, the recent researches mention a concept of energy efficiency as one of the basic indicators of the accomplished level of development within the national energy sector. This could be supported by the fact that the increasing number of strategic documents and guidelines give an emphasis on development of energy efficiency regarded as obligation adopted by governments of signatory countries. (Jebaraj, Iniyan, 2006, p 302)

Government of the Republic of Croatia confirmed in 1998 the Protocol on energy efficiency and related ecological matters, by which it obliged to develop strategy for energy efficiency, to implement proper legal frames, to develop specific programs for promoting the energy efficiency and to develop programs for reduction of the unfavourable ecological effects generated by ecologic sector. The Republic of Croatia has adopted the National Action Plan for Energy Efficiency which covers time period 2008-2016 and defines the final savings in energy of 0.47 Mtoe in construction, transport and small size industries. (Energy Efficiency Profile, Croatia)The major incentive for energy efficiency projects in industry come from Environmental protection and energy efficiency Fund which provides assets for financing the audit of energy projects and improvement measures. Financial support is provided by other organisations as well, e.g. European Bank for Reconstruction and Development, that finances development of energy efficiency projects, implemented in small and medium-size companies.

One cannot accomplish energy efficiency goals without active participation of responsible authorities and relevant organisations, which should implement precise national energy policies, at the reasonable cost of regulation. A challenge put in front of national authorities derives from detecting the proper modus operandi that will enable realisation of defined goals at the smallest price. Literature which elaborates matters of energy efficiency recognizes two approaches to reducing the negative ecologic effect in industry: top-down approach and bottom-up approach. (Feijoo et al, 2002, p 405) The first approach claims improvements in reduction of harmful emissions can be achieved by simple promotion of energy efficiency. On the contrary, bottom-up approach refers to quick and indirect intervention through energy taxes, limitation in usage of energy inputs and likewise. Obviously, top-down approach seems quite attractive to political decision-makers, considering its simplicity and possibilities in minimizing the risk of climate unbalances. Subsequently, an analysis of energy efficiency in the industrial sector should be made, together with the measures of its improvement.

2. ECONOMETRIC MODELS FOR ENERGY EFFICIENCY

Measuring energy efficiency of the analysed system or process represents a basic step towards the control of energy consumption. The most frequently used indicator in industry represents Specific energy consumption (SEC) of certain output or input. Energy efficiency, usually defined as simple ratio between useful process output and energy input, doesn't represent a unique quantitative definition of energy efficiency. Therefore, other indicators should be analysed as well, such as thermal efficiency which implies a proportion of share in which energy process alienates from theoretical optimum and specific energy consumption, referred as unit of energy spent on individual product. (Giacone, Manco, 2012, p 332) Literature which elaborates energy economics suggests different approaches to solutions of problems connected to usage of simple monetary indicators of energy efficiency, such as ratio between energy and GDP, otherwise known as Index decomposition analysis (IDA) and Frontier analysis approach. Index decomposition analysis represents a top-down approach and it can be used for creation of energy efficiency indicators at national economics level. While frontier analysis is based upon evaluation of parametric and nonparametric indicators, the optimal production frontier is defined for existing level of energy, so energy efficiency is calculated as difference between real energy consumption and planned energy consumption. (Filippini, Hunt, 2009, p 15)

Many studies have tried to develop energy econometric model which could specify industry energy demand. Among them special place belongs to Adeyemi and Hunt study that analyses connection between energy adequate technical change (progress) and asymmetric price reaction. (Adeyemi, Hunt, 2006, p 20) Adeyemi and Hunt examined whether energy demand model that comprises either asymmetry in price response either exogenous technical change, or both, in acceptable way determines industrial aggregate consumption in OECD countries. The majority of studies tried to determine whether simple deterministic trend should be included or not in evaluation in order to consider the effect of technical approach. Special discussion was directed towards question whether it is realistic to expect that deterministic time trend will embed technical approach and other relevant exogenous factors (e.g. government policies, important changes in economic structure etc.) so it allows for Underlying energy demand trend (UEDT) to be stochastic. Finally, there is no consensus about evaluation mode of industry energy demand, especially how to include the effect of technical change into the model (and other relevant exogenous factors). Researchers accepted the principle proposed by Hunt et al who claimed that every evaluated model should be flexible enough and every limited version acceptable only if proved by empirical data. (Hunt et al, 2003, p 93-118) It is important to emphasize that asymmetry is less inherent to energy demand of industrial sector than to the complete energy demand of certain country; for instance, introduction of greater number of efficient automobiles in sense of fuel consumption hardly will lead to decrease of oil price. However, if the price of energy-generating products stimulates installation of more efficient equipment in industrial sector, probability of abolishing that trend is extremely small even if the price of energy-generating products increases.

Several studies have also examined question of energy efficiency on macroeconomic level, so they tried to define prevailing factors in reaching the maximum possible level of energy efficiency. The most important variables that affect energy efficiency are total factor productivity and purchase power parity. Technologically advanced economies have higher energy efficiency, ceteris paribus. Still, countries with undervalued courses try to become more energy efficient. Derived trends imply that energy efficiency has improved during the time in most developing countries. (Stern, 2012) Linear programming models have also given their contribution to the recent energy models, and they put special emphasis to the following important factors of energy consumption: gross income, gross output, profit, amount of energy, ratio between GDP and energy, energy performance and energy production. The general conclusion is that technology, efficiency, offer, demand, employment and resource accessibility are used as limiting factors. Behavioural or econometric model and statistic one-side models reflect total aggregate characteristics of energy supply and demand and they are oriented towards predictions. Linear programming models of different sorts can be used profitable in all time frames, while econometric models are more appropriate to short-term and long-term predictions. (Jebaraj, Iniyan, 2006, p 302)

2.1. Measuring energy efficiency in industry: a parametric frontier approach

Aside Index decomposition analysis, elaborated in former chapter, many researchers have also used Data envelopment analysis (DEA) due to comparison of energy efficiency between different countries or regions. Despite its advantages, DEA represents nonparametric mathematic approach which doesn’t consider statistical deviations. In order to include statistical deviations in analysis of energy efficiency, a parametric frontier approach has been introduced to measure energy efficiency on level of economy or its certain sector. The proposed approach uses Shephard distance function in order to define energy efficiency index and it applies Stohastic frontier approach (SFA) to evaluate index. Theoretically, this approach isn’t different from regression analysis, which is momentarily especially popular tool for comparison of energy efficiency development. The only difference is that simple regression analysis reflects “central tendencies” in behaviour, while SFA represents “frontier” statistic technology that examines the best performance. In scientific literature, SFA is used for comparison of energy efficiency in construction and industry. For instance, Feijoo et al use Cobb-Douglas SFA model to analyse energy efficiency of Spanish industry. (Feijoo et al, 2002, p 405-423) In more recent study, Boyd proposes usage of regression analysis of stochastic frontier due to evaluation of energy efficiency in certain plant. (Boyd, 2007, p 12)
Parametric frontier model analyses neoclassic aggregate production in which capital (C), labour (L) and energy (E) represent inputs while GDP (Y) is observed as output. (The same approach has been used in evaluation of casual relationship between energy consumption and

economic growth). Conceptually, production technology can be described through following model:

$$T = \{(K, L, E, Y) : (K, L, E) which produces Y\} \quad (1)$$

where T comprises all possible input-output vectors and is usually displayed as production technology figure, commonly described by group of inputs or outputs. In production theory T is usually observed as closed or limited group. Besides, the assumption is that inputs and outputs are widely available. The presumption is that $(K', L', E', Y') \in so that (K', L', E') \geq (K, L, E)$ and $Y' \leq Y$. In order to measure energy efficiency from aspect of production efficiency, Shephard sub-vector distance function is employed as follows:

$$D_E(K, L, E, Y) = \sup\{\alpha : (K, L, E / \alpha, Y) \in T\} \quad (2)$$

Equation (2) tries to reduce energy consumption in the biggest possible measure by holding the existent combination of inputs and outputs within boundaries of production technology defined in (1). As a result, $E / D_E(K, L, E, Y)$ reflects hypothetical usage of energy if object of analysis becomes energy efficient. In that case, relationship between hypothetical energy consumption and real energy consumption, which is reciprocal to function of sub-vector distance, can be defined as aggregate index of energy efficiency, e.g.

$$EEI = 1 / D_E(K, L, E, Y) \quad (3)$$

Definition of EEI implies its value will amount one (1) if the energy unit evaluated is placed upon best position on a frontier. On the contrary, EEI will amount less than one, so that the higher value also implies a better performance of energy efficiency. Figure 1 illustrates energy efficiency index.

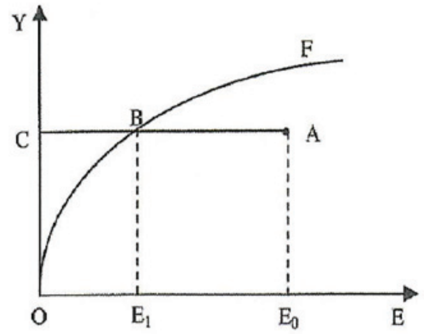

Figure 1. Graphical display of energy efficiency index

Curve OF represent production isoquant for variables E and Y when C and L are fixed. The assumption is that energy efficiency index for point A should be evaluated. It is necessary to decrease its existing energy level from E_0 to E_1 so to reach desired production isoquant. As the result, function of Shephard energy distance becomes equal to CA/CB and reciprocal to value of energy efficiency index.

3. EMPIRICAL ANALYSIS OF THE CROATIAN INDUSTRIAL SECTOR

Starting with the National classification of activities for 2007, this analysis encompasses four industrial sectors: (B) Mining and quarrying, (C) Manufacturing, (D) Electricity, gas, steam and air conditioning supply, and (E) Water supply: sewerage, waste management and remediation activities (division 36). (Croatia in figures, 2011) Before the concrete calculation of energy efficiency indexes, it is necessary to define variables that will be used in the considered model: capital (C) defined as total value of sold industrial products according to National classification for 2009. It is necessary to accommodate capital data to other observed values represented in indexes, so as the relevant value numbers outlined for manufacturing will be used, since it had the highest results (*Manufacturing=100*). Afterwards, labour will be examined (L) as indexes of totally employed in industry, energy (E) as total consumption in industry (besides energy). In comparison to total energy consumption which in 2009 amounted 15.915 GWh, industry segment derived 3.284 or app 21%. This value will be multiplied to each sector's output as to express app energy output. Finally, one should define output (Y) as index of physical volume of industry production. Calculation of energy efficiency from aspect of production efficiency also requires additional variable, α, which represents a constant specific to certain energy object, and it will be analysed at evaluated level of 4.241 used in aggregate models with time random variables. (Filippini, Lester, 2009, p 17) More complex analyses evaluate constant α through software, such as FRONTIER 4.1. However, due to the complexity of software and numerous variable required, that sort of analysis will be excluded from this research.

Table 1. Index values of parametric frontier variables according to examined industrial sectors

Industrial sector according to National class. 2007	*Capital (C)*	*Labour (L)*	*Energy (E) Y*0.21*	*Output (Y)*	*Constant* α
(B) Mining and quarrying	4	89	19	92	4.241
(C) Manufacturing	100	91	19	91	4.241
(D) Electricity, gas, steam and air conditioning supply	11	100	21	100	4.241
(E) Water supply	2	108	21	101	4.241

Analysis of the collected data requires a definition of production technology value that can be done through equation (1):

(B) Mining and quarrying

$$T_b = \{(4,89,19,92) : (4,89,19)\} = 204 : 112 = 1,82 \quad (4)$$

(C) Manufacturing

$$T_c = \{(100,91,19,91) : (100,91,19)\} = 301 : 210 = 1,43 \quad (5)$$

(D) Electricity, gas, steam and air conditioning supply

$$T_d = \{(11,100,21,100) : (11,100,21)\} = 232 : 132 = 1,76 \quad (6)$$

(E) Water supply: sewerage, waste management and remediation activities

$$T_e = \{(2,108,21,101) : (2,108,21)\} = 232 : 131 = 1,77 \quad (7)$$

Further on, energy efficiency from aspect of production efficiency should be evaluated, for which purpose Shephard sub-vector distance function is applied as in equation (2):

(B) Mining and quarrying

$$D_{Eb}(K,L,E,Y) = \sup\{4.241 : (4{,}89{,}19/4.241{,}92) \in 1.82\} \quad (8)$$

(C) Manufacturing

$$D_{Ec}(K,L,E,Y) = \sup\{4.241 : (100{,}91{,}19/4.241{,}91) \in 1.43\} \quad (9)$$

(D) Electricity, gas, steam and air conditioning supply

$$D_{Ed}(K,L,E,Y) = \sup\{4.241 : (11{,}100{,}21/4.241{,}100) \in 1.76\} \quad (10)$$

(E) Water supply: sewerage, waste management and remediation activities

$$D_{Ee}(K,L,E,Y) = \sup\{4.241 : (2{,}108{,}21/4.241{,}101) \in 1.77\} \quad (11)$$

Given values serve to calculate energy efficiency index, according to model presented in equation (3)

(B) Mining and quarrying

$$EEI_b = 1/D_E(K,L,E,Y) = 1/1.82 = 0.549 \quad (12)$$

(C) Manufacturing

$$EEI_c = 1/D_E(K,L,E,Y) = 1/1.43 = 0.699 \quad (13)$$

(D) Electricity, gas, steam and air conditioning supply

$$EEI_d = 1/D_E(K,L,E,Y) = 1/1.76 = 0.568 \quad (14)$$

(E) Water supply: sewerage, waste management and remediation activities

$$EEI_e = 1/D_E(K,L,E,Y) = 1/1.77 = 0.565 \quad (15)$$

Since by definition, energy efficiency index is set at one (1) for energy subject which produces in energy efficient way, calculated results of this research imply that among analysed sectors the best results are achieved in manufacturing (deviation from energy frontier -0.310). Electricity, gas, steam and air conditioning supply is on the second place with deviation -0.432, followed by water supply (-0.435) and finally, mining and quarrying (-0.451). Numerical analysis implies necessary improvement measures for energy efficiency in all analysed sectors that can also be illustrated in Figure 2, showing the significant deviations in all sectors.

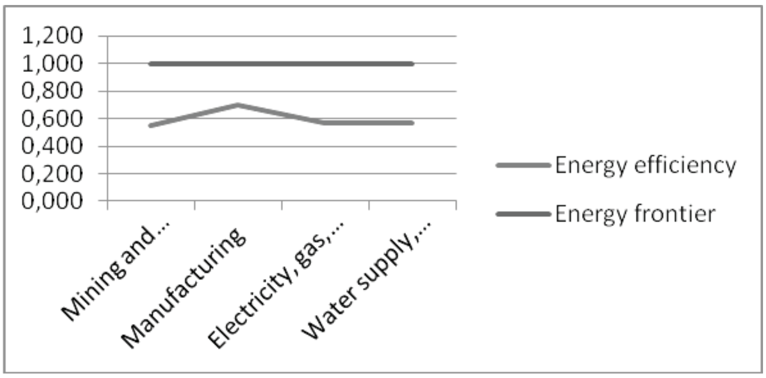

Figure 2. Energy efficiency indexes for chosen industrial sectors

Improvements of energy efficiency in analysed sectors can be achieved from different aspects, and commonly used successful tool, implemented by developing countries, are eco-innovations. In their study, Faucheux and Nicolaï analyse the concept of eco-innovation that decreases naturally set boundaries and contributes to approaching goals of the sustainable development. (Faucheux, Nicolaï, 2011, p 2020-2027) In sense of research and development, IT sector has become the biggest investor and employer in Europe, USA and Japan. In OECD countries this sector engages 26% of private research and development sector, employs 32% of researchers and is responsible for 21% of all patents. In Europe annual employment rate in IT sector amounts 8%. Every work place opened in this sector is connected to creation of four additional work places in total European economy, whether it is along suppliers' sector or industrial software sector.

The main reason for implementation of smart grid of energy resources is more efficient usage of production infrastructure, transmission and distribution of electricity. This could help distribution sector to improve its management of energy demand and supply. Smart grid represents a set of software and hardware tools which enable plant to deliver energy in more efficient way by reducing need for surpluses. It also enables double-sided lines of information with the consumers in order to duly determine demand. Successful application of smart grid in energy sector demands a cooperation between all sector participants so to provide support to new activities and integration of all participants included in energy production, cooperation between regulatory bodies to learn from the international experiences in order to better manage the risks, and finally support of technological, managerial and organisation policies for better control of changes in consumers' behaviour. Naturally, energy efficiency increase cannot be obtained without operative usage of modern information and communication system which functionally integrates all participants in this complex and especially important system and process.

4. POSSIBLE NEGATIVE EFFECTS IN ENERGY EFFICIENCY IMPROVEMENTS AND RECOMMENDATIONS FOR THEIR ELIMINATION

House of Lords report on energy in Great Britain in 2009 outlined negative effects as possible explanation why energy efficiency improvements didn't lead to the corresponding decrease of energy consumption on macroeconomic level. Popularity of CGE.computable general equilibrium model in this context reflects its multi-sector nature in combination with their specific demand, making the analysis of economic and ecologic policies much easier. CGE models are especially adequate for analysis of negative rebound effects initiators since they enable evaluation of energy efficiency improvements. The effect of disinvestments can be obtained in domestic sector of electricity supply, when direct and derived demand for energy aren't elastic enough so to prevent decrease of energy prices which cause decrease of incomes, profitability and return on capital. This all limits the elasticity of energy supply, that is, it produces an additional pressure on real energy price. Disinvestment effect will generate globally acceptable importance in analysis of energy efficiency improvements within economy that independently provides its energy. It can also be applied on a global level, where, despite OPEC and its influence over the marginal supply, negative pressure on demand generates a negative pressure on prices. In sense of further development of model, a special attention should be given to evaluation of capital regarding its influence over the disinvestment effect. Empirical evaluation of elasticity in production and exchange is also required, as is the evaluation of other factors influencing the general balance of price elasticity for energy. Not less important is try to moderate real, politically relevant scenarios. (Turner, 2009, p 652)

Considering the above described negative rebound effects if energy efficiency improvements, as well the ambitious goals described by the EU in sense of efficiency development, numerous instruments of national policy have been developed. They aim at removing barriers to cost-effective investments in energy efficiency. Many of these political initiatives overtake the shape of voluntary agreements in which industry companies earn right to smaller taxes if they implement proposed measures of energy efficiency improvements. If a certain company makes an agreement with government, the government ensures any release of paying taxes (e.g. lower taxes on carbon-dioxide) or it promises more flexible regulations for environment protection in future. Great Britain has implemented Climate change programme which tries to reduce emissions of carbon dioxide in industry sector, based upon Climate change agreement (CCA) introduced in 2001. According to these documents energy intensive industry companies can sign ten-year agreements with government so to accomplish more efficient energy usage or to decrease carbon emissions. By signing such agreements, companies ensures 80% decrease of so-called "climate change leverage" that comprises tax on energy consumption. Not every company can sign such an agreement; their production processes have to be energetically intensive and submissive to strong international competition. During the first three years of programme, carbon dioxide emissions have been decreased for totally 3.5 million tons of which 70% of reduction has been achieved in metal industry. Described voluntary programmes are just one of positive practice examples in promoting energy efficiency, and every national government had to adopt relevant ecological measures according to their cost acceptability, existing state of national energy economics and relevant institutional and regulatory directives. (Henriksson, Söderholm, 2009, p 238)

5. CONCLUSION

Most developing countries today testify the global energy crisis, so more attention has been given to promoting energy efficiency measures. This problem has been recognized by governments of relevant countries which promote energy efficiency in strategic and operative documents through which they try to improve achieved development level of energy sector. The Republic of Croatia, as signatory of Kyoto protocol, adopted National action plan for energy efficiency 2008-2016 by which it defines energy saving in construction, transportation and small size industries. Presently there are numerous models and programs for evaluation of accomplished energy efficiency level, among which special place belongs to parametric frontier that includes statistic deviations. Namely, wrong choice of methodology in calculation of energy efficiency can cause wrong results and misled carriers of political decisions. Among analysed industrial sectors in Republic of Croatia the best results in energy efficiency have been recorded in manufacturing. However, the general trend has implied an urge for introducing instant measures of energy efficiency improvement nationally. Aside fact that is extremely important to accurately choose methodology for energy efficiency calculation, it is equally important to choose right, costly effective ecologic policies that will provide best possible results in a long time period. The Government of Great Britain obtained a detailed study in 2009 to analyse negative rebound effects that emerged despite energy efficiency improvements. Analysis implied that special attention should be given to capital evaluation considering its effect on disinvestment, though elasticity evaluation in production and exchange equally matter. Despite fact that condition of energy sector in each national economy reflects their specific ecological, political and legislative conditions, examples of positive practices can be recognized and adjusted to specific terms. As exceptionally successful instrument of political initiatives, the voluntary agreements emerged by which industrial companies earn right to lower taxes if they implement the right energy efficiency improvements. Considering the fact these are voluntary agreements, each energy subjects should independently decide upon strengths and weaknesses of such agreements so to make future decision about their energy orientation. Further investments in developing appropriate models and software programmes are necessary so they could precisely evaluate existing condition in Croatian energy sector, or vice versa, to define future guidelines for carriers of political decisions.

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ENERGETSKA EFIKASNOST I NJEZINE IMPLIKACIJE U INDUSTRIJI

Sažetak: *RH usvojila je Nacionalni akcijski plan energetske efikasnosti 2008.-2016. koji definira finalne uštede energije od 0.47 Mtoe/5.47 TWh u građevinarstvu, transportu i malim industrijama. Energetska efikasnost uobičajeno se izražava kao odnos korisnog outputa i energetskog inputa, što često navodi na pogrešne zaključke pa se nosioci odluka u energetskom sektoru oslanjanju na dodatne pokazatelje poput termalne efikasnosti i specifične energetske potrošnje (SEC). SEC je najčešće korišten vrijednosni pokazatelj u industriji. Iako povećanje energetske efikasnosti predstavlja jedan od najvažnijih strateških ciljeva razvijenih zemalja, on se ne smije promatrati nezavisno od ostalih razvojnih ciljeva. Da bi se izbjegli negativni učinci koje porast energetske efikasnosti može prouzročiti u investicijskim ciklusima, potrebno je osigurati usklađeno djelovanje svih subjekata energetskog i ekonomskog sektora pojedine zemlje.*

Ključne riječi: RH, energetska efikasnost, industrija, specifična energetska potrošnja (SEC), negativni učinci

PLANIRANJE ODRŽIVOG RAZVOJA RURALNIH ZAJEDNICA

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Sažetak: *Jedan od bitnih preduvjeta ublažavanja negativnih klimatskih utjecaja na globalnoj razini je značajno smanjenje potrošnje svih tipova energije. Posljednjih 20-tak godina, prvenstveno razvijene zemlje Europe i svijeta nastoje pronaći najbolje načine kako bi postigle ciljeve na koje su se obvezale kroz Međunarodni sporazum o klimatskim promjenama, Protokol iz Kyota i druge međunarodne ugovore. Kroz godine djelovanja na nacionalnoj razini, postalo je jasno kako država ne može ostvariti značajnije rezultate bez aktivnog sudjelovanja regionalne i lokalne vlasti.*

Sporazum gradonačelnika (eng. Covenant of Mayors) je odgovor naprednih europskih gradova i općina na izazove globalne promjene klime, a ujedno prva i najambicioznija inicijativa Europske komisije usmjerena direktno na aktivno uključenje i kontinuirano sudjelovanje gradskih i općinskih uprava i samih građana u borbi protiv globalnog zatopljenja. Potpisivanjem Sporazuma gradonačelnici se obvezuju na primjenu brojnih mjera energetske učinkovitosti kojima će u konačnici do 2020. godine smanjiti emisije CO_2 *u svom gradu za više od 20% na koliko obvezuje Prijedlog Europske energetske politike iz 2007. godine. Do srpnja 2012. godine Sporazum je potpisalo 4 104 gradova (cca 164 751 156 stanovnika), a interes za pristupanjem novih gradova sve je veći. Uz više od 4 000 europskih gradova, Sporazumu su pristupili i gradovi iz Argentine, Novog Zelanda i Kirgistana. Od hrvatskih gradova i općina inicijativi su se prvi tijekom 2008. godine pridružili Zagreb, Rijeka i Ivanić Grad, a do danas Sporazum je potpisalo 38 lokalnih zajednica (gradova i općina). Jedan od osnovnih ciljeva inicijative Sporazum gradonačelnika je poticanje lokalnih zajednica na izradu planskih dokumenata za povećanje energetske učinkovitosti, korištenja obnovljivih izvora energije i zaštite okoliša na njihovom području. Kvalitetno i precizno planiranje s jasno definiranom vizijom važan su preduvjet uspješnog energetski održivog razvitka. Iz tog je razloga, konkretna obveza lokalne zajednice nakon priključenja inicijativi izrada Akcijskog plana energetski održivog razvitka (eng. Sustainable Energy Action Plan - SEAP) koji jasno i realno definira strateške ciljeve i prioritete održivog energetskog razvitka do 2020. godine.*

Lokalne zajednice uključene u inicijativu različitih su karakteristika, potreba, veličina i kapaciteta, pri čemu veliki broj njih raspolaže ograničenim financijskim sredstvima i stručnim resursima za izradu složenih planova energetski održivog razvitka i provedbu identificiranih projekata. Metodologija izrade planova je relativno komplicirana i potrebno je približiti je i prilagoditi manjim lokalnim, prvenstveno ruralnim zajednicama. Prepoznavši problematiku, Europska je komisija pokrenula programe financiranja za jačanje kapaciteta ruralnih zajednica u tom smislu. Niz manjih hrvatskih gradova i općina uz pomoć europskih programa i fondova razvijaju svoje Akcijske planove energetski održivog razvitka te provode konkretne projekte povećanja energetske učinkovitosti i korištenja obnovljivih izvora energije.

Ključne riječi: energetska učinkovitost, globalno zatopljenje, Akcijski plan energetski održivog razvitka (SEAP), Sporazum gradonačelnika, ruralne zajednice

1. UVOD

Pred državama Europske unije su brojni izazovi budućeg gospodarskog i energetskog razvitka na nacionalnim, regionalnim i lokalnim razinama. Razvitak gospodarstva i porast životnog standarda uvjetuje sve veću potrošnju energije što se iznimno negativno odražava na klimu i okoliš. U cilju sprječavanja negativnih posljedica, Europska unija je postavila strateške ciljeve 20%-20%-20% (20% smanjenje CO_2, 20% povećanje energetske učinkovitosti i 20% povećanje korištenja obnovljivih izvora energije) do 2020. godine. Ambiciozni cilj smanjenja emisija stakleničkih plinova za više od 20% u odnosu na referentnu godinu moguć je samo uz aktivno uključenje i sudjelovanje gradskih uprava, brojnih interesnih skupina, obrazovnih i znanstvenih institucija, nevladinih udruga i samih građana što većeg broja europskih gradova i općina.

Jedinice lokalne i regionalne samouprave prihvatile su izazove i odlučile samostalno kreirati vlastiti energetski razvitak. O navedenom svjedoči iznimno velik odaziv europskih, lokalnih i regionalnih vlasti uključenih u EC inicijativu Sporazum gradonačelnika. Pokretanjem ove inicijative, Europska je komisija još jednom istaknula važnost donošenja ispravnih odluka i pokretanja projekata održivog energetskog razvitka na lokalnim razinama za razvitak čitave države na načelima održivosti, energetske učinkovitosti i zaštite okoliša.
Ovdje je važno naglasiti da se uključivanjem u inicijativu te preuzimanjem obveze za vlastiti energetski razvitak jedinice lokalne samouprave susreću s brojnim izazovima i barijerama.

Osobito je veliki izazov malih, ruralnih jedinica lokalne samouprave koje često nemaju tehničkih, financijskih ili organizacijskih kapaciteta za provođenje preuzetih obveza. Ruralne zajednice su specifične po tome što veliki broj njih raspolaže sa znatnim potencijalom obnovljivih izvora energije koji zbog brojnih barijera, od organizacijskih do financijskih ostaje neiskorišten.

2. EUROPSKA ENERGETSKA POLITIKA I RURALNI RAZVOJ

2.1. Europska energetska politika

Europska energetska politika jasno je usmjerena na postizanje ciljeva 20%-20%-20% do 2020. godine. Usvajanjem Europske energetske politike u 2007. godini postavljeni su temelji za aktivno sudjelovanje regionalne i lokalne uprave u energetskom razvitku zemalja članica Europske unije te prijenosa dijela odgovornosti na regionalne i lokalne vlasti.

Iz tog je razloga, početkom 2008. godine Europska komisija pokrenula inicijativu Sporazum gradonačelnika, s osnovnim ciljem povezivanja gradonačelnika energetski osviještenih europskih gradova u trajnu mrežu kroz koju će zajedničkim radom i naporima izgraditi energetski održivu Europu. Sporazum gradonačelnika je ustvari odgovor naprednih europskih gradova na izazove globalne promjene klime te prva i najambicioznija inicijativa Europske komisije koja izravno potiče lokalne vlasti i građane na njihovo aktivno uključivanje u zajedničku borbu protiv globalnog zatopljenja. Potpisivanjem Sporazuma gradonačelnici se obvezuju na provedbu konkretnih mjera energetske učinkovitosti koje će omogućiti provedbu Europske energetske politike do 2020. godine.

Sporazumom su definirane i konkretne obveze potpisnika:

- Informiranje građana o mogućnostima i prednostima korištenja energije na učinkoviti način;
- Organiziranje Energetskih dana ili Dana Sporazuma gradova, u suradnji s Europskom komisijom i dionicima;
- Prisustvovanje i doprinos godišnjim Konferencijama gradonačelnika EU o energetski održivoj Europi;
- Razmjena iskustava i znanja s drugim gradovima i općinama;
- Izrada Akcijskog plana energetski održivog razvitka grada do 2020. godine (u nastavku Akcijski plan) u skladu s priručnikom Europske komisije: Kako izraditi Akcijski plan?
- Izrada Referentnog inventara emisija CO2 (u nastavku Inventar) kao temelja za izradu Akcijskog plana;
- Provedba konkretnih mjera smanjenja emisija CO2 identificiranih u Akcijskom planu;
- Osiguranje potrebnog stručnog potencijala za provedbu Akcijskog plana;
- Kontrola i praćenje uspješnosti i dinamike provedbe Akcijskog plana;
- Podnošenje izvješća o realizaciji Akcijskog plana Europskoj komisiji svake dvije godine;
- Redovno informiranje lokalnih medija o rezultatima provedbe Akcijskog plana.

Akcijski plan energetski održivog razvitka grada predstavlja osnovni dokument koji, na temelju prikupljenih podataka o zatečenom stanju, identificira i daje precizne i jasne odrednice za provedbu projekata, mjera energetske učinkovitosti, korištenja obnovljivih izvora energije i ekološko prihvatljivih goriva na gradskoj razini, sa ciljem smanjenja emisije CO_2 za više od 20% do 2020. godine.
Akcijski plan je usmjeren na dugoročne pretvorbe energetskih sustava unutar gradova te daje mjerljive ciljeve i rezultate racionalnog gospodarenja energijom, smanjenja potrošnje energije, primjena obnovljivih izvora energije te ekološki prihvatljivih goriva i emisija CO_2.

Do srpnja 2012. godine Sporazum je potpisalo 4 104 gradova (cca 164 751 156 stanovnika), a interes za pristupanje novih gradova sve je veći. Uz više od 4 000 europskih gradova, Sporazumu su pristupili i gradovi iz Argentine, Novog Zelanda i Kirgistana.

Slika 1. Gradovi potpisnici Sporazuma gradonačelnika u Europskoj uniji i RH

Od hrvatskih gradova inicijativi su se prvi tijekom 2008. godine pridružili Zagreb, Rijeka i Ivanić Grad, a do danas Sporazum je potpisalo 38 hrvatskih lokalnih zajednica (gradova i općina), odnosno oko 30% gradova u Republici Hrvatskoj. Ukupno 20 hrvatskih gradova je izradilo i prihvatilo Akcijski plan energetski održivog razvitka (SEAP) kao službeni, provedbeni dokument.

Tablica 1. Hrvatski gradovi potpisnici Sporazuma gradonačelnika

Br.	**Hrvatski gradovi potpisnici**	**Datum pristupanja**	**Datum prihvaćanja SEAP-a**
1	Zagreb	30.10.2008.	20.4.2010.
2	Ivanić – Grad	24.02.2009.	17.5.2010.
3	Rijeka	10.02.2009.	27.5.2010.
4	Klanjec	24.09.2009.	24.9.2010.
5	Zaprešić	16.03.2010.	21.4.2011.
6	Velika Gorica	15.03.2010.	12.10.2011.
7	Ozalj	25.11.2009.	15.11.2011.
8	Duga Resa	17.12.2009.	28.12.2011.
9	Opatija	08.12.2010.	27.3.2012.
10	Koprivnica	29.07.2010.	26.7.2011.
11	Jastrebarsko	09.03.2010.	14.12.2011.
12	Slunj	12.07.2011.	1.2.2012.
13	Sisak	09.03.2010.	29.11.2011.
14	Gospić	01.07.2011.	31.05. 2012.
15	Barban	13.04.2011.	-
16	Ogulin	08.07.2011.	29.06.2012.
17	Samobor	22.07.2010.	29. 03. 2012.
18	Sveta Nedelja	15.12.2010.	25. 01. 2012.
19	Karlovac	16.02.2010.	15.05.2012.
20	Sveti Ivan Zelina	06.12.2010.	-
21	Pregrada	01.02.2010.	27.02.2012.
22	Kastav	24.02.2011.	-
23	Oprtalj	17.03.2011.	-
24	Umag	14.04.2011.	-
25	Buje	18.03.2011.	-
26	Brtonigla	07.04.2011.	-
27	Labin	16.05.2011.	-
28	Buzet	19.05.2011.	-
29	Rovinj	20.05.2011.	-
30	Bjelovar	14.10.2011.	-
31	Brdovec	15.11.2011.	-
32	Dugo Selo	3.11.2011.	-
33	Grožnjan	22.10.2011.	-
34	Križevci	12.7.2011.	17.07.2012.
35	Krk	25.5.2011.	-
36	Osijek	6.12.2011.	-
37	Otočac	22.12.2011.	-
38	Pula	26.4.2011.	-

Slika 2. Prva svečanost potpisivanja Sporazuma gradonačelnika u Europskom parlamentu kojem su prisustvovali i gradonačelnici Zagreba, Ivanić-grada i Rijeke, Bruxelles, 10. veljače 2009. godine

Pristupanjem Sporazumu gradonačelnika, te provedbom akcijskog plana, lokalne zajednice postižu sljedeće učinke:

- postavljaju temelje energetski održivom razvitku baziranom na načelima zaštite okoliša, korištenja obnovljivih izvora energije, održive gradnje i primjena mjera energetske učinkovitosti u svim segmentima života i rada svojih stanovnika,
- povećavaju kvalitetu života na svom području (poboljšanje kvalitete zraka, smanjenje prometnih zagušenja i sl.);
- osiguravaju nove financijske mehanizme za provedbu mjera energetske učinkovitosti, korištenja obnovljivih izvora energije i ekološko prihvatljivih goriva na svom području (na pr. EU fond Elena);
- omogućuju pretvorbu urbanih ili ruralnih sredina u ekološki održive;
- razmjenjuju iskustva s energetski razvijenim lokalnim zajednicama i provedbom provjerenih projekata dobre prakse osiguravaju ekonomsko-energetski optimalna rješenja.

Europska i hrvatska energetska politika tehnički i financijski podupire održiv energetski razvoj te aktivno potiče jedinice lokalne samouprave na djelovanje u tom kontekstu. No na njima je samima da na najbolji način osmisle vlastiti energetski razvitak kroz dugoročno strateško planiranje i uspješnu provedbu identificiranih mjera. Akcijski planovi predstavljaju dobar alat svim lokalnim zajednicama za dugoročno sagledavanje i iskorištavanje vlastitih energetskih potencijala. Problem s kojim se manji gradovi i ruralne zajednice često suočavaju, kako u Republici Hrvatskoj, tako i u ostalim zajednicama u Europskoj uniji je nedostatak stručnih kapaciteta koji bi iskoristili navedene mogućnosti.

2.2. Europska politika ruralnog razvoja

Europska unija ruralnu Europu prepoznaje kao područje koje se prostire diljem regija različitih država, a obuhvaća područja netaknutog krajobraza te poljoprivrednog i šumskog zemljišta, sela, male gradove i naselja koja okružuju industrijske i regionalne centre. Politika ruralnog razvoja Europske unije posljednjih je godina znatno ojačala te su definirane konkretne smjernice i prioriteti. Strateške smjernice europskog ruralnog razvoja daju makropolitički kontekst i temelj za izradu nacionalnih strateških planova pojedinih zemalja članica. Nacionalni strateški planovi ruralnog razvoja definiraju se na razini resornih ministarstava pojedine države članice, a uključuju izradu analize stanja i prepoznavanje odgovarajućih prioriteta za ruralna područja pojedinih država, a koji su u skladu s ciljevima Strateških smjernica Europske unije.

Nacionalni strateški planovi postaju referentni okvir za izradu detaljnih programa ruralnog razvoja (PRR) zemalja članica. Programi ruralnog razvoja stvoreni su kako bi se bavili specifičnim nacionalnim i regionalnim prioritetima, a predstavljaju glavni operativni mehanizam za provedbu politike ruralnog razvoja Europske unije u pojedinim zemljama članicama.

Pred politikom ruralnog razvoja Europske unije su brojni izazovi od kojih treba posebno istaknuti optimalno korištenje obnovljivih izvora energije i mjere za ublažavanje klimatskih promjena. U tom smislu europska energetska politika i politika ruralnog razvoja međusobno su povezane.

Kako bi dala podršku i vjetar u leđa provedbi ciljeva ruralnog razvoja Europska unija definirala je i financijske mehanizme potpore, prvenstveno Europski poljoprivredni fond za ruralni razvoj (EPFRR). Europski poljoprivredni fond za ruralni razvoj sufinancira aktivnosti zemalja članica u sklopu definiranog programa ruralnog razvoja koje se baziraju na tri prioritetne osi:

- 1. prioritetna os – Unaprjeđenje konkurentnosti sektora poljoprivrede i šumarstva,
- 2. prioritetna os – Potpora upravljanju zemljištem i okolišem
- 3. prioritetna os – Poboljšanje kvalitete života i potpora diverzifikaciji gospodarskih aktivnosti.

U sklopu 3. prioritetne osi financijski se podržavaju energetski projekti lokalnih samouprava, prvenstveno ruralnih zajednica, a posebno izgradnja toplana na biomasu i bioplin. Ovdje je važno spomenuti da komplicirana prijavna procedura za dobivanje ovih sredstava zahtjeva zavidnu razinu tehničkog znanja koja vrlo često nedostaje upravnim tijelima ruralnih zajednica u Republici Hrvatskoj.

Politika ruralnog razvoja i na razini Europske unije i Republike Hrvatske podupiru održivo iskorištavanje vlastitih energetskih potencijala ruralnih sredina. Nažalost, realna je situacija takva da je zbog brojnih razloga, osim energetskog planiranja upitna i tehnička mogućnost iskorištavanja energetskih potencijala na razini malih lokalnih zajednica.

3. PROBLEMI ENERGETSKOG RAZVOJA RURALNIH ZAJEDNICA

3.1. Analiza barijera za energetski razvoj ruralnih zajednica

Kroz IEE projekt „Energetska mreža znanja održivih ruralnih zajednica“ (eReNet) u kojem sudjeluje šest ruralnih zajednica iz raznih dijelova Europe - Judenburg (Austrija), Assenovgrad (Bugarska), Dugo Selo i Sveta Nedjelja (Hrvatska), Amyntaio (Grčka) i Sertã (Portugal) provedena je analiza glavnih barijera za provođenje energetskih projekata u ruralnim sredinama.

Projekt ima za cilj potaknuti aktivnosti u ruralnim zajednicama, pomoći im u energetskom planiranju te izraditi web alate za razvoj Akcijskih planova energetski održivog razvoja (SEAP-a).

U 6 gore navedenih gradova provedeno je anketno istraživanje koje je obuhvatilo 951 predstavnika iz različitih interesnih skupina – nacionalne, regionalne i lokalne institucije, škole, sveučilišta, građani, poljoprivrednici, energetske agencije, energetska poduzeća, razvojne institucije i dr. Cilj istraživanja je bio analizirati trenutne aktivnosti u ruralnim zajednicama vezane uz energetski održivi razvoj, najznačajnije barijere za provođenje projekata te potencijale koje bi ruralne zajednice trebale iskoristiti u planiranju vlastitog energetskog razvoja.

Ispitani dionici u gradovima ruralnog područja pokazali su generalno nisku razinu zadovoljstva s aktivnostima vezanima uz energetsku učinkovitost i obnovljive izvore energije provedenima u svojim lokalnim zajednicama. Ovdje je važno istaknuti da lokalne zajednice s više financijskih sredstava imaju i bolje rezultate te višu razinu zadovoljstva dionika. Kao najznačajniji dionici za pokretanje i provedbu aktivnosti održivog razvoja od većine ispitanih dionika percipirane su regionalne i lokalne agencije i lokalna samouprava.

Lokalna samouprava i energetske agencije imaju vrlo značajnu ulogu u planiranju i provođenju aktivnosti na lokalnom nivou. Provedeno istraživanje pokazuje da iako imaju izrazito značajnu ulogu kao pokretači energetskog razvoja malih lokalnih zajednica, istovremeno se susreću s nizom različitih barijera.
Prema rezultatima provedenog istraživanja glavne barijere energetskog razvitka ruralnih zajednica su sljedeće:

- nedostatak direktnih inicijativa na lokalnoj razini;
- nedostatak financijskih sredstava za provedbu energetskih projekata;
- neodgovarajuća organizacija unutar lokalnih samouprava;
- nedovoljno uključivanje dionika u proces odlučivanja;
- nedostatak stručnog kadra;
- neodgovarajuća proračunska politika za stimuliranje energetskih projekata;
- nedovoljna upućenost u nove tehnologije i mogućnosti.

Jedna od najznačajnijih barijera za provođenje energetskih projekata na razini ruralnih zajednica je nedostatak financijskih sredstava. S ovom se preprekom suočavaju i veći gradovi, regionalna samouprava i nacionalne vlasti brojnih država, no važno je istaknuti da male ruralne zajednice još jače osjećaju financijske probleme. Analiza rezultata ispitivanja pokazuje izrazitu neupućenost uprava ruralnih zajednica u mogućnosti financiranja energetskih projekata putem nacionalnih ili europskih fondova. Može se zaključiti da se lokalne vlasti ali i regionalne i lokalne energetske agencije izrazito slabo koriste raspoloživim izvorima financiranja.

Broj projekata ili promocijskih aktivnosti vezanih uz održivi razvoj koje su prepoznate od strane različitih dionika u ruralnim zajednicama je nizak, tj. broj aktivnosti koje su se do sada provodile vrlo malen. S druge strane istraživanje pokazuje vrlo veliku zainteresiranost svih dionika za pokretanje i provedbu konkretnih projekata, kao i kontinuirane informativno-promotivne aktivnosti u lokalnim zajednicama.

Lokalne vlasti svjesne su, i nezadovoljne zbog činjenice da se provodi izrazito mali broj energetskih projekata. Dio anketnog upitnika odnosio se na ocjenu prioriteta projekata, tj. koje bi se vrste aktivnosti ili projekata trebale provoditi u lokalnim zajednicama. Lokalne su vlasti pokazale neodlučnost vezano uz prioritetne aktivnosti u vlastitim ruralnim zajednicama. Iz toga je vidljivo da u malim ruralnim zajednicama često nedostaje jasna vizija održivog energetskog razvoja u skladu s njihovim mogućnostima, karakteristikama i potencijalima. S obzirom da ruralne zajednice često imaju više mogućnosti za iskorištavanje vlastitih resursa i energetsku samoodrživost, potrebno je potaknuti upravo ovakve zajednice na definiranje jasne strategije energetskog razvoja.

Za ruralne zajednice karakteristična su područja poljoprivrednog i šumskog zemljišta te sela. Iz toga razloga u istraživanje je kao posebna kategorija dionika uključena kategorija poljoprivrednika. Rezultati za ovu grupu lokalnih dionika ukazuju na neupućenost o mogućnostima upotrebe biomase te ostataka iz poljoprivredne proizvodnje za proizvodnju energije kao niti mogućnostima financiranja ovakvih projekata iz različitih fondova. U tom je smislu potrebno na razini lokalnih zajednica potaknuti poljoprivrednike i male šumovlasnike na udruživanje te promovirati i informirati ih o mogućnostima iskorištavanja vrijednih energetskih potencijala.

3.2. Preporuke za smanjenje barijera

Kao što je istaknuto, male lokalne zajednice često nisu u mogućnosti prepoznati vlastite prioritete energetskog razvoja i provesti ih na lokalnoj razini. Razlog leži u već opisanim problemima i preprekama koje lokalne zajednice trebaju prevladati na razne načine.

Jedan od načina podizanja razine informiranosti i kompetencija je zajedničko djelovanje na lokalnoj, regionalnoj i nacionalnoj razini te sudjelovanje u inicijativama na razini Europske unije, kao npr. u inicijativi Sporazum gradonačelnika. Kroz međusobno umrežavanje male ruralne zajednice imaju priliku dobiti uvid u najbolje primjere održivog energetskog planiranja i provedbe projekata te razmijeniti pozitivna iskustva s drugim lokalnim zajednicama.

Na razini Republike Hrvatske djeluje inicijativa pod nazivom Hrvatski klub Covenant of Mayors u koju se aktivno uključilo devetnaest hrvatskih gradova – Zagreb, Velika Gorica, Ozalj, Sveta Nedelja, Ivanić-Grad, Jastrebarsko, Karlovac, Duga Resa, Sv. Ivan Zelina, Rijeka, Zaprešić, Pregrada, Koprivnica, Klanjec, Sisak, Samobor, Opatija, Krk i Kastav te pet hrvatskih energetskih agencija - Regionalna energetska agencija sjeverozapadne Hrvatske, Međimurska energetska agencija, Istarska regionalna energetska agencija, Regionalna energetska agencija Kvarner i Regionalna energetska agencija Sjever.

Potpisivanjem Povelje o utemeljenju Hrvatskog kluba Covenant of Mayors, hrvatski gradovi i energetske agencije prihvatile su obvezu ostvarenja ciljeva koje je postavila Europska unija do 2020. – smanjenje emisije CO_2 za najmanje 20 posto kroz provedbu Akcijskih planova energetski održivog razvitka gradova. Također su se obvezali i na razmjenu znanja i iskustava te aktivnu suradnju na tom području s gradovima i drugim teritorijalnim jedinicama u Republici Hrvatskoj te na promoviranje održivog razvoja lokalnih zajednica.

Na taj način uspostavljena je suradnja između svih gradova Republike Hrvatske koji žele razvijati svoju budućnost ne temeljima održivog energetskog razvoja.

Energetsko planiranje jedan je od najvažnijih preduvjeta za dugoročno energetski održiv razvoj ruralnih zajednica, ali istovremeno i značajna prepreka. Vizija energetskog razvoja i njezino uobličenje u strateški dokument često nije nimalo jednostavan posao. Akcijski planovi održivog korištenja energije predstavljaju dobar primjer strateškog dokumenta, prihvaćenog od velikog broja lokalnih zajednica. Proces izrade, provedbe i praćenja ovakvih dokumenata uključuje provedbu više koraka:

- Pripremne radnje za pokretanje Procesa (politička volja, koordinacija, stručni resursi, dionici i dr.);
- Izrada Akcijskog plana;
- Prihvaćanje Akcijskog plana kao službenog, provedbenog dokumenta grada;
- Provedba identificiranih mjera i aktivnosti koje će se provoditi na razini grada;
- Praćenje i kontrola provedbe identificiranih mjera;
- Priprema izvještaja o realiziranim projektima u vremenskim intervalima od 2 godine.

Za uklanjanje financijskih barijera postoji mogućnost dobivanja dodatnih financijskih sredstava za energetske projekte u ruralnim zajednicama iz Europskog fonda za ruralni razvoj. Ove mogućnosti stoje na raspolaganju hrvatskim gradovima nakon ulaska u Europsku uniju.

4. PRIMJERI USPJEŠNOG ENERGETSKOG PLANIRANJA PROJEKATA

Već spomenuti projekt Inteligentne energije za Europu, eReNet (Energetska mreža znanja održivih ruralnih zajednica) ima za osnovni cilj podržati energetske aktivnosti u ruralnim sredinama, poticati ruralne zajednice u energetskom razvoju, izradi, provedbi i praćenju Akcijskih planova energetski održivog razvitka te djelovati na podizanje razine znanja i sudjelovanja svih relevantnih lokalnih interesnih skupina u energetskom razvitku svog područja. Nadalje, cilj projekta je i identifikacija konkretnih lokalnih energetskih projekata, kao i mogućih izvora njihova financiranja.

Dva hrvatska grada, Dugo Selo i Sveta Nedjelja kroz realizaciju projekta će podignut razinu znanja relevantnih lokalnih aktera vezano uz energetsko planiranje i izradu strateških energetskih dokumenata te raspoloživih izvora financiranja energetskih projekata.

Aktivnosti ovog projekta usmjerene su na:

- Jačanje kapaciteta potrebnih za izradu Akcijskih planova energetski održivog razvitka i praćenje njihove implementacije;
- Jačanje kapaciteta svih dionika kroz prijenos znanja preko iskusnijih partnera;
- Razvitak najboljih praksi održivog energetskog razvitka;
- Povezivanju s ostalim dionicima na nacionalnoj razini;
- Izmjena iskustava na EU razini.

Općina Pokupsko primjer je uspješne lokalne zajednice koja se odlučila za izgradnju područnog grijanja na biomasu. Implementacijom ovakvog projekta općina će ostvariti godišnje energetske uštede u iznosu od 2.133 MWh.

Ukupni troškovi projekta iznose oko 1 000 000 EUR, od čega će 80% ukupne investicije biti financirano iz IPARD programa, a 20% iz Fonda za zaštitu okoliša i energetsku učinkovitost. Postrojenje koje će biti izgrađeno imat će instaliranu snagu 1MW. Biomasa koja će se koristiti kao gorivo prikupljat će se od privatnih šumovlasnika te će se tako pozitivno djelovati na razvoj lokalnog poduzetništva i otvaranje novih radnih mjesta. Ukupno će mreža toplovoda pokrivati 9 javnih zgrada i oko 60 kućanstava. Kućanstva koja će biti spojena na sustav područnog grijanja do sada su koristila lož ulje ili cjepanice te će uvođenjem novog sustava znatno profitirati u pogledu ostvarenja razine veće udobnosti u vlastitom životnom prostoru.

5. ZAKLJUČAK

U Hrvatskoj, kao i u drugim europskim zemljama postoji niz barijera koje sprečavaju energetski održiv razvoj jedinica lokalne samouprave, posebno manjih, ruralnih zajednica. Istovremeno potrošnja energije u svim europskim zemljama kontinuirano raste, posebno u kućanstvima i uslužnom sektoru. Dugoročno planiranje smanjenja potrošnje energije na razini lokalnih zajednica ključan je preduvjet za prevladavanje nadolazećih problema vezanih uz povećanje potrošnje energije i posljedični rast emisija stakleničkih plinova u atmosferu.

Dosadašnja praksa provođenja energetske politike na nacionalnoj razini nije dala zadovoljavajuće rezultate. Iskustva pokazuju da je od velike važnosti proces planiranja energetskog razvitka s nacionalne spustiti na lokalnu razinu. Spomenuti je problem prepoznala i Europska komisija koja se posljednjih nekoliko godina kroz brojne inicijative, programe i instrumente financiranja trudi što više uključiti regionalne i lokalne uprave u planiranje energetskog razvitka svojih područja na načelima zaštite okoliša, primjene mjera energetske učinkovitosti i korištenja obnovljivih izvora energije.

Jedna od najvažnijih inicijativa Europske komisije je sigurno Sporazum gradonačelnika Pokretanjem ove inicijative, Europska komisija je još jednom istaknula važnost donošenja ispravnih odluka i pokretanja projekata održivog, energetskog razvitka na lokalnim razinama za nacionalni razvitak na načelima održivosti, energetske učinkovitosti i zaštite okoliša.

Važan preduvjet energetski održivog razvitka Hrvatske u cijelosti je upravo uspješno iskorištavanje energetskih potencijala ruralnih zajednica. Prvi je korak u tom smjeru, uspostava organizacijske sheme unutar lokalnih samouprava, zadužene za energetsku problematiku. Dobrom organizacijom i uspostavom komunikacijskih kanala između svih interesnih skupina osigurati će se povoljni uvjeti za uspješno planiranje i provedbu konkretnih projekata energetske učinkovitosti i korištenja obnovljivih izvora energije na lokalnoj razini. Europska komisija će kroz svoje inicijative, programe i mehanizme financiranja poticati energetski razvitak ruralnih sredina a na hrvatskim je lokalnim upravama i energetskim agencijama da u što većoj mjeri iskoriste raspoložive mogućnosti u cilju vlastitog energetskog i gospodarskog razvitka.

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PLANNING OF SUSTAINABLE DEVELOPMENT OF RURAL COMMUNITIES

Abstract: *One of the essential prerequisites to mitigate the negative climate impacts on the global level is significant reduction in consumption of all types of energy. The last 20-odd years, mainly developed countries of Europe and the world are trying to find the best ways to achieve goals that they were committed through the International Agreement on Climate Change, Kyoto Protocol and other international agreements. Through the action on the national level, it becomes clear that state cannot achieve significant results without the active participation of regional and local authorities.*

Covenant of Mayors is the response of advanced European cities and municipalities to the challenges of global climate change, and also the first and most ambitious European Commission initiative aimed directly at the active involvement and continued participation of city and municipal governments and citizens in the fight against global warming. By signing the Covenant, Mayors committed to the implementation of numerous energy efficiency measures that will ultimately decrease CO_2 *emission in their cities until year 2020 for more than 20% as much is binding by the Proposal of the European energy policy in year 2007. Up to July 2012 the Covenant was signed by 4104 cities (approx. 164 751 156 inhabitants), and interest in joining the new towns is growing. Along with more than 4000 European cities, the Covenant also joined cities of Argentina, New Zealand and Kyrgyzstan. From Croatian cities and municipalities, Zagreb, Rijeka and Ivanic Grad were the first to join the initiative in 2008, and to date the Covenant was signed by 38 local communities (cities and municipalities). One of the main objectives of the Covenant of Mayors initiative is to encourage local communities to create planning documents for improving energy efficiency, renewable energy sources and environmental protection in their area. Quality and precise planning with clearly defined vision is an important prerequisite for the successful sustainable energy development. For this reason, the specific obligation of the local community after joining the initiative is a preparation of Sustainable Energy Action Plan - SEAP) that clearly and realistically defined strategic goals and priorities for sustainable energy development until year 2020.*

Local communities involved in the initiative have different characteristics, needs, size and capacity, and furthermore, large number of them has limited financial and technical resources for preparation of complex plans for sustainable energy development and implementation of identified projects. Methodology for the SEAP preparation is relatively complicated and should be adapted to smaller local communities, especially rural. Recognizing the problem, the European Commission has launched programs of capacity building funding for rural communities. A series of small Croatian towns and municipalities develop Sustainable Energy Action Plans and implement specific EE and RES projects with the support of different European programs and funds.

Key words: energy efficiency, global warming, Sustainable Energy Action Plan (SEAP), Covenant of Mayors, rural communities

OTPADNE SIROVINE ZA PROIZVODNJU BIODIZELA

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Sažetak: *Biodizel je alternativno gorivo koje je trenutno po svojim fizikalno kemijskim i uporabnim karakteristima najrealnija zamjena za naftni dizel. Za proizvodnju biodizela može se koristi cijeli niz sirovina na bazi ulja i masti tj. triglicerida uključujući i ulja i masti koje nastaju kao otpad od prženja i pripreme hrane ili kao sporedni proizvod industrijske proizvodnje prerade mesa i ribe, rafinacije jestivih ulja i obrade otpadnih voda. Za sada se učinkovito koriste otpadna jestiva ulja i masti te masti i primarno izdvojene životinjske masti, dok se moguća primjena tehničkih kafilerijskih masti te lipida od rafinacije jestivih ulja i obrade otpadnih voda još istražuje. Biodizel proizveden iz otpadnih sirovina ima lošija hladna svojstva u usporedbi s biodizelom proizvedenim iz biljnih ulja, ali po svim drugim karakteristikama može zadovoljiti zahtjeve kakvoće. Procjena količine pojedinih otpadnih sirovina za proizvodnju biodizela može se napraviti prema količini primarnih sirovina iz kojih one dolaze i to; za otpadno jestivo ulje i mast: 20-25 % ukupne količine jestivog ulja i masti koje se stavi na tržište, za ulja i masti kao sporedne proizvode životinjskog porijekla: primarne masti od industrije crvenog mesa; 10-15 % na masu žive vage, kafilerijske tehničke masti; 3-4 % na masu žive vage za crveno meso i 0,6 % na masu žive vage za meso peradi, za otpadne lipide od rafinacije jestivih ulja: 6 % na početnu količinu ulja, za lipide iz mulja otpadnih voda: 0,4 % na količinu otpadnih voda.*

Ključne riječi: otpadne sirovine, biodizel, sporedni proizvod, otpadno jestivo ulje

1. UVOD

Biodizel je alternativno gorivo koje privlači sve više ineteresa kao moguća zamjena za dizel gorivo.

Pod pojmom biodizel smatraju se esteri masnih kiselina i jednovalentnih alkohola. Navedeni esteri se najčešće dobivaju transesterifikacijom triglicerida ili esterifikacijom masnih kiselina. Najpodesniji jednovalentni alkohol koji se koristi kao sirovina za transesterifikaciju i esterifikaciju je metanol, pa se biodizel često naziva i metilesterom [1].

Iako prava zamjena naftnim gorivima još nije pronađena, trenutno se od svih poznatih i dostupnih alternativnih izvora energije za pokretanje cestovnih vozila, biodizel se čini kao najrealnije rješenje. Razlozi tome su njegova njegove fizikalno-kemijske i uporabne karakteristike koje su vrlo bliske, ili čak malo bolje od naftnog dizel goriva. Za korištenje biodizela potrebne su male ili nikakve modifikacije na motorima i sustavima ubrizgavanja. Transport, skladišenje i distribucija biodizela moguće je korištenjem postojeće infastrukture bez većih modifikacija. Iako ima nižu energetsku vrijednost, (33 MJ/L naspram 36 MJ/L za naftni dizel) bolja mazivost biodizela, i viši stupanj iskoristivosti dizel motora pokretanih biodizelom čini da je razlika u potrošnji između biodizela i naftnog dizela u cestovnim vozilima minimalna ili ta razlika čak niti ne postoji.

Biodizel je biorazgradiv u jednakoj mjeri kao i šećer [2], nije toksičan niti ekotoksičan. Izgaranjem biodizela znatno se smanjuju emisije štetnih plinova ; ugljikovodika za 9 %, policikličkih aromatskih ugljikovodika za 75-90 %. Znatna su i smanjenja ispusta štetnih čestica i ugljik monoksida.
Sirovine za proizvodnju biodizela jesu trigliceridi i masne kiselina porijeklom iz triglicerida.
Potencijalne obnovljive sirovine za proizvodnju biodizela su jestiva i nejestiva biljna ulja, ulje algi, životinjska ulja i masti, otpadna jestiva ulja i masti, sporedni proizvodi na bazi ulja i masti iz industrije jestivih ulja, mesne i mliječne industrije, te ostale zasićene i nezasićene masne kiseline različitog porijekla. Kriteriji za odabir sirovina za proizvodnju biodizela su dostupnost, cijena, i kakvoća. Sa stanovišta održivog razvoja važan faktor za odabir sirovine su ekološka prihvatljivost i omjer neto energije. Pod ekološkom prihvatljivosti smatra se utjecaj proizvodnje i prerade navedene sirovine na okoliš, dok se pod omjerom neto energije podrazumjeva kvocjent energije dobivene iz goriva i energije uložene u sve procese proizvodnje goriva koja dolazi iz već postojećih goriva.
Pod pojmom otpadne sirovine za proizvodnju biodizela smatraju se ulja i masti koje su nastale kao sporednii proizvodi u različitim industrijskim procesima i one koje su nastale kao otpad od korištenja jestivog ulja u procesima pripreme hrane.
Omjer neto energije za otpadne sirovne je pozitivan jer se energija koja je utrošena za proizvodnju osnovne sirovine u procesu iz kojeg se dobiva otpad ne ubraja u ukupnu energetsku bilancu. Proizvodnja biodizela iz otpadnih sirovina ima pozitivan utjecaj na okoliš jer se otpad na taj način oporabljuje i pretvara u ekološki prihvatljivo gorivo.
Prednosti korištenja otpadnih sirovina u proizvodnji biodizela su niža cijena sirovine, smanjenje količine otpada, pozitivan omjer neto energije i izostanak kompeticije sa proizvodnjom hrane [3]. Nedostaci su niža kakvoća sirovine, i ograničena dostupnost.

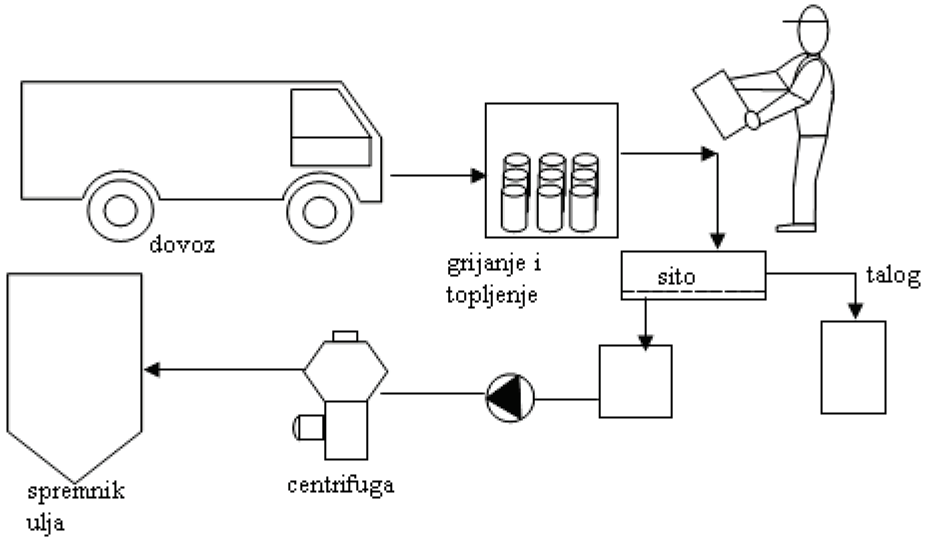
2. VRSTE, KOLIČINE I KAKVOĆA OTPADNIH SIROVINA ZA PROIZVODNJU BIODIZELA

Trigliceridi se mogu podijeliti na ulja i masti, pri čemu se termin ulja koristi za one koje su na sobnoj temperaturi u čvrstom stanju dok se termin masti koristi za one koje su na sobnoj temperaturi u tekućem stanju. Za trigliceride životinskog porijeka često se koristi izraz masti, a za trigliceride biljnog porijekla izraz ulja. Izuzetak su riblje ulje i palmina mast koji se prema svojem porijeklu i fizikalnim svojstvim mogu svrstati i u ulja i u masti, pa se za njih izrazi ulja i masti koriste naizmjenično. Prema sadržaju slobodnih masnih kiselina otpadna ulja i masti semogu podijeliti na žute masti (yellow grease) sa sadržajem slobodnih masnih kiselina do 15 % i smeđe masti (brown grease) sa sadržajem slobodnih masnih kiselina ispod 15 %.

2.1. Otpadno jestivo ulje i mast

Prženje hrane odvija se na temperaturama od 160-200°C, pri čemu se dio ulja apsorbira u proizvod, a dio proizvoda koji se prži se raspada i odvaja te zaostane u ulju. Ulje također reakcijama u samom ulju i reakcijama ulja i hrane, kao i samim prisustvom upijenog ulja u hrani, stvara fizikalno-kemijske promjene na površini i u samom proizvodu, a to se očituje u promjeni nutritivnih, senzorskih i reoloških karakteristika prženog proizvoda
Najvažnije promjene kojes se događaju u ulju prilikom pržanja jesu hidroliza, autooksidacija, te oksidativna i termalna polimerizacija. Ovi procesi održavaju se na povećanje kiselinskog

broja, sniženje jodnog broja, i povećanog sadržaja vode. Fizikalne promjene u ulju nastale kao rezultat kemijskih promjena jesu povećanje viskoznosti, točke dimišta, tendancije ka pjenjenju, indeksa refrakcije i boje koja postaje tamno smeđa do crvena.
Spojevi nastali razgradnjom ulja mogu negativno utjecati na senzorsku i zdravstvenu ispravnost proizvoda, te je stoga ulje za prženje potrebno pravodobno mjenjati. Europske regulative nalažu da se ulje mora zamjeniti kada kada udio polarnih spojeva u ulju prijeđa 25 %, ili kada udio polimernih sojeva prijeđe 10 %.
Otpadno jestivo ulje kao i ostali organski otpad svojom razgradnjom troši kisik, te ga na taj način uklanja iz vode i tla što stvara nepovoljne uvjete za rast i život organizama kojima je kisik potreban, a na račun razgradnje ulja množe se organizmi kojima ono pogoduje kao hrana, što se odvija na štetu ostalih organizama te tako remeti prirodnu ravnotežu. Jedna litra otpadnog jestivog ulja može zagaditi milijun litara vode.
Velike količine otpadnog ulja otežavaju proces prerade otpadnih voda, a mogu i začepiti kanale. Kako je otpadno jestivo ulja vrlo pogodno za preradu u biodizel, a i iz već navedenih ekoloških i zdravstvanih razloga, ističe se potreba da se ono odvaja i sakuplja kao zasebni otpad. Zavisno do vrste ulja ili masti koji se koriste u procesima pripreme hrane i stupnja degradacije, otpadno jestivo ulja može biti u tekućem ili čvrstom stanju pa se stoga u katalogu otpada vodi pod nazivom otpadno jestivo ulje i mast. Udio slobodnih masnih kiselina u otpadnom jestivom ulja iznosi najčešće do 5 % što ga svrstava u žute masti. Otpadno jestivo ulje pogodno je za preradu alkalano katalitičkim postupcima transesterifikacije uz nužnu prethodnu obradu i neutralizaciju. Omjer neto energije za otpadni jestivo ulja iznosi 5-6.
Biodizel proizveden iz otpadnog jestivog ulja ima lošija hladnna svojstva.
Prethodna obrada podrazumjeva uklanjenje mehaničkih primjesa (taloga i vode).
Europska i svjetska statistika govore da se 40-50% jestivog ulja upotrijebljenog za pripremu hrane utroši u restoranima i industriji, a ostatak u kućanstvima, od čega se oko 50% upije u hranu, a ostatak ostane kao otpad. Ako se uzme da se ulje za proizvodnju biodizela prikuplja isključivo iz restorana, dobije se da je potencijalna količina takve sirovine 20-25% na količinu ulja koje se utroši za pripremu hrane. Prema podacima iz Europske unije ukupna količina otpadnog jestivog ulja je oko 5 kg po glavi stanovnika godišnje [3][5].
Slika 2.1. prikazuje prethodnu obradu otpadnog jestivog ulja. Sakupljeno otpadno jestivo ulje u posudama se istovari, izvaže, eveidentira i po potrebi stavlja u grijane komore. U komorama je temperatura 40-50 °C i ondje posude uljem stoje dok se ulje ne otopi što može iznosti do 12 h. Otopljeno ulje se iz posuda izljeva na sita gdje se uklone grube mehaničke primjese tj. talog. Ulje se potom centrifugira u svrhu uklanjanja vode i finih mehaničkih primjesa te potom skladišti u spremniku koji ima mogućnost grijanja.



Slika 1. Prethodna obrada otpadnog jestivog ulja

2.2. Ulja i masti kao sporedni proizvodi industrije mesa i ribe

Sporedni proizvodi industrije mesa koji se mogu iskoristiti za proizvodnju biodizela su masti kopnenih životinja i riblja ulja.

Masti kopnenih životinja mogu se podijeliti na svinjsku mast, goveđi loj, i mast peradi. Izraz loj koristi se i općenito za masnoće kojima je temperatura topljenja iznad 40 °C. Salo jest osobito čvrsta mast koja se nalazi u predjelu bubrega i butina. Oporci su masno tkivo koje okružuje crijeva. Koštana mast je tehnička mast koja se dobiva isprešavanjem kostiju. Životinjske masti karakteriziraju masne kiseline kraćih lanaca, višeg stupnja zasićenosti, viši udio slobodnih masnih kiselina u sirovini, i nedostatak prirodnih antioksidanasa. Među masnim kiselinama prevladavaju oleinska (40-50 %) i palmitinska (17-37 %), Masti životinjskog porijekla sadrže i znatno manje količine fosfolipida i neosapunjivih tvari (<0,05 %) [6]. Sadrže i nešto kolesterola (850-1100 mg/kg), što za proizvodnju biodizela ne predstavlja problem.

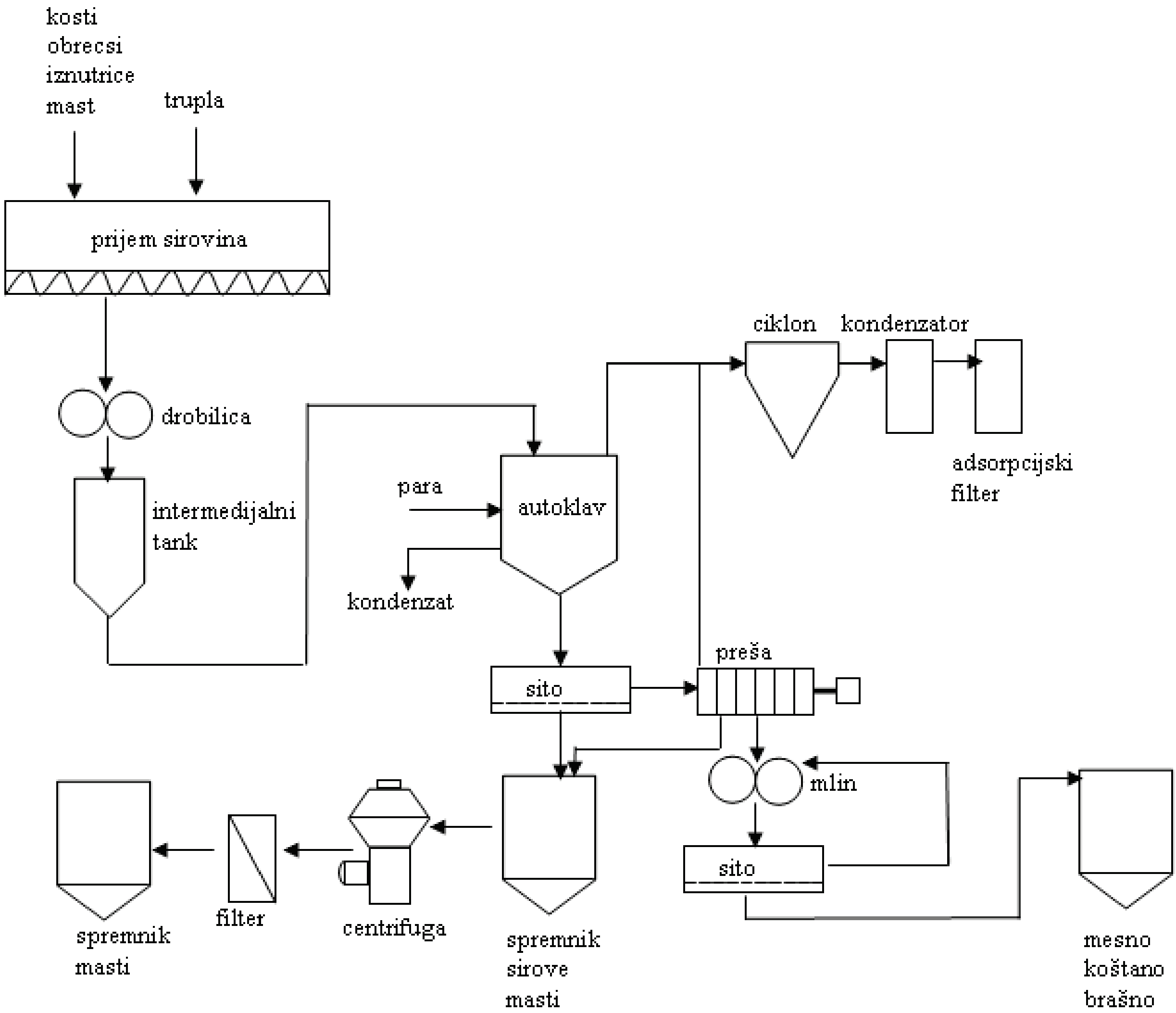
Životinjska mast može se podjeliti na onu koja se primarno izdvoji u klaonicama i pogonima za preradu mesa i kao takva preradi topljenjem suhim ili vlažnim postupkom u svinjsku mast, goveđi loj i sl., te onu mast koja se izdvoji u tvornicama za preradu životinjskih otpadaka (kafilerijama), kao tehnička mast (kafilerijska mast). Primarno izdvojena mast je jestiva dok je tehnička mast nejestiva. Primarna mast ima udio slobodnih masnih kiselina najčešće ispod 2 % što ju čini pogodnom za preradu klasičnim alkalno katalitičkim postupcima uz prethodnu neutralizaciju, dok tehničke mast životinjskog porijekla imaju udio slobodnih masnih kiselina često preko 5-30 %, pa bi za njih bio najpogodniji dvostupanjski proces prerade u biodizel gdje kiselo kataliziranoj esterifikaciji slijedi alkalno katalizirana transesterifikacija.

U usporedbi sa onim iz biljnih ulja, biodizel proizveden iz životnjskih masti ima višu energetsku vrijednost, viši cetanski broj, ali lošija hladna svojstva i oksidativnu stabilnost [3].

Problem sa životinjskim mastima može biti sadržaj polietilena i sumpora. Polietilen dolazi od zostatka pakiranja i folija koje se koritse u procesima prerade, dok sumpor nastaje iz bjelančevina koje djelomično hidroliziraju prilikom obrade i topljenja primarno izdvojenih masti ili huhanjem i sterilzacijom u kafilerijama.

Ulja porijeklom od ribe imaju masne kiseline duljih lanaca i nižeg stupnja zasićenosti u odnosu masne kiselina biljnih ulja, što ih čini podložnijim oksidaciji, a imaju i nešto niži

sadržaj energije. Hladna svojstva ribljih ulja bolja su od onih iz životinjskih masti. Dvije najvažnije polinezaićene masne kiseline iz omega-3 skupine u ribljim uljima jesu eikosapentenska (EPA) i dokosaheksenska (DHA) [7].
Ukupna količina sporednih proizvoda na živu vagu u industriji mesa i ribe je oko 50% za stoku, 42% za svinje, 37% za perad i 57% za većinu riba, a za malu plavu ribu 25 % [8]. Količina primarne masti koja se izdvoji u industriji crvenog mesa iznosi je 10-15 %. U kafilerijama završi 30-40 % mase žive vage iz industrije crvenog mesa, čijim se prešanjem i ekstrakcijom dobije oko 10 % tehničke masti i 25-30 % mesnog-koštanog brašna pa slijedi da je količina masti iz kafilerija crvenog mesa 3-4 % na masu žive vage. Iz kafilerija industrije peradi dobije se 0,6 % masti na živu vagu.
2004. godine u SAD-u je funkciji bilo 200 tvornica za preradu sporednih proizvoda životinjskog porijekla koje su prerađivale malo više od polovine ukupne godišenje proizvodnje industrije mesa. Iste godine svjetska proizvodnja crvenog i bijelog mesa bila je 250 milijuna tona žive vage. Ako se uzme u obzir procjena da su 50% od toga sporedni proizvodi, tada je raspoloživo 125 milijuna tona za preradu. Prema okvirnom omjeru žive vage naspram ukupne količine dobivenih bjelančevina i masti iz procesa obrade sporednih proizvoda od 5:1, i približno jednakoj zastupljenosti masti i bjelančevina u sporednim proizvodima, dobiva se da je godišnje od sporednih proizvoda mesne industrije moguće dobiti 25 milijuna tona masti. Međutim prerada i recikliranje sporednih proizvoda industrije mesa se još ne provode u svim djelovima svijeta. Dio sporednih proizvoda(iznutrice i obresci, masno tkivo, kože), a koji sadrže mast mogu se primarno iskoristiti za proizvodnju hrane za kućne ljubimce, a dio masti se može koristiti za stočnu hranu i za proizvodnju sapuna. Masno tkivo koje se primarno izdvoji sa trupova može se upotrijebiti za proizvodnju jestive masti, prehrambenih aditiva te za proizvodnju emulzija i kobasica, posebno obarenih kobasica. Tako se količina sporednih proizvoda koji završe u kafilerijama snizi na 30 % žive vage, iz kojih se izdvoji 10 % masti [9]. Međutim izvjesno je da će briga za zdravlje i buduće zakonske regulative ograničiti primjenu životinjskih masti u ishrani stoke i kućnih ljubimaca pa će veće količine ostati za proizvodnju biodizela što je i najprihvatljivije rješenje.
Ribe sadrže znatno manje masti i udio masti koji se može dobit iz otpadaka ribe je oko 10 % na količinu otpadaka [10]. Pri preradi male plave ribe dobije se 25 % otpadaka, pa se može zaključit da se ribljeg ulja može dobiti u količini od 2,5 % na ribu.
Jedna od varijanti procesa prerade životinjskih otpadaka pojednostavljeno je prikazana slikom 2.2.. Zaprimljeni materijal koji sadrži otpad iz klaonica i prerade mesa te trupla uginulih životinja se drobi u drobilici, zatim slijedi kuhanje u autoklavu suhim ili mokrima postupkom na 140 °C 4-5 h pri čemu se unište svi mikroorganizmi, a materijal omekša i optusti mast. Oslobođena mast se od čvrstih ostataka odvoji cijeđenjem, a čvrsti ostaci odlaze u prešu gdje se iscijedi preostala mast. Takva mast još sadrži dio vode i zaostale mehaničke primjese koje se odvoje centrifugiranjem i filtracijom. Talog iz centrifuge i filtera se vraća u autoklav. Čvrsti ostaci iz preše se melju i prosijavaju. Prijelaz sa sita koji sadrži prevelike čestice vraća se u mlin. Propad sita se transportira u spremnik gdje se skladišti i dalje otprema kao mesno koštano brašno. Odušci autoklava se su spojeni na ciklon, kondenzator i adsorpcijksi filter kako bi se uklonile čvrste čestice i plinoviti produkti koji izlaze iz autoklava i preše nakon odzračivanja i tako spriječilo njihovo ispuštanje u okoliš.
Masti se iz životinjskih otpadaka mogu izdvojiti i tako da se otpadci najprije podvrgnu sušenju, pa zatim ekstrakciji sa n-heksanom, nakon čega slijedi kuhanje u autokalvima i postupak kao već opisan



Slika 2. Proces prerade životinjskih otpadaka

2.3. Otpadni lipidi od rafinacije jestivog ulja

Rafinacijom ulja dobije se rafinerijski nusprodukt masti (engl. *Refinery Byproduct Lipid*, RBL) u količini od oko 6%. Saponifikacijom rafinerijskog nusprodukta i razbijanjem nastale emulzije kiselinom na povišenoj temperaturi dobije se oko 40% masnih kiselina na početnu količinu RBL-a, koje je moguće kombiniranom kiselo-baznom transesterifikacijom pretvoriti u metilestere [11].

2.4. Otpadni lipidi iz mulja otpadnih voda

Iz otpadnih lipida primarnog mulja dobivenih ekstrakcijom suhe tvari moguće je dobiti 14,5% metilestera, dok je iz sekundarnog mulja moguće dobiti 2,5% metilestera na ukupnu količinu

suhe tvari mulja. U Europi ispitivan primarni mulj čini 50-60% mulja u otpadnim vodama i ima prosječno 4,5% ukupne suhe tvari, dok sekundarni mulj sadrži 0,5% ukupne suhe tvari, pa slijedi da je količina metilestera koja se može dobiti iz ukupnog mulja iz otpadnih voda 0,4% na ukupnu količinu mulja [12].
Vrlo niska cijena, pola cijene novog biljnog ulja i ekološke prednosti čine ova ulja ekonomičnim izvorom za proizvodnju biodizela. Viskoznost i ostaci ugljika, koksa, kod dobivanja metilnog estera iz ovog ulja su nešto veći nego kod repičinog metilestera (RME). Nisko temperaturna svojstva biodizela su slabija nego kod RME i potrebno ga je tijekom hladnijeg perioda miješati s fosilnim dizelom. Mogućnost dobivanja biodizela iz mulja otpadnih voda još je nedovoljno istražena.

3. ZAKLJUČAK

Proizvodnjom biodizela iz otpadnih sirovina se otpadni i za zdravlje i okoliš štetan materijal pretvara u netoksično, ekološki prihvatljivo i visokouporabljivo gorivo. Time se čuva okoliš i štedi energija te povećava energetska učinkovistost jer je omjer neto energije za bidodizel proizveden iz otpadnih sirovina pozitivan ili čak veći nego iz primarnih sirovina. Niža cijena otpadnih sirovina snizuje i proizvodni trošak.
Otpadne sirovine za proizvodnju biodizela mogu biti otpadno jestvo ulje i mast, ulja i masti životinjskog prijekla, otpadni lipidi iz prerade jestivog ulja, te lipidi iz mulja otpadnih voda.
Od otpadnih sirovina za proizvodnju biodizela koriste se otpadno jestivo ulje i mast i životinjske masti, dok se primjena otpadnih lipida iz prerade i rafinacije jestivih ulja i iz mulja otpadnih voda još istražuje. Biodizel proizveden iz otpadnih sirovina većinom zadovoljava sve zahtjeve kakvoće s izuzetkom hladnih svojstava.
Procjena količina količina pojedinih otpadnih sirovina za proizvodnju biodizela može se napraviti prema količini primarnih sirovina iz kojih one dolaze i to; za otpadno jestivo ulje i mast: 20-25 % ukupne količine jestivog ulja i masti koje se stavi na tržište, za ulja i masti kao sporedne proizvode životinjskog porijekla: primarne masti od industrije crvenog mesa; 10-15 % na masu žive vage, kafilerijske tehničke masti; 3-4 % na masu žive vage za crveno meso i 0,6 % na masu žive vage za meso peradi, za otpadne lipide od rafinacije jestivih ulja: 6 % na početnu količinu ulja, za lipide iz mulja otpadnih voda: 0,4 % na količinu otpadnih voda.

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WASTE RAW MATERIALS FOR PRODUCTION OF BIODIESEL

Abstract: *Biodiesel is alternative fuel which is as per its phisico-chemical characteristics currently the most realistic repleacement for petrodiesel. for production of biodiesel it is possible to use variety of raw materials on the basis of oils and fats i.e. triglycerides, including oils and fats which arises as waste material at fying and pšreparation of food, or as by-product of inustrial production of meat and fish, refinement of edible oils and treatment of waste waters. At present sre effctively utilised used frying oils ansd fats, and also primary separated animal fats, while possible appliance of technical rendering plant fats as well as lipids from refinement of edible oils and waste water treatment is still investigated. Biodiesel produced from waste raw materials has inferior cold flow properties than biodiesel prduced from vegetable oils, however in terms of all other characteristics it can meet requirements of quality. Estimation of quantity of particular waste raw material for production of biodiesel can be made according quantity of primary raw meterial from which they originete namely: for used frying oils and fats: 25-25 % of totoal quantity of edible oils ans fats which are put on market, for oils and fats as animal by-products: primary fat from red meat industry 10-15 % on basis of live weight, fats from renderign plant; 3-4 % on basis of live weight for read meat and 0,6 5 on basis of live weight for poultry, for refinery byproduct lipid: 6 % on initial quantity of oil, for lipds from waste water sludge: 0,4 % on quantity of waste waters.*

Key words: waste raw materials, biodiesel, by-product, used fying oil

FINE AEROSOL POLLUTION IN RIJEKA

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Abstract: *X ray fluorescence (XRF) technique has been used to provide multi-elemental analysis of fine particulate matter $PM_{2.5}$ (aerodynamic diameter $\leq$ 2.5 μm) of aerosols collected in the City of Rijeka. Sampling was performed by means of ANSTO's fine aerosol sampling unit. Since this is the first time such samples were collected and analysed in this region, our aim was to identify elements and their concentrations that are characteristic for the road traffic, with the aim to identify so called road traffic fingerprint. To achieve this goal, we have set our sampler at two different sites. The first site was based at the residential area (within the new University campus, Trsat, in September 2011) as this site has the expected very low traffic loading. Samples were collected in 24 hours periods during 9 days. The other site was at a very busy road in the City centre. Due to heavy loadings at this site, samples were collected in 12 hours periods. To enable easier identification of the traffic fingerprint samples were collected during day time (high traffic density) and night time (low traffic density) for 9 days in February and in March 2012. Our preliminary results show large differences in concentrations of elements at the two monitored sites. The concentrations of Cu, Pb, Cr, Fe, Zn, K and Ti in fine fraction of aerosols in the city centre area are found to be 4 and more times higher than in the residential area out of centre. A summary of our findings is presented and discussed in this paper.*

Keywords: aerosols, air pollution, XRF, fine particulate matter $PM_{2.5}$

1. INTRODUCTION

Particles with aerodynamic diameter smaller than 2.5 μm are named $PM_{2.5}$ fractions or fine fractions of aerosols. Fine fractions mostly consist of sulfates, nitrates, soot (black carbon), metals, etc. These are mostly generated in fossil fuel burning processes such as burning in internal combustion engines, power generation, refineries, etc. $PM_{2.5}$ fractions therefore indicate air pollution caused by so called antropogenic activities such as industry and road traffic. This fraction is dangerous for human health because fine particles freely enter lungs and soft tissues. A long-term exposure to fine fractions leads to a chronic cough, bronchitis, atherosclerosis, inflammation of the blood vessels, increased risk of lung and heart disease and ultimately to an increase in mortality (Churg A. et al, 2003; Pope, C.A., 2000; Pope C.A., Burnett R.T., 2002).
$PM_{2.5}$ fraction is also dispersing yellow/red wavelengths of sunlight and therefore produces characteristic gray-yellow haze and loss of visibility. It creates an uncomfortable feeling of stuffiness and gray environment (Malm, W. C. et al,1994; Kim Y. J. et al, 2006; McDonald, K. and Shepherd, M. 2004; Begum B. A. et al, 2006).

Due to recent developments at the new University campus of the University of Rijeka a number of new laboratories are established, one of which is the Laboratory for Elemental

Microanalysis (LEMA). Elemental microanalysis is in this Laboratory based on X ray fluorescence spectroscopy. One of our first application is in the field of environmental pollution monitoring, i.e. the analysis of fine fractions of aerosols. The City of Rijeka was selected as our first monitoring location. Rijeka is the biggest Croatian port and the capital of the Primorsko-goranska County as well as the third city by size in the Republic of Croatia. It has about 130 000 inhabitants. Industrial activities in Rijeka are relatively large and major polluters include the thermo power station and the refinery.

2. SAMPLING AND ANALYSIS

Our aim was to identify major pollutants in the city of Rijeka and if possible to identify the elemental fingerprint of the road traffic. To achieve this goal, we set our sampler at two different sites. The first site was based at the residential area (within the new University campus at Trsat) as this site was expected to have very low traffic loading. The second site was at a very busy road, Trpimir's street, in the City centre. Sampling was performed by means of ANSTO's (*Australian Nuclear Science and Technology Organisation)* fine aerosol sampling unit (www.ansto.gov.au). This is the first time such samples ($PM_{2.5}$) were collected and analysed in this region. Aerosols were collected on R2P1025 teflon membrane (CF_2) filters with 25 mm in diameter, supplied by Pall.

Samples at Campus were collected during 9 days in September 2011 in 24 hours periods, about 130 m above the sea level, on the third floor of the building of the Science and Technology Park, STeP Ri. Samples at Trpimir's street were collected also during 9 days, in February and March 2012. Due to expected heavy loadings samples were collected in 12 hours periods. In this case, sampler was positioned about 6 m above the sea level and 5 m above the road level (in the office of the *Croatian Education and Teacher Training Agency* building). To enable easier identification of the traffic fingerprint, the samples were collected during day time (high traffic density) and at night time (low traffic density).

In this report all results of multielemental analysis of air samples were obtained by means of X-ray fluorescence (XRF) method (Fig. 1). For excitation, low-power X-ray tube (manufactured by *X- Ray Optical Systems,* model *X-Beam)* is used, with working parameters as follows: 50 kV of high voltage and 1 mA tube current. Samples were irradiated by an X-ray beam of homogenous circular profile with 1 mm in diameter. The X-rays emitted from the sample were measured with thermoelectrically cooled silicon drift detector Amptek X-123SDD having typical energy resolution (FWHM) of about 140 eV for Mn-Ka line (5.9 keV). All measurements were performed at the atmospheric pressure (Fig. 1), with 10 mm source to sample distance, and 25 mm target to detector distance. The aerosol samples from the Campus and Trpimir's street were irradiated for 1800 s and 2700 s respectively. The system was calibrated for quantification of concentrations by means of Micromatter thin film multielemental standards.

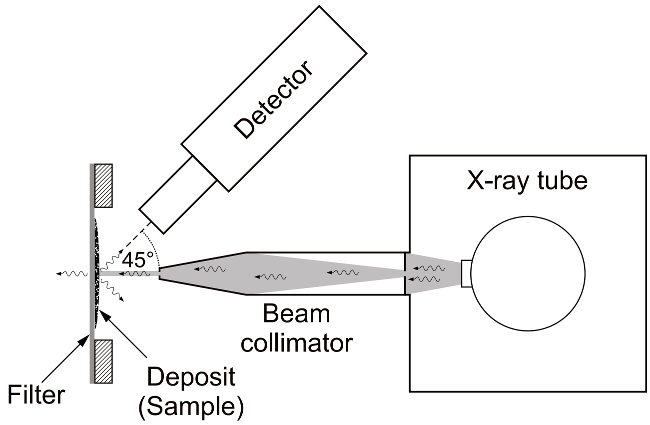

Figure 1. Set up for XRF in the LEMA

Spectra of characteristic X rays are processed by special software *Quantitative X ray Analysis System* QXAS (Van Espen et al, 1986) produced by the *International Atomic Energy Agency* IAEA). By analyzing the values of emitted X rays we can determine the presence and concentration of various element.

3. RESULTS AND DISCUSSION

The sample spectrum is shown in Figure 2 for the sample collected during daytime on 25 February 2012. Positions of Kα and Kβ characteristic X-ray lines are emphasised for most analysed elements, with exception of lead, for which L X-ray lines are shown. In total, the aerosol samples were analyzed for concentrations of 17 elements (Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Pb). The used XRF technique has not the same sensitivity and detection limit (DL) for all present elements. The sensitivity is very good (i.e. low DL) for elements with atomic number close to Fe, but very low for elements as Al and Si (high DL).
In general, two main groups of elements were identified: a group of major elements and a group of minor elements. We have found that S, K, Ca and Fe are major elements, while Si, V, Ti, Mn, Ni, Cu, Zn and Pb are minor elements.

Table 1 shows averages of measured elemental concentrations in nanograms per cubic-meter of air. For the marked averages, the values are obtained for data sets containing more than 30% of samples with concentrations below the detection limit for a particular element. For comparison, the table also contains average concentrations for the three-year period (2009-2011) calculated from the data available in the Annual Air quality reports of the *Teaching Institute of Public Health of the Primorsko-goranska County* (TIPH) (www.nzzjzpgz.hr, 2012). TIPH collects PM_{10} fraction systematically and analyzes filters by atomic absorption spectrometry (AAS) for concentrations of Pb, Cd, Fe, Zn and Cu. Although different fractions during different periods were measured, we found the selected TIPH data suitable for comparison with our data because those are the only existing data on elemental air quality in this region. It can be seen that our results obtained by the XRF technique are generally in a good agreement with the results of the AAS.

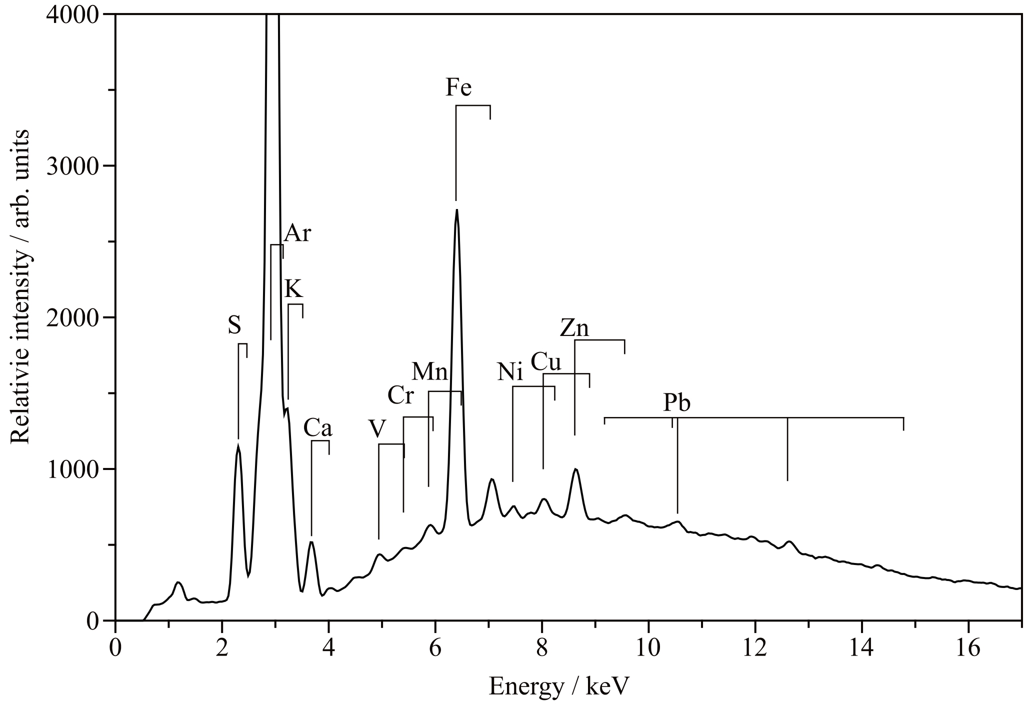

Figure 2. XRF spectrum of an aerosol sample collected at Trpimir’s street for date 25. February 2012.

Table 1. Average elemental concentrations from the two monitored sites and comparison with average annual reports from the Teaching Institute of Public Health of the Primorsko-goranska County (TIPH)

Average concentrations (ng/m^3)			
Elements	Campus at Trsat	Trpimir's street	TIPH
Si	78.0*	143*	-
P	7.24	12.4*	-
S	39.6	1048	-
K	63.7	334	-
Ca	73.3	167	-
Ti	2.38	9.43	-
V	6.57	9.62	-
Cr	0.45	4.57	-
Mn	5.05	12.2	-
Fe	58.0	388	540
Ni	2.57	3.78*	-
Cu	1.77	26.5	57.5
Zn	9.95	56.4	52.5
Pb	1.02*	12.9	8.67

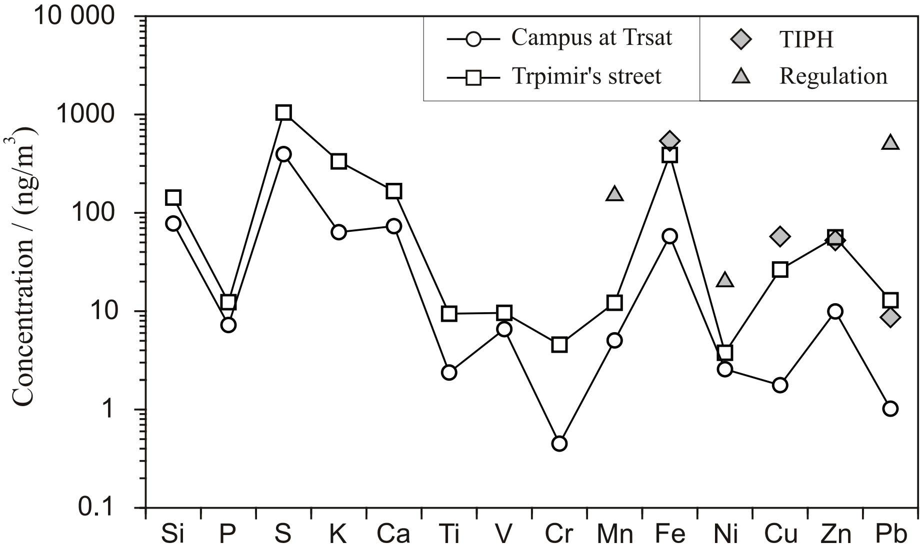

Figure 3. Average concentrations for the elements at the two monitored sites, TIPH data, and the limits values in the Regulation

It is known that the presence of Cu is a consequence of using tires and brakes in traffic, while Zn is added as an additive into fuel for vehicles. Zn and Fe are often indicators of emission of two-stroke engines(Begum B. A. et al, 2007). K is an indicator of smoke from the burning biomass (Begum B. A. et al, 2011). Cu, Zn, Pb and Cr are indicators of emission from cars and industry (Cohen D. D. et al, 2004). The higher concentrations of Cu, Pb, Cr and Zn in the Centre confirm the impacts of traffic and industry on the composition of $PM_{2.5}$ aerosol fraction. These results indicate the higher air quality at the Campus and lower air quality in Trpimir's street.

For Trpimir's street we have collected separated samples for day-time (6 AM – 6 PM) and night-time (6 PM – 6 AM) in order to investigate possible reflections of traffic density and other human activities in the air. Figure 4 shows averaged concentrations of the major elements: S, K, Fe and Ca for day and night-time. The highest difference in concentrations is found for potassium, which is about 3 times higher during night periods. Other selected elements do not show significant differences. Obtained results are in contrary to our expectations that high difference in traffic density will have impact on day-night concentrations ratio.

Table 2. The ratio of concentrations of elements at the Trpimir's street and the Campus at Trsat

Element	Ratio
Cu	15.0
Pb	12.7
Cr	10.3
Fe	6.7
Zn	5.7
K	5.2
Ti	4.0
S	2.6
Mn	2.4
Ca	2.3
Si	1.8
P	1.7
Ni	1.5
V	1.5

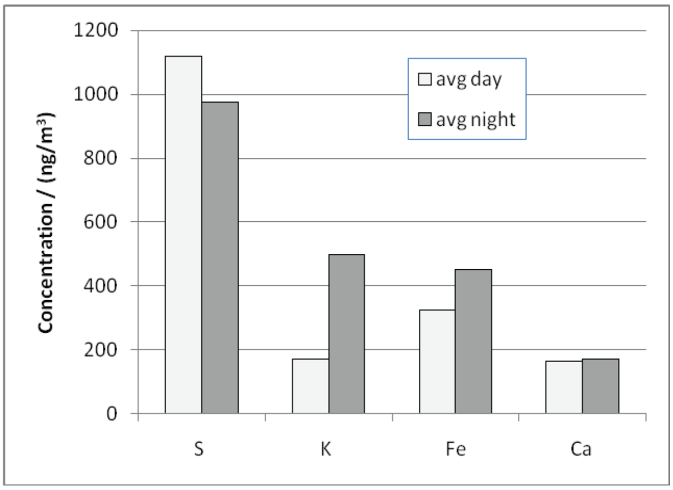

Figure 4. Day and night average concentrations of major elements in the Trpimir's street

Visible air pollution occurred and was documented during the sampling period. Figure 5 shows the view from the centre during the days with and without the haze. Such low visibility episodes in Rijeka appear up to 10 times per month, mostly during the extended calm periods which are quite characteristic for Rijeka. Concentrations data for these days are given separately in Table 3.

Figure 5. Visibility in Rijeka; view from centre toward West. There was no haze on 27 February 2012 (up) and there was visible haze on 29 February 2012 (bottom)

Table 3. Concentration of elements in ng/m^3 for the two days, 27 and 29 February 2012 at Trpimir's street

Date	S	K	Fe	Ca	Cu	Zn
27 Feb 2012	256	67	130	87	10	18
29 Feb 2012	1343	217	393	345	22	71
Ratio	5.3	3.2	3.0	4.0	2.3	4.0

The concentration of S is more than 5 times higher and concentrations of Zn, Ca, K and Fe are more than 3 times higher in the period of haze (Table 3). The main sources of S are refineries and power plants, and the main source of K is burning biomass (Orlić et al, 1999). The emission from two-stroke engines (motorbikes and scooters) is characterized by high concentration of Zn and Fe.

4. CONCLUSION

Preliminary investigation of elemental composition of $PM_{2.5}$ fine aerosol fraction in Rijeka has been performed. Aerosols were collected on teflon filters and analyzed by the XRF technique. Measured concentrations in ng/m^3 for 17 elements (Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Pb) showed significant differences between two monitored sites, Campus at Trsat and Trpimir's street. The Trpimir's street sampling site shows higher concentration of all detected elements. Besides the general presence of sulphur and pottasium, typical indicators of traffic source such as Cu, Pb, Zn, and Fe were identified. During the sampling period daily concentration did not exceed the limits proposed by the *Regulation on limit values for pollutants in air* in the Republic of Croatia. Concentrations of Pb, Cu, Fe and Zn were in good agreement with the data given by the AAS technique for PM_{10} fraction provided by TIPH, which were selected as the most suitable data for comparison.

The study has proved that the XRF is a suitable analytical tool for aerosol research and monitoring. However, further investigation are needed in order to build the location specific database, and to identify fingerprints of other pollution sources such as industry, soil, marine etc. Our intention is to establish source apportionment analysis and to perform systematic monitoring of $PM_{2.5}$ air-pollution in Rijeka.

Acknowledgement

The authors are gratefull to Mr. Zoran Matić for his technical contribution to this research work.

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ZAGAĐENJE FINIM LEBDEĆIM ČESTICAMA U RIJECI

Sažetak: *U ovom radu korištena je tehnika flourescencije X-zraka za određivanje elementnog sastava finih lebdećih čestica areodinamičkog promjera manjeg od 2.5 mikrometra ($PM_{2.5}$ frakcija) prikupljenih iz zraka na području grada Rijeke. Za uzorkovanje lebdećih čestica korišten je uzorkivač Australske nacionalne organizacije za nuklearna istraživanja i razvoj (ANSTO). Obzirom da je ovaj tip uzorkovanja po prvi put izveden u Rijeci, za cilj istraživanja postavljena je identifikacija elemenata karakterističnih za cestovni promet. Istraživale su se i njihove karakteristične koncentracije i odnosi, koje ovom tipu zagađanja daju određenu prepoznatljivost (eng. fingerprint). U tu svrhu odabrane su dvije lokacije za uzorkovanje . Za prvu lokaciju odabrano je stambeno područje oko Sveučilišnog kampusa na Trsatu zbog male gustoće cestovnog prometa. Za drugi lokaciju odabrana je Trpimirova ulica u užem centru grada s vrlo gustim prometom tijekom čitavog dana. Uzorkovalo se 9 dana po 24 sata tijekom rujna 2011. godine na Kampusu i 9 dana po 12 sati tijekom veljače i ožujka 2012. godine u Trpimirovoj ulici. Za cestu s gustim prometom odabrano je uzorkovanje od 12 sati kako bi se eventualno mogla uočiti povezanost dnevne i noćne promjene u gustoći prometa na zagađenje zraka finim lebdećim česticama. Preliminarni rezultati koncentracija elemenata u $PM_{2.5}$ frakciji pokazuju da su koncentracije Cu, Pb, Cr, Fe, Zn, K i Ti u finim frakcijama sakupljenim u centru grada 4 i više puta veće od onih sakupljenih u stambenoj četvrti izvan centra grada. U radu je dan sažeti prikaz naših rezultata i diskusija istih.*

Ključne riječi: lebdeće čestice, onečišćenje zraka, flourescencija x-zraka, fine lebdeće čestice $PM_{2.5}$

PRODUCTION OF BIOMETHANE FROM FERMENTABLE ORGANIC BIOMASS USING A PLUG-FLOW ANAEROBIC DIGESTION

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Abstract: *Anaerobic Digestion (AD) is a biological process that takes place naturally when bacteria break down organic matter in environments with or without oxygen. Controlled anaerobic digestion of organic waste in enclosed landfill will generate methane. Almost any organic material can be processed with AD, including waste paper and cardboard (of a grade that is too low to recycle because of food contamination), grass clippings, leftover food, industrial effluents, sewage and animal waste. AD produces biogas which is comprised of around 60 per cent methane (CH_4) and 40 per cent carbon dioxide (CO2). This biogas can be used to generate heat or electricity and/or can be used as a vehicular fuel. If the intended use is for power generation the biogas must be scrubbed to remove a number of impurities. After conditioning the biogas can be used for onsite power generation, to heat homes or can be added to the national natural gas grid. In recent years several research groups have shown the possibility of upgrading the biogas for biomethane production[1]. This study will show the feasibility of integrating anaerobic digestion plant with onsite polymeric membrane purification system for conditioned biomethane production.*

Key words: biomethane, anaerobic digestion, biomass, landfill gas, organic waste, decentralized power generation, CO_2 removal.

1. INTRODUCTION

Energy and, in particular, the clean energy, is certainly an important scientific topic that needs special attention by the scientific community world-wide and, more so, in the context of the developing countries. Increasing awareness about power generation and biomethane production from fermentable organic substances using anaerobic digesters, is certainly creating a lot of interest worldwide. It is a well established fact that use of anaerobic digester for biomass valorisation, especially in the developing countries, will not only help to meet ever increasing energy demand and environmental pollution but will certainly stimulate both agricultural and industrial development. So, priority is to make use of organic biomass, such as agricultural waste which is available in abundance.
Needless to say that to develop better technologies and adopt best practices for conversion of organic wastes into energy, an intensive research and development work has already been undertaken worldwide. Anaerobic digestion (AD) is an effective means of degrading organic wastes which leads to Biogas generation by the synergistic effort of a consortium of microorganisms. It is a natural treatment process and, as in composting, bacteria break down bulk organic matter into bio-methanated spent wash. Unlike composting, anaerobic digestion is carried out in an oxygen-free (anaerobic) environment. Biogas generation is an eco-friendly process of energy production from wastes.
In spite of anaerobic digestion ability to handle both agro-industrial/ municipal solid waste and wastewater sludge, the fact remains that still a scope to upgrade the process to realize

carbon negative chain through possible substitution of fossil natural gas by biomethane, needs to be investigated.[1]. Moreover, it is worth to note that its quite possible to install small scale AD plants in rural areas of both developed and under developed countries and that too without any major involvement of the processing industry.
Also, biogas can be used in a cogeneration system, for biomethane production, supplied to the national network of natural gas, stored to be used as bio-combustible in the automotive sector.

2. THE PROCESS

Anaerobic digestion is a process by which almost any organic waste can be biologically converted in absence of oxygen. This is a complex process, which requires specific environmental conditions and different bacterial populations. Mixed bacterial populations degrade organic compounds thus producing as end product, a valuable high-energy mixture of gases (mainly CH_4 and CO_2) termed as biogas. Biological process that occurs in the absence of oxygen, can be described under three main stages, i.e. hydrolysis, acidogenesis and methanogenes (Fig.1).

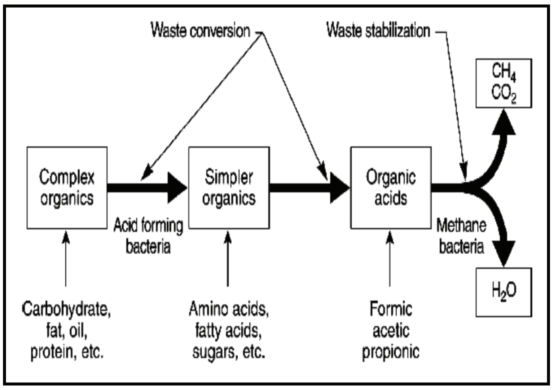


Figure 1. Anaerobic Digestion scheme process

Anaerobic fermentation significantly reduces the total mass of wastes, generates solid or liquid fertilizer and yields energy. It can occur under psychrophilic (12-16 °C, e.g. in landfills, swamps or sediments), mesophilic (35-37 °C, e.g. in rumen and anaerobic digester) and thermophilic conditions (55-60 °C; e.g. in anaerobic digesters or geothermally heated ecosystems). It is to be noted that on one hand while thermal destruction of pathogenic bacteria at elevated temperatures is the main advantage both the reduced process stability and need for thermal energy for dewatering of fermented sludge, on the other hand, are the disadvantages of thermophilic anaerobic fermentation [2]. Also, slightly higher rate of hydrolysis and fermentation do not affect significantly the total methane yield from fermentation of organic matter in the temperature range of 30 °C to 60 °C[3, 4].
By means of enzymes produced by different kind of bacteria the organic wastes undergo three main reactions (i.e. hydrolysis, acetogenesis and methanogenesis).
Hydrolysis: In the first stage of hydrolysis, or liquefaction, fermentative bacteria convert the insoluble complex organic matter, such as cellulose, into soluble molecules such as sugars, amino acids and fatty acids. The complex polymeric matter is hydrolyzed to monomer, e.g., cellulose to sugars or alcohols and proteins to peptides or amino acids, by hydrolytic enzymes, (lipases, proteases, cellulases, amylases, etc.) secreted by microbes. The hydrolytic

activity is of significant importance in high organic waste and may become rate limiting. Use of chemical reagents not only enhance the performance of the hydrolysis process but reduces digestion time and provide higher methane yield [5]. So in brief, organic macromolecule i.e. carbohydrates, proteins and fats are de-polymerised by extra-cellular enzymes. Thus produced monomers undergo degrading reaction, which produce acetic acid, long chain fatty acids and CO_2.

Acetic acid formation: In the second stage, acetogenic bacteria, also known as acid formers, convert the products from first phase to simple organic acids, carbon dioxide and hydrogen. Acetic acid (CH_3COOH), propionic acid (CH_3CH_2COOH), butyric acid ($CH_3CH_2CH_2COOH$), and ethanol (C_2H_5OH) are the principal acids produced. The products formed during acetogenesis are mainly due to number of different microbes, e.g., syntrophobacter wolinii (a propionate decomposer) and sytrophomonos wolfei (a butyrate decomposer). Other acid formers are clostridium spp. (obligate anaerobes capable of producing gendospores)., peptococcus anerobus, lactobacillus and actinomyces.

An acetogenesis reaction is shown below:

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 \quad (1)$$

So, different bacteria degrading long chain fatty acids later produce acetic acid, molecular hydrogen and CO_2. Acetic acid can even be produced from CO_2 and H_2, and from fatty acids, alcohol and carbohydrates. Bacteria that produce enzymes for such reactions are generically called "Acetogens".

Production of methane: Finally, the bacteria called methane formers (methanogens) are used to produce methane in the third stage. The methane is produced either from the generation of carbon dioxide and methane through cleavage of acetic acid molecules or by reduction of carbon dioxide with hydrogen. Methane production is higher from reduction of carbon dioxide but limited hydrogen concentration in digesters results in that the acetate reaction is the primary producer of methane[6]. The methanogenic bacteria include methanobacterium, methanobacillus, methanococcus and methanosarcina. Methanogens can be divided into acetate and H_2/CO_2 consumers. Methanosarcina spp. and methanothrix spp. (also, methanosaeta) are considered to be important in AD both as acetate and H2/CO2 consumers.

Acetic acid is finally degraded with methane production by so-called methanogenic bacteria or "Methanogens". The methanogenesis reactions can be expressed as:

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (2)$$

$$2C_2H_5OH + CO_2 \rightarrow CH_4 + 2CH_3COOH \quad (3)$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H2O \quad (4)$$

These bacteria are highly sensitive to O_2 concentration in the system. Their inactivity holds to an uprising fatty and acetic acids concentration within the environment, consequently lowering pH, whose measure, in a well-balanced system, has to range between 7 and 8.

Produced biogas from anaerobic digestion comprises of methane, carbon dioxide, hydrogen, hydrogen sulphide, ammonia, siloxane and other substances that that may inhibit the anaerobic digestion process or cause corrosion of pipelines or the distribution network[7].

Removal of impurities (such as water vapour, CO_2 and H_2S) present in raw biogas, is essential prior to its use as fuel for various applications. For example, for biogas to be used in a biogas based engines for power generation, it is a must that Hydrogen Sulphide (H_2S) be scrubbed to minimum permissible levels for corrosion free operation of biogas based engines.

Gas cleaning systems include H_2S Scrubber and CO_2 removal. Upgrading and feeding biogas into the natural gas grid offers the possibility to use the upgraded biogas at the location of demand for electricity, heat, cold or fuel.

It is possible to upgrade clean biogas to pipeline-gas quality by using different gas cleaning technologies. For example, H_2S scrubber system with both H_2S reduction less than 100 ppm and H_2S removal efficiency (over 99%) can be used for H_2S removal from all type of gases [8]. After upgrading of biogas its calorific value, density and Wobbe Index are similar to natural gas. Biogas can be adapted to the quality of natural gas. Depending on the upgrading method, the gas pressure vary from 0 up to 6 - 10 bar (at the outlet). Biomethane has to be adapted to the pressure of the gas grid. The difference between biogas and natural H-gas, are reported in table 1.

Table 1. Difference between biogas and natural H-gas

Substance	Biogas	Biomethane	Natural gas
Methane	45 - 70 %	94 - 99.9 %	93 – 98 %
Carbon dioxide	25 – 40 %	0.1 – 4 %	1 %
Nitrogen	< 3 %	< 3 %	1 %
Oxygen	< 2 %	< 1%	-
Hydrogen	Traces	Traces	-
Hydrogen Sulphide	Up to 10000 ppm	< 10 ppm	-
Ammonia	Traces	Traces	-
Ethane	-	-	< 3 %
Propane	-	-	< 2 %
Siloxane	Traces	-	-

Pressurized water scrubbing, pressurizes swing absorption, chemical (water) scrubbing and membrane separation are the main upgrading technologies. At the present moment, polymeric membranes appears to be in good competition with the conventional technologies applied for separation of CO_2 and H_2S from biogas both in term of performance and operating costs.[9,10]

In the above context, ENEA research centre Trisaia, with vast working experience in the field of biogas production using different agro-industrial and municipal solid waste, has planned to focus its research and development activities on biogas upgrading using polymeric membrane. For that purpose, an already existing anaerobic digester will be coupled with an upgrading section comprises of a polymeric membrane. It is expected that the system under investigation will not only provide the biogas compression from atmospheric pressure to 31 bar but will separate carbon dioxide, sulphidric acid, nitrogen and hydrogen from the biogas, as well. Moreover, it has also been observed that to obtain a retentate stream (stream that has been depleted of penetrants that leaves the membrane modules without passing through the membrane to the downstream) with methane concentration of more than 95%, it is necessary to have double stage upgrading to recover methane from permeate in the first stage. The above has been shows in Fig. 2.

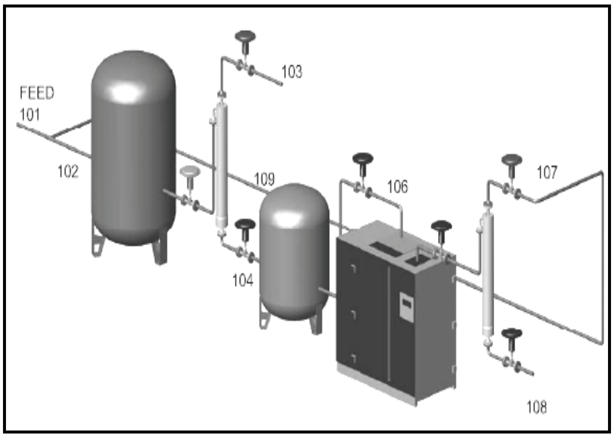


Figure 2. Process scheme for biogas upgrading

The plant comprises of a biogas compressor for updating of biogas derived from anaerobic digestion. Compressed biogas is stored in a tank to stabilize pressure and regulate the flow to be fed to the membrane. The exit from the polymeric membrane is at the biomethane flow (with methane composition > 95% in volume) and permeate stream (with high concentration carbon dioxide at about 2 bar). This one can be re-circulated at the compression stage and subsequently fed to the second stage membrane. High concentration methane recovery (> 85%) is possible at the second membrane. Low content methane permeate at the second stage can be used for thermal energy or burned to flame. To improve gas quality, Porogen's provided, PEEK-SEP™ poly ether ketone composed hollow fiber membranes was used to remove heavy hydrocarbons (C3+), acid gases, and water vapors from raw natural gas or biogas.
The membranes used for biogas upgrading are shown in the figure given below (Fig. 3).

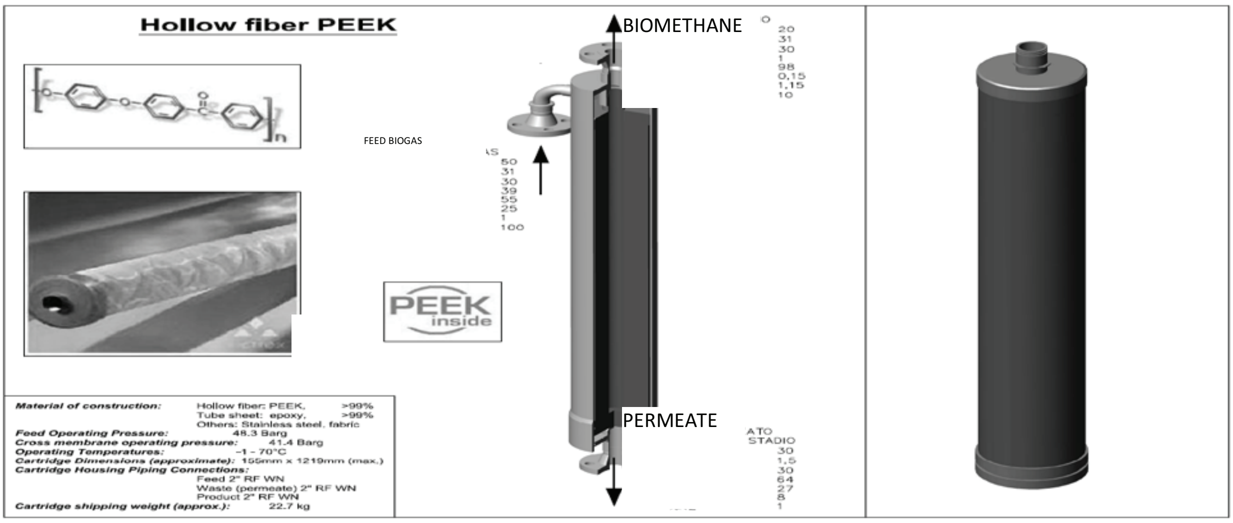


Figure 3. PEEK-SEP membrane for biogas upgrading

PoroGen products are made from VICTREX® PEEK high performance polymers and are used in the most demanding separation applications. The VICTREX® PEEK polymer was chosen for its outstanding combination of high heat and chemical resistance. Membrane pore size and surface chemistry of each membrane product is tailored to meet a specific separation

application. For high precision separation, composite membranes are manufactured by depositing an additional ultra-thin separation layer on top of the porous PEEK membrane. Composite membrane technology platform enables rapid commercialization of new applications by tailoring separation layer material characteristics towards the target application.
PEEK-SEP™ membranes offer the best overall property profile of any polymeric membrane on the market today-allowing it to perform in the most demanding environments. PEEK-SEP™ membranes can operate at temperatures as high as 200 ºC and are not affected by aggressive chemicals present in "real life" process streams. PoroGen membranes are inexpensive, yet sufficiently durable to be employed in industrial applications (high temperature gas separations, natural gas treatment, and aggressive solvent filtration) under operating conditions in which other polymeric membranes cannot be used.
ENEA's biomethane plant is coupled with only one membrane module. Control, regulation of the valves, acquisition of process parameters, is managed by a PLC.

3 ANAEROBIC PLUG-FLOW TYPE DIGESTER UNDER INVESTIGATION

The principal objective of developing such a design was to provide low initial investment, high efficiency and relatively simple operational and maintenance operations. Anaerobic inclined reactor, grinding system, mixer, loading unit, biogas discharging system, gas analyser, gas purifying unit and a data acquisition device are the main components of the system under investigation (Fig. 4). The cylindrical shaped anaerobic reactor is 350 cm long, 70 cm in diameter and has an internal volume of nearly 1.35 m3.
Contrary to the conventional practices, the reactor has been installed at 20° with respect to the horizontal. A 40-dm3 – volume gasholder (tank) has been provided at the upper end. Heating of the reactor body (35 – 45 °C under mesophilic condition) was ensured by means of the auto-controlled electrical resistance.

Figure 4. Anaerobic Digestion plant

With the Anaerobic Digestion plant at ENEA Research Centre Trisaia, sampling of the material in 3 different zones of the reactor, is possible. Different mixtures of fermentable organic substances (animal wastes and agro-industrial residual) with different fractions, as shown in Table 2, were tested:

Table 2. Load to the anaerobic digester

Days of Load	***Type of Biomass***	***Volume loaded(liters)***	***Total volume into reactor(liters)***
1	Pig manure	200	200
13	Fruit & Vegetables	24	522,5
26	Fruit & Vegetables	33	783,5
27	Fruit & Vegetables	34	817,5
34	Fruit & Vegetables	45	1018,5

Produced biogas was composed of methane, carbon dioxide, hydrogen sulfide, nitrogen, hydrogen, mercaptans and oxygen, etc..
As is obvious from the experimental results (Fig. 5) that CH_4 content in the biogas was in the range 50-60% by volume [12].

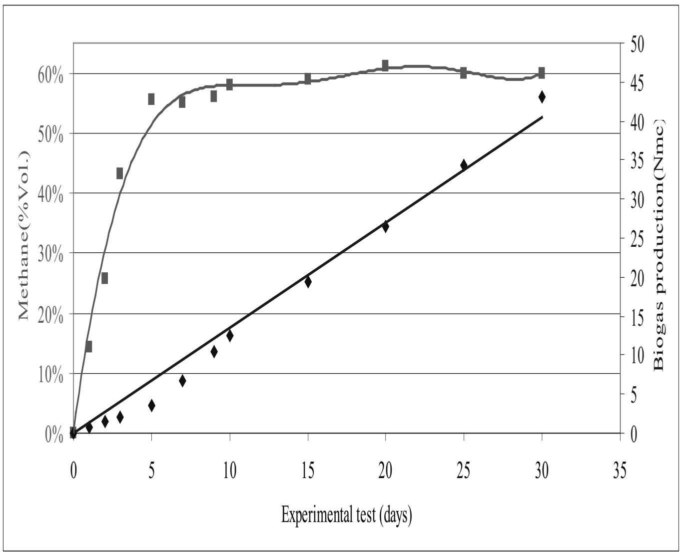


Figure 5. Methane and biogas production

It is easy to observe that after first five days, the concentration of biomethane production is about 55-60% by volume.
It was only during the last year that the reactor, in question, was coupled with an upgrading section composed of polymeric membrane. Preliminary simulation showed that whenever the biogas is compressed till to 40 bar it's possible to obtain a biomethane (96%Vol.) at high pressure, about of 38 bar, hydrogen sulphide free and a permeate flow, at low pressure, about of 2-3 bar composed by carbon dioxide, hydrogen, nitrogen and low methane percentage. The upgrading plant is shown in the Fig. 6 where is possible to see the AD plant coupled with the polymeric membrane for biogas upgrading:

Figure 6. Integrated plant AD coupled with polymeric membrane upgrading

It has been observed from the simulation results that to obtain good quality methane enriched biogas, it is necessary to have double stage. In fact, with single stage, methane content is about 28%Vol. whereas in case of double stage configuration, methane content increases up to 95% by volume.

It is worth to note that methane recovery with double stage depends on the type of configuration used. As shown in Fig. 9, two different configurations i.e. two stage tandem design and two stage cascade design, have been proposed in the present work.

In the first case, produced biogas, after an intermediate compression stage, is mixed with outlet retentate stream at the second stage separation. In case of tandem configuration, with fixed biogas flow rate to the upgrading plant, energy consumption is about 0.32kW per kgh of biomethane at 31 bar.

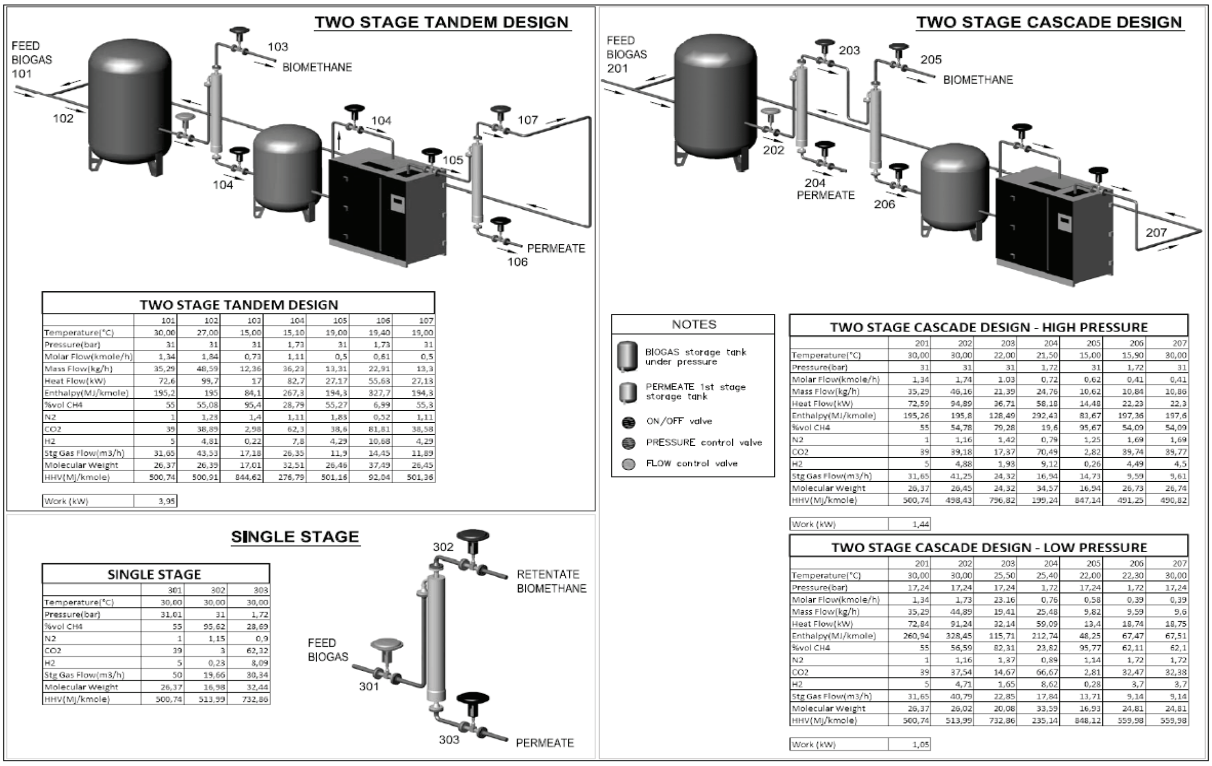
The two stage cascade design, on the other hand, comprises of two membrane in series, with recycling after compression of the permeate outlet stream at the second stage. For this configuration, a power consumption of about 0.14kW/kgh of biomethane at the same pressure with respect to the previously configuration, is necessary.

Based upon the investigation, it can be stated that in comparison to the tandem configuration, cascade configuration certainly appears to be more competitive.

Moreover, in order to verify the effect of pressure on the tandem design, another configuration was simulated, as well.

With biogas at a pressure of about of 17bar, compression was done at 0.11kW/kgh. It is to be observed that with fixed biomethane purity and inlet mass flow rate to biogas upgrading plant, the pressure influence on the outlet pressure, compression work and methane content in the low pressure cascade configuration was nearly 24% in volume. The value was higher than the same configuration at high pressure, that is by approx. 20% in volume.

Different configurations for biomethane production fuelled by biogas, are reported in Fig. 7.



TWO STAGE TANDEM DESIGN

	101	102	103	104	105	106	107
Temperature(°C)	30,00	27,00	15,00	15,10	19,00	19,40	19,00
Pressure(bar)	31	31	31	1,73	31	1,73	31
Molar Flow(kmole/h)	1,34	1,84	0,73	1,11	0,5	0,61	0,5
Mass Flow(kg/h)	35,29	48,59	12,36	36,23	13,31	22,91	13,3
Heat Flow(kW)	72,6	99,7	17	82,7	27,17	55,63	27,13
Enthalpy(MJ/kmole)	195,2	195	84,1	267,3	194,3	327,7	194,3
%vol CH4	55	55,08	95,4	28,79	55,27	6,99	55,3
N2	1	1,23	1,4	1,11	1,83	0,52	1,11
CO2	39	38,89	2,98	62,3	38,6	81,81	38,58
H2	5	4,81	0,22	7,8	4,29	10,68	4,29
Stg Gas Flow(m3/h)	31,65	43,53	17,18	26,35	11,9	14,45	11,89
Molecular Weight	26,37	26,39	17,01	32,51	26,46	37,49	26,45
HHV(Mj/kmole)	500,74	500,91	844,62	276,79	501,16	92,04	501,36

Work (kW)	3,95

TWO STAGE CASCADE DESIGN - HIGH PRESSURE

	201	202	203	204	205	206	207
Temperature(°C)	30,00	30,00	22,00	21,50	15,00	15,90	30,00
Pressure(bar)	31	31	31	1,72	31	1,72	31
Molar Flow(kmole/h)	1,34	1,74	1.03	0,72	0,62	0,41	0,41
Mass Flow(kg/h)	35,29	46,16	21,39	24,76	10,62	10,84	10,86
Heat Flow(kW)	72,59	94,89	36,71	58,18	14,48	22,23	22,3
Enthalpy(MJ/kmole)	195,26	195,8	128,49	292,43	83,67	197,36	197,6
%vol CH4	55	54,78	79,28	19,6	95,67	54,09	54,09
N2	1	1,16	1,42	0,79	1,25	1,69	1,69
CO2	39	39,18	17,37	70,49	2,82	39,74	39,77
H2	5	4,88	1,93	9,12	0,26	4,49	4,5
Stg Gas Flow(m3/h)	31,65	41,25	24,32	16,94	14,73	9,59	9,61
Molecular Weight	26,37	26,45	24,32	34,57	16,94	26,73	26,74
HHV(Mj/kmole)	500,74	498,43	796,82	199,24	847,14	491,25	490,82

Work (kW)	1,44

TWO STAGE CASCADE DESIGN - LOW PRESSURE

	201	202	203	204	205	206	207
Temperature(°C)	30,00	30,00	25,50	25,40	22,00	22,30	30,00
Pressure(bar)	17,24	17,24	17,24	1,72	17,24	1,72	17,24
Molar Flow(kmole/h)	1,34	1,73	23.16	0,76	0,58	0,39	0,39
Mass Flow(kg/h)	35,29	44,89	19,41	25,48	9,82	9,59	9,6
Heat Flow(kW)	72,84	91,24	32,14	59,09	13,4	18,74	18,75
Enthalpy(MJ/kmole)	260,94	328,45	115,71	212,74	48,25	67,47	67,51
%vol CH4	55	56,59	82,31	23,82	95,77	62,11	62,1
N2	1	1,16	1,37	0,89	1,14	1,72	1,72
CO2	39	37,54	14,67	66,67	2,81	32,47	32,38
H2	5	4,71	1,65	8,62	0,28	3,7	3,7
Stg Gas Flow(m3/h)	31,65	40,79	22,85	17,84	13,71	9,14	9,14
Molecular Weight	26,37	26,02	20,08	33,59	16,93	24,81	24,81
HHV(Mj/kmole)	500,74	513,99	732,86	235,14	848,12	559,98	559,98

Work (kW)	1,05

SINGLE STAGE

	301	302	303
Temperature(°C)	30,00	30,00	30,00
Pressure(bar)	31,01	31	1,72
%vol CH4	55	95,62	28,69
N2	1	1,15	0,9
CO2	39	3	62,32
H2	5	0,23	8,09
Stg Gas Flow(m3/h)	50	19,66	30,34
Molecular Weight	26,37	16,98	32,44
HHV(Mj/kmole)	500,74	513,99	732,86

Figure 7. Different configurations for upgrading of biogas plant with polymeric membrane.

Wobbe Index (WI) or Wobbe number, an important parameter used to determine combustible quality as well as an indicator of the interchangeability of fuel gases and frequently defined in the specifications of gas supply and transport utilities, has also been studied. If Vc is the higher heating value, or calorific value and Gs the specific gravity then the Wobbe Index, Iw is defined as:

$$Iw = Vc/(Gs)^{0.5} \tag{5}$$

The Wobbe Index is used to compare the combustion energy output of different fuel gases in an appliance (fire, cooker etc.). In case of two fuels with identical Wobbe Indices, energy output for a given pressure and valve settings, will be identical. The Wobbe Index is a critical factor to minimize the impact of changeover when analyzing the use of substitute natural gas (SNG) fuels such as propane-air mixtures.

Based upon the Wobbe index, there families of fuel gases have been agreed, internationally. As shown in table 3, family 1 covers manufactured gases, family 2 covers natural gases (with high and low ranges) whereas family 3 covers liquefied petroleum gas (LPG). Combustion equipment is typically designed to burn a fuel gas within a particular family, i.e. hydrogen-rich gas, natural gas or LPG.

Table 3. Different Wobbe index for town gas, natural gas and LPG

Family	*Type of gas*	*Wobbe Index range (MJ/Sm^3)*	*Wobbe number range from [13]*
1	Town gas / Syngas	22.5 – 30	24 – 29
2 L	Natural	39 – 45	
2 H		45.5 – 55	48 – 53
3	LPG	73.5 – 87.5	72 – 87

The simulation results shows that the biomethane product in cascade configuration has a Wobbe index in the range 46-51 corresponding to family 2H similar to the natural gas and than it is possible to use this biomethane in the gas grid injection of natural gas.
Currently there are no unified, European technical standards, which regulate the conditions for injection of biogas into the gas grid[11]. It is because of the above-mention reason that the European Commission is currently working to develop standards to determining the quality parameters for biomethane.
In other European Union countries, such as, in Germany, the quality parameters for the biogas (biomethane) are based upon on the ones defined for natural gas. The standards allows the injection of two types of biogas in to the gas grid, i.e. Type "H"(High), a gas having a high calorific value and type "L" (Low) – gas with low heating value. Table 4 shows quality requirements for injection for biogas into gas grid, in Germany.

Table 4. German quality requirements injection to the gas grid

Parameter	*Unit*	*Value*
Wobbe Index	MJ/Nm^3	46,1-56,5 H
		37,8-46,8 L
Relative density	-	0,55-0,75
Dust	-	Technically free
Water dew point	°C	<t^2 (where t is the earth temperature)
CO_2	%Vol.	<6
O_2	%Vol.	<3(in dry distribution grids)
S	mg/Nm^3	<30

As you can see the biomethane product by AD has the quality for the gas grid injection, In fact the only problem will be caused by sulphur content in the biogas, because usually the sulphuric acid content in the biogas is 0,01-0,2% in volume depending to the organic matter processed. With the POROSEEP membrane is also possible to separate the H_2S from the biomethane and obtained a stream with a sulphuric acid content lower than 30mg/Nm^3.

4. CONCLUSIONS

The production of biomethane using biogas produced through anaerobic digestion of organic matter, is an alternative way to the natural gas. The European Directive 2003/55, has authorized the gas grid connection in a natural gas. Particularly, it is interesting to know about the possibility of injecting biomethane, that is, a biogas with refined quality comparable to

those of natural gas (CH_4 concentration greater than 95%) and used in place of the fossil in all its network applications. For production of biomethane using biogas obtained from AD process, it is necessary to proceed to the elimination of water, sulfur compounds, halogenated organic molecules, carbon dioxide, oxygen and metals.
Considering the cost of electric energy to be 20 €cent for each kWh, it has already been shown by several researchers that depending on the organic matter, each cubic meter of biogas cost about 8-10 €cent , whereas the upgrading cost is about of 7-8 €cent. Thus in view of the fact stated above, the total process cost for each cubic meter of compressed biomethane to be injected in gas grid at 30bar, is about 20-22€cent.
It is further to be noted that in view of the market price of natural gas (40.09 €cent/Nm3 referred to January 2010) fixed by the national authority for electrical energy and gas, in Italy, certainly justify the great interest shown for the feasibility of this process, on the industrial scale.

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PROIZVODNJA BIOMETANA IZ RAZGRADLJIVE ORGANSKE BIOMASE KORIŠTENJEM NEPREKIDNOG ANAEROBNOG VRENJA

Sažetak: *Anaerobno vrenje je biološki proces koji se odvija prirodno kada bakterije razgrađuju organske tvari u sredinama sa ili bez kisika. Kontroliranim anaerobnim vrenjem organskog otpada u zatvorenom odlagalištu proizvodi se metan. Gotovo svaki organski materijal se može obraditi anaerobnim vrenjem, uključujući stari papir i karton (u stanju koje nije pogodno za recikliranje zbog kontaminacije hranom), pokošenu travu, ostatke hrane, industrijski otpad, otpadne vode kao i životinjski otpad. Anaerobnim vrenjem proizvodi se bioplin koji se sastoji od oko 60 posto metana (CH_4) i 40 posto ugljičnog dioksida (CO_2). Ovaj bioplin može se koristiti za proizvodnju topline ili električne energije i / ili se može koristiti kao gorivo u motorima vozila. Ako je bioplin namijenjen za proizvodnju električne energije, on mora biti pročišćen radi uklanjanja brojnih nečistoća. Nakon pročišćavanja, bioplin se može koristiti za proizvodnju električne energije na mjestu potrošnje, za grijanje stambenih prostora ili se može koristiti kao dodatak prirodnom plinu u plinskoj mreži. U posljednjih nekoliko godina nekoliko istraživačkih skupina pokazalo je mogućnost poboljšanja bioplina za proizvodnju biometana [1]. Ova studija će pokazati mogućnosti integriranja procesa anaerobnog vrenja ostataka biljnog porijekla sa sustavom pročišćavanja polimernim membranama za proizvodnju pročišćenog biometana.*

Ključne riječi: biometan, anaerobno vrenje, biomasa, plin iz odlagališta, organski otpad, decentralizirana proizvodnja električne energije, smanjenje CO_2

PERFORMANCE EVALUATION OF A BIOMASS BRIQUETTE BASED THROATLESS DOWNDRAFT GASIFIER

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Abstract: *The increasing prices of petroleum based fuels and their exhaustible nature compel us to search new options for energy generation. The renewable sources of energy are environmentally friendly. As the wind energy being localized energy source, solar energy depends upon the weather, there is a need to another renewable energy source also. This problem can be solved by using biomass as energy source. It can be used to produce producer gas which can be used to generate power by running internal combustion engines as well as gas turbines. In the present article, a briquette based closed top throatless downdraft gasifier of 20 kW has been designed and its performance has been evaluated. Cylindrical briquettes of soybean stalks of 25, 40 and 60 mm diameters and length 6-10 cm were prepared and used as fuel in the gasifier during the experiment. Process of briquette formation Involves subjecting the biomass to high pressure and temperature which helps in the release of lignin from the biomass. This lignin acts as a natural binder and the loose biomass matter gets tightly packed and takes the size and shape of the die. The 60 mm diameter briquette was found to have best performance with least choking in the gasifier. The Heating value for soybean briquettes was found to be 17.568 MJ/kg. Maximum Heating value of producer gas was 5.02 MJ/m^3. The optimum gasifier efficiency was found to be 65.18% with 60 mm with soybean briquette for specific gasification rate of 230.34 kg/h-m^2. The 60 mm diameter briquette was found to be best for the operation in gasifier.*
TWh = Terawatt-hour
LHV = Lower Heating Value
ER = Equivalence Ratio
TOE = tonnes oil equivalent

Keywords: gasifier, gasification, briquettes, biomass

1. INTRODUCTION

Due to the high price rise of petroleum based fuel in the international market, there is a need for other options for power generation. Solar energy is dependent on the seasons and wind energy generation is dependent on locality. However, power generation through gasification is not dependent on seasons and locality. According to Hall et al. biomass provides about 1250 million TOE which is about 14% of the world's annual energy consumption [1]. According to Hall et al. and Werther et al. biomass is a major source of energy in developing countries, where it provides 35% of all the energy requirements [1, 2].
Gasification is a process that converts carbonaceous materials, such as coal, petroleum, biomass into carbon monoxide and hydrogen during reaction of the raw material with a controlled amount of oxygen and/or steam at high temperatures. The resulting gas mixture is

called producer gas and is a fuel. Various processes occurring in the gasifier reactor are mainly in four reaction zones viz. oxidation, reduction, pyrolysis and drying zones. The sequence of reaction zones in a gasifier depends on the type of gasifier and direction of flow of fuel and air or gas. In the oxidation zone, carbon and hydrogen of the biomass are oxidised to carbon dioxide and water vapour in accordance with the following reactions [3].

$$C + O_2 \longrightarrow CO_2 + 393.8 \text{ MJ/ kg-mol....} \quad (1)$$

$$H_2 + 1/2\ O_2 \longrightarrow H_2O + 241.1 \text{ MJ/kg-mol....} \quad (2)$$

The temperature in the oxidation zone range from 800 to 1300°C. In reduction zone, carbon dioxide and water vapours are reduced to carbon monoxide, hydrogen and methane in accordance with the following reactions.

Boudauard reaction:

$$CO2 + C \longrightarrow 2CO - 172.6 \text{ MJ/ kg-mol...} \quad (3)$$

Water gas shift reaction:

$$CO2 + H2 \longrightarrow CO + H2O - 41.2 \text{ MJ/ kg-mol...} \quad (4)$$

Methane formation reaction:

$$C + 2H2 \longrightarrow CH4 + 83.3 \text{ MJ kg-mol....} \quad (5)$$

$$H2O + C \longrightarrow CO + H2 - 122.6 \text{ MJ kg-mol....} \quad (6)$$

The application of producer gas can be broadly classified in two categories: for power generation and thermal applications. The power has been successfully generated by the producer gas by running the prime movers like IC engines and gas turbines. In rural areas the decentralized power generation with biomass gives a clean and economical option of power generation and utilization.

Jain and Goss designed and tested, four open core throatless batch fed rice husk gasifier reactors having internal diameters of 15.2, 20.3, 24.4 and 34.3 cm were designed and fabricated [4]. They found that for each reactor the gasifier performance was the best at a specific gasification rate of around 192.5 kg/h-m^2. Under the best operating conditions, the equivalence ratio was 0.40 and the gasification efficiency was around 65%. These parameters may be used for designing rice husk operated throatless gasifiers in the capacity range of 3-15 kW. The lower heating value of producer gas under the optimum conditions was about 4 MJ/Nm^3.

Singh et al. carried out studies on the fuel properties of cashew nut and its gasification feasibility for open core down draft gasifier. It was found that producer gas calorific value and volumetric percentage of its combustible constituents along with gasification efficiency, in general, increased with the increase in gas flow rate. The maximum gasification efficiency was found to be 70% at a gas flow rate of 130 m^3/h and specific gasification rate of 167 kg/h-m^2. Studies revealed that cashew nut shells could successfully be used as feedstock for open core down draft gasifier [5].

Vyas and Singh presented the results of investigation carried out in studying the fuel properties of Jatropha seed husk and its gasification feasibility for open core down draft gasifier. It was found that producer gas calorific value and concentration of CO along with gasification efficiency, in general, increased with the increase in gas flow rate. The maximum gasification efficiency was found to be 68.31% at a gas flow rate of 5.5 m^3/h and specific gasification rate of 270 kg/h/m^2. Jatropha seed husk could successfully be used as feedstock for open core down draft gasifier [6].

Dogru et al. used a pilot scale (5 kWe) downdraft gasifier to investigate gasification potential of hazelnut shells. The gasifier was efficiently and consistently operated with a range of feed rate between 1.7 and 5.5 kg/h (3:1 turndown). The optimum operation of the gasifier was found to be between 1.44 and 1.47 N m^3/kg of air fuel ratios at the values of 4.06 and 4.48 kg/h of wet feed rate which produced the producer gas with a good gross calorific value of about 5 MJ/m^3 at a volumetric flow of 8– 9 Nm^3/h product gas. At this optimum, low tar and char were produced at a ratio of 0.005 and 0.051 of the feed, respectively. Maximum temperatures in drying, pyrolysis and throat zones were determined as 125, 566 and 1206°C but the throat temperature fell to about 1020°C at the optimum. With hazelnut shells there was no sign of bridging or ash fusion at the optimum throat temperature of about 1000–1050°C. Optimum nut shells feed rate for this size of the gasifier was around 4.02 kg/h. Maximum combustible gas flow was obtained as 10.96 N m^3/h. Optimum char output rate was determined as 0.201 kg/h. Optimum tar output rate was found as 0.023 kg/h. Maximum gross calorific value of the producer gas was analysed as 5.15 MJ/Nm^3. It was concluded that hazelnut shells could be easily gasified in a downdraft gasifier to produce good quality gas with minimum polluting by-products [7].

Zainal et al. conducted experimental investigation on a downdraft biomass gasifier using furniture wood and wood chips under various operating conditions. An increasing and then decreasing trend with equivalence ratio, with a peak at about 0.38, is seen for the CO and CH_4. The variation of the calorific value with equivalence ratio shows a peak value indicating that there is an optimum equivalence ratio (0.38) for the best performance of the downdraft gasifier. The cold gas efficiency is found to be about 80 %. Overall efficiency of the biomass electrical power producing system is 10-11 %. Specific consumption of the biomass material is found to be of the order of 2 kg/kW/h [8].

Wander et al. showed that the sawdust residues can be used for gasification and can be used in IC engines. A small, fixed bed, downdraft, stratified, open top gasifier was built 12 kg/h capacity. Mass and energy balances were studied and cold gas, global and mass conversion efficiencies were determined [9].

Tong et al. investigated the application of biomass gasification to generate renewable energy, using three different types of agricultural and forestal residues: rice husk, almond shell, and waste wood. The field work was carried out in a full-scale gasification plant in Jiangxi, China. The heat value of product gas and the environmental pollution impacts of different biomasses under different gasifying temperatures were studied. Under the carbon feed rate in the range of 200–400 kg/h and similar biomass moisture content, increasing carbon feed rate had positive effect on the concentration of carbon-containing fuel gas components CO and CH4, whereas the concentration of C_nH_m was not much affected. Another fuel gas component H_2 was affected by the moisture content of the biomass as it was generated by hydrolysis. In addition, the mobility of trace elements in biomass during the gasification process was evaluated and correlated with the concentration of gas pollutants produced. Thus, the potential environmental impacts can be preliminarily assessed by the elemental analysis of feedstock and ash residues [10].

Ahmed and Gupta examined the evolutionary behavior of syngas characteristics evolved during the gasification of cardboard using a batch reactor with steam as a gasifying agent. Evolutionary behavior of syngas chemical composition, mole fractions of hydrogen, CO and CH_4, as well as H_2/CO ratio, LHV (kJ/m^3), hydrogen flow rate, and percentage of combustible fuel in the syngas evolved were examined at different steam to flow rates with fixed mass of waste cardboard. A new parameter called coefficient of energy gain (CEG) was introduced that provides information on the energy gained from the process. This new parameter elaborates the importance of optimizing the sample residence time in the reactor. Qualitatively the syngas chemical composition showed a notable dependency on time duration in the reactor and a slight dependency on steam flow rate. Increase in the sample residence time in the reactor decreases the CEG while it increases the carbon conversion and the

apparent thermal efficiency. Hydrogen flow rate peaked close to about second minute into of gasification process which was due to the combined effect of decrease in syngas flow rate with time, increase in hydrogen mole fraction with time, and the evolution of hydrogen as a result of pyrolysis that also occurs at the onset prior to the gasification. However, increase in the steam flow rate had a positive effect on pure fuel yield, hydrogen yield, LHV, apparent thermal efficiency, carbon conversion and coefficient of energy gain [11].
Yoon et al. performed gasification of rice husk and rice husk pellet in a bench-scale downdraft fixed-bed gasifier. Gasification was done in a temperature range of 600-850°C, fuel feeding rate of 40-60 kg/h and gasification agent, air, feeding rate of 50-75 Nm^3/h. From the results, synthetic gas heating value and cold gas efficiency of more than 1300 $kcal/Nm^3$ and 70% were achieved, respectively. The heating value of synthetic gas and cold gas efficiency from rice husk pellet gasification shows higher value than that of rice husk gasification. To make power generation, the CD800L reciprocating engine designed to basically use LPG fuel was conducted by supplying synthetic gas produced from rice husk pellet gasification. It was confirmed that stable power generation of 10 kW was achieved [12].

Granada et al. states that, since, the density of residual lignocellulosic biomass is low, its use as energy source is limited. Therefore, briquetting of biomass residue gives a good option for its use as an energy source. Briquetting of biomass is a densification process which improves its handling characteristics, enhances its volumetric calorific value, reduces transportation cost and produces a uniform, clean, stable fuel or an input for further refining processes [13]. Briquetting of biomass can be done either by mixing it with some kind of binder (roll and char briquetting, pelletising) or by direct compacting (piston press technology and screw technology). The technologies used for binderless biomass briquetting include machines based on screw and piston-pressed technology.

Sridhar et al have described the reasons of not using the biomass residues directly in a gasifier for gasification due to following reasons [14]:

1. The material movement by gravity is hampered by low bulk density and wall friction
2. Tunneling of air may occur by the creation of a hole in the bed which can affect the gas quality
3. High temperature near air tuyers due to influence of high velocity air from tuyres on the char leads to ash softening and clinker formation which in turn reduces the effective area for flow through the reactor, deteriorating the performance of gasifier
4. Thin walled residues when exposed to high temperature can undergo fast pyrolysis due to high surface area available for reaction. This leads to generation of higher amount of tarry components which can condense and cause deposits in pipe lines and downstream elements.

2. MATERIALS AND METHODS

A closed top throatless co-cylindrical downdraft gasifier has been designed for the biomass briquette fuels and tested, which gives excellent results with biomass briquettes. Two mild steel sheet were rolled concentrically with appropriate holes to be used as tuyers. The system is designed, developed and fabricated at the CIAE (Central Institute of Agricultural Engineering), Bhopal. A down draft gasifier has the advantage of low tar formation and as such is very successful for operating engines [15]. The briquettes are also produced at CIAE, Bhopal using piston-press technology based briquetting machine. The gasifier is tested with briquettes of soybean of three diameters, viz. 25, 40 and 60 mm.

2.1. Experimental set up

The experimental set up consists of a gasifier with cooling and cleaning units along with a blower and burner. The ray diagram of the experimental set up is shown in figure 1. A brief description of different units is given in following sections.

Gasifier The gasifier developed is closed top downdraft gasifier. It is co- cylindrical whose inner diameter is 30 cm. the outside diameter of the gasifier is 36 cm. Between the space of these co- cylindrical gasifier the gas is extracted towards the gasifier with the help of blower. The air tuyers are located at a height of 40 cm from the grate. The water sealing is provided at the bottom of the gasifier with the help of a trough. Ash is removed manually for which handle is provided at the bottom of the trough. Other technical specifications are given in table 1.

Table 1. Technical specification of the gasifier

Type	Downdraft, throatless, closed top
Capacity, biomass	75 kg
Diameter of inner cylinder	30 cm
Diameter of outer cylinder	36 cm
Material used	Mild steel
Ash removal unit	Manual- rotating type

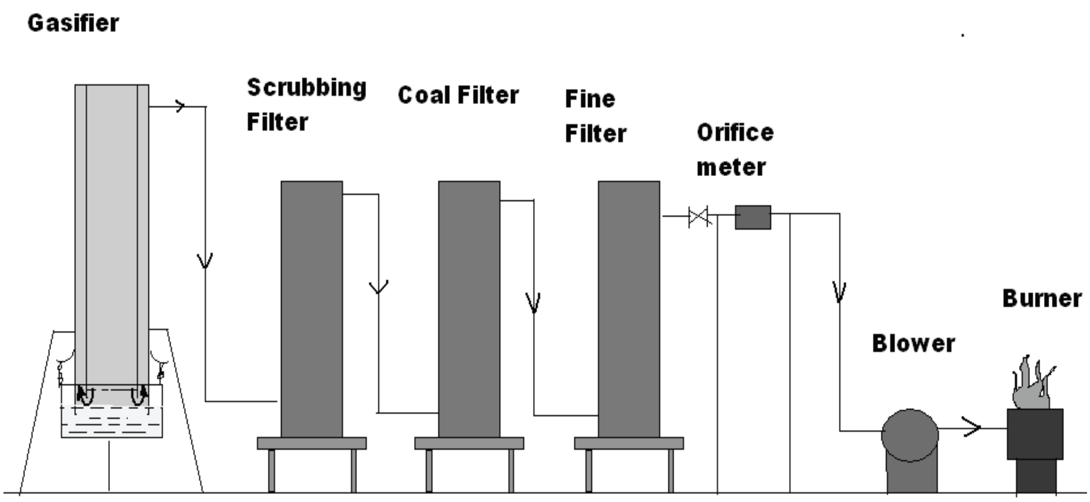

Figure 1. Experimental set up of gasifier unit

Gas cleaning unit Three filters have been used for cleaning and cooling purpose. First one consists of hollow cylindrical iron pieces of 2 cm length and 2 cm diameter, in which water is continuously recirculated from a tank with the help of a pump. This filter serves the purpose of cleaning as well as cooling. The second filter has coal pieces, in which, also, water is continuously recirculated from a tank. This filter further cools and cleans the producer gas. The third filter has coir pith and sheet of foam (3 mm thick) as filter material and it is a fine filter which filters the tar and hence a clean gas is received at the exit.

Blower The blower used in the suction mode is Tawde Pollutech India Pvt. Ltd, having a capacity of 1000 m^3/h. The suction capacity is regulated with the help of a valve during the operation. The rated power of blower is 746 W and rated speed is 2880 rpm.

Burner A burner of 20 cm diameter has been designed for the study whose flame shows a successful operation.

2.2. Raw materials

Briquettes were prepared using a briquetting machine based on piston-press technology in which soybean stalks are pushed into a die of 60 mm diameter by a reciprocating ram by high pressure. These briquettes are broken in the length of 8-12 cm manually and are fed to the gasifier from the top lid which is later closed during the operation. The raw material used in the study is shown in figure 2.

Figure 2. Soybean briquettes being prepared in briquetting machine

3. EXPERIMENTAL PROCEDURE

First the cooling system is started by switching on the pump which recirculates the water in the first two filters from a tank. After that the blower is started and thus suction is created and fire is ignited from the tuyers externally. After about 10 minutes the quality gas is produced. The flame at the burner gives the indication of quality gas.
The heating value of briquettes was measured with the help of bomb calorimeter.
S type thermocouple has been used for measuring the temperature of oxidation zone. Data taker system was used for recording the data continuously.
An orifice meter was developed by designing orificeplate and U- tube manometer, whose coefficient of discharge was found to be 0.65 by calibration.
The heating value was measured with the help of Junker's calorimeter in which water is heated with the burnt gas.

4. RESULTS AND DISCUSSION

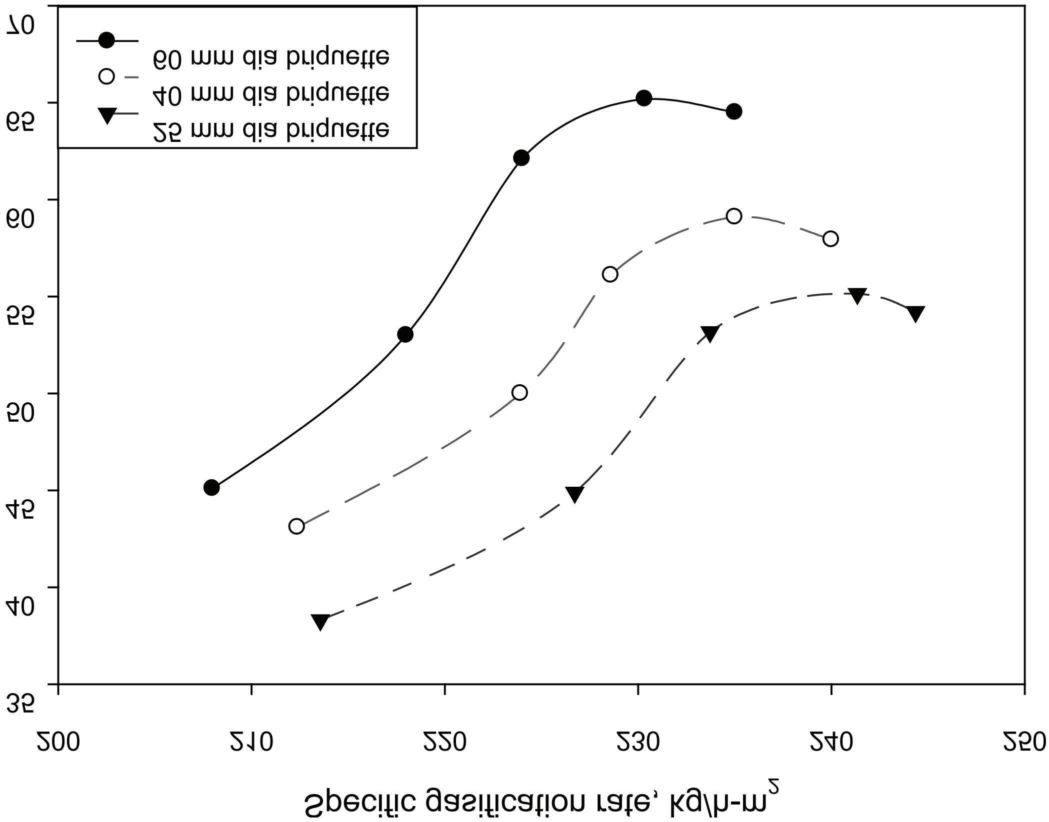

Figure 3. Effect of specific gas production rate on efficiency with different sizes of soybean briquettes

It was found that 3-4 minutes are required to warm up the gasifier. The maximum temperature attained in the oxidation zone was about 1200°C. By extensive experimenting it the optimum length of the briquette was found to be 8-12 mm with minimum choking during the flow of briquettes during the operation. 60 mm diameter briquettes size was found to be optimum for gasifier. Heating value was found to be 17.568 MJ/kg. Maximum Heating value for producer gas was found to be 5.02 MJ/m^3 using 60 mm diameter briquettes. The optimum gasifier efficiency was found to be 65.18% with 60 mm with soybean briquette for specific gasification rate of 230.34 kg/h-m^2. The 60 mm diameter briquette was found to be best for the operation in gasifier as shown in figure 3. As the size of the briquette reduces the specific gasification rate increases which shows that the biomass fuel consumption has increased.

5. CONCLUSION

It is concluded that the gasifier designed runs successfully with negligible clinker formation. The operation of gasifier shows that

1. The maximum temperature attained in the oxidation zone was about 1200°C which is enough to minimize the tar content.

2. The optimum length of the briquette was found to be 8-12 mm with minimum choking during the flow of briquettes during the operation.
3. The 60 mm diameter briquette was found to have best performance with least choking in the gasifier. The Heating value for soybean briquettes was found to be 17.568 MJ/kg. Maximum Heating value of producer gas was 5.02 MJ/m3.
4. The optimum gasifier efficiency was found to be 65.18% with 60 mm with soybean briquette for specific gasification rate of 230.34 kg/h-m^2. The 60 mm diameter briquette was found to be best for the operation in gasifier

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OCJENA UČINKOVITOSTI POTISNOG RAPLINJAČA LOŽENOG BRIKETIMA IZ BIOMASE

Sažetak: *Povećanje cijene naftne derivate i njihova iscrpljivost natjerava nas da tražimo nove mogućnosti za proizvodnju energije. Obnovljivi izvori energije su ekološki prihvatljivi. Budući da je energija vjetra izvor energije ovisan o mjesnoj raspoloživosti vjetra, a solarna energija ovisi o vremenskim uvjetima, postoji potreba za dodatnim obnovljivim izvorom energije. Ovaj problem se može riješiti korištenjem biomase kao energenta. Biomasa se može koristiti za proizvodnju plina koji se može koristiti za dobivanje električne energije pomoću motora s unutarnjim izgaranjem ili plinskih turbina. U ovom radu, osmišljen je potisni rasplinjač zatvorenog tipa ložen briketima snage 20 kW te je ocijenjena njegova učinkovitost. Tijekom eksperimenta kao gorivo su korišteni cilindrični briketi od stabljika soje promjera 25, 40 i 60 mm i duljine 6-10 cm. Proces izrade briketa uključuje podvrgavanje biomase visokom tlaku i temperaturi, što pomaže oslobađanju lignina iz biomase. Ovaj lignin djeluje kao prirodno vezivo te čvrsto formira biomasu na potrebnu veličinu i oblik kalupa. Utvrđeno je da briketi promjera 60 mm daju najbolju učinkovitost bez efekta gušenje u rasplinjaču. Ogrjevna vrijednost sojinih briketa iznosi 17,568 MJ/kg. Najveća ogrjevna moć proizvedenog generatorskog plina bila je 5,02 MJ/m^3. Optimalna učinkovitost rasplinjača utvrđena je u iznosu od 65,18% korištenjem sojinih briketa promjera 60 mm i sa stupnjem preobrazbe od 230,34 kg/h-m^2. Utvrđeno je da su za uporabu u rasplinjaču najbolji briketi promjera 60 mm.*

TREATY ON THE APPROPRIATENESS OF THERMAL ENERGY STORAGE

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Abstract: *Energy consumption is steadily increasing and the limited primary resources will prevent to meet the need of future generations. Efficient use of energy (Energy Efficiency) and a wide development of renewable and alternative energy faced with the fossil resources depletion are probably, with the management of world freshwater, the major challenges for this 21rst century. Furthermore, energy demand is fluctuating, seasonal, unsteady with peaks and slack period consumption. The right strategy for a delayed use is to store thermal energy, leaving so the possibility to choice the better price period of energy acquisition, that is a real tool for energy management. In this paper, after reminding the adequate context of development of energy storage follow introductive elements about storage. After that we describe several materials, equipments and systems suitable for Thermal energy storage. At last we give an overview of valuation techniques and heat energy potential of technical solutions for storage suitable for various sectors.*

Key words: Thermal Energy Storage (TES), Thermal Energy Transportation, energy recovery, energy valorization, sensible heat storage, latent heat storage, Phase Change Material (PCM), thermo-chemical heat storage, energy efficiency.

1. INTRODUCTION

Today reduction of our fossils energetic reserves, the imperative need to preserve our environment under threat to see extinction of the human species, commit us to promote sustainable strategies for energy management. Efficient use of energy (Energy Efficiency) and a wide development of renewable and alternative energy faced with the fossil resources depletion are probably, with the management of world freshwater, the major challenges for this 21rst century. Generally, consumers of these energies aren't close such places of production. So, energy has to be transported over long distances. According to the energy form, technical and economic conditions of its storage and transport will influence the feasibility and profitability. Furthermore, energy demand is fluctuating, seasonal, unsteady with peaks and slack period consumption. The right strategy for a delayed use is to store thermal energy, leaving so the possibility to choice the better price period of energy acquisition, that is a real tool for energy management. With various technical implications storage may take place on the production site or on the site of use.

2. THERMAL ENERGY STORAGE (TES) - ISSUES AND REFLECTIONS IN THE INDUSTRIAL THERMAL AND ENERGETIC SYSTEMS [1]

It is now recognized that storage has a significant impact in the optimization of the coupling between energy production and use, including minimization of sizes for conversion systems in order to approach their nominal operating speed and so reaching the best performance, the thermal energy doesn't escape this necessity. As we say in the introduction, we think this is the best strategy to put the same impedance between the power available and the need for the end user and of course it leaves the possibility to watch over the price and to choice the better period for consumption and to install a real strategy for energy management.

Various technical applications storage may take place on the production site or on the site of use, in any cases it is an essential factor for an efficient installation. Storage devices to heat or cold are therefore essential components for optimizing thermal energy. These are the best tools to ensure consistency of applications and uses energy, intermittent or discontinuous unsynchronized.

It is known that the potential for energy recovery, based on a simultaneous production and use and located on the same place, is extremely small. The non-simultaneity and a significant distance between production and use is the general rule. This observation leads us to consider studying ways needed to treat most common cases that we identified where production and use are unsynchronized and not localized in one place:

- Thermal storage associated with the production site where the site of use should allow to synchronize the energy resources and the need;
- Transport of heat (or cold) to allow movement of the heat source to the storage or storage for use in conditions where energy costs are minimized: energy circulating pumps, loss / heat input on pipes or transport devices.

Regarding the thermal storage, many technologies have been studied and already developed to a certain industrial stage: the diversity of solutions is more related to the principles of storage, than the materials with thermal capacity required, or to the profile of charge and discharge than the only acceptable costs. The principles of thermal energy storage are three in number. This is the sensible heat storage, the latent heat storage and thermo-chemical heat storage. These are principles that involve specific power and storage temperature range.

Thus, the specific capabilities - ratio of energy stored in the volume of active materials in play in these different methods of storage are shown below and give a sight of the real differentiation between these solutions:

- Sensible heat (solid or liquid media): ~ 50 kWh/m3;
- Latent heat (phase change material) ~ 100-150 kWh/m3;
- Thermo-chemical > 300-500 kWh/m3.

To understand the challenge and complexity of the issue for optimal management of an energy resource as heat, it is interesting to imagine the structure of an energy network starting from the heat source to the use that we know extremely various. Indeed, the chain of the heat source for use is a succession of phases of heat transfer, transport, and energy conversion as the transformation of thermal energy into mechanical or electrical energy and too different heat temperature level.

In Figure 1 (data from CEREN (Center of Economical Studies and Researches on Energy)), we summarized conversion technologies and energy transfer that it's reasonable to consider when the heat source is below 250 °C. We have added the thermal demands (only for industrial processes in France) and the potential for thermal recovery possible. It will be noted as well in Figure 1, the technologies of transfer and conversion that follow:

- The Heat exchangers (2) are positioned in the entire temperature spectrum and they can permit heat recovery and his valorization through the use of static recuperators or regenerators;
- The heat pumps (3 and 7) enable heat valorization between 10 and 70°C (by including high temperature heat pumps) to ensure the production of heat at a higher temperature (about 120°C with current technology);
- The cold sorption machines (6) can be used to valorize waste heat from 80 to 140°C for the cold production (-40 to 0°C) for industrial uses (agrifood, chemistry, plastic industry...) or at 0°C to 15°C for the housings/tertiary uses;
- The Rankine cycle machine (ORC / with organic fluid) or Stirling (5) are likely to valorize waste heat (> 140° C) as mechanical and electrical energy.

The location of thermal storage can be:

- Near the heat source and in this case he will present a high storage temperature with relatively short storage periods (hourly at daily) to limit the heat losses (in the case of thermal energy storage with sensible or latent heat) which reduce the interest of the device. The solution "thermo-chemical" could however avoid this;
- Close to use (after transfer or conversion of thermal energy from the source) and under these conditions, temperatures and thermal requirements of the uses will impose the storage characteristics:
  - In the case of uses associated with industrial processes, a wide variety of situations can obviously be considered: direct use at storage temperatures levels, valorization with a high temperature heat pump or with sorption machine;
  - In the case of uses for the Housing/Tertiary, it is clear that temperatures will be in a narrow-spectrum and enhanced thermal capacity/storage periods can be spread for daily storage to an inter-seasonal storage. The valorization of the thermal energy stored will be realized by heat pumps or direct use with heat exchangers (sub-station heating and Domestic Hot Water (DHW)).

In all cases, the energy transport arises and involves a reflection on the choice of transfer media and this to temperature levels that range from the source temperature and that of the use. This allows us to understand that the thermal valorization that will be envisaged must incorporate the possibility of thermal energy storage allowing various performances following the intended use:

- At low temperature (30/70°C) and high capacity (weekly/inter-seasonal) for uses associated with the Housing/Tertiary;
- At High temperature (100/250°C) for industrial thermal uses;
- At very high temperatures (> 250°C) for power generation with a Rankine cycle engine or Stirling.

And following the specificities of the production apparatus and characteristics of waste heat:

At High or very high temperature for the storage near the production plant.

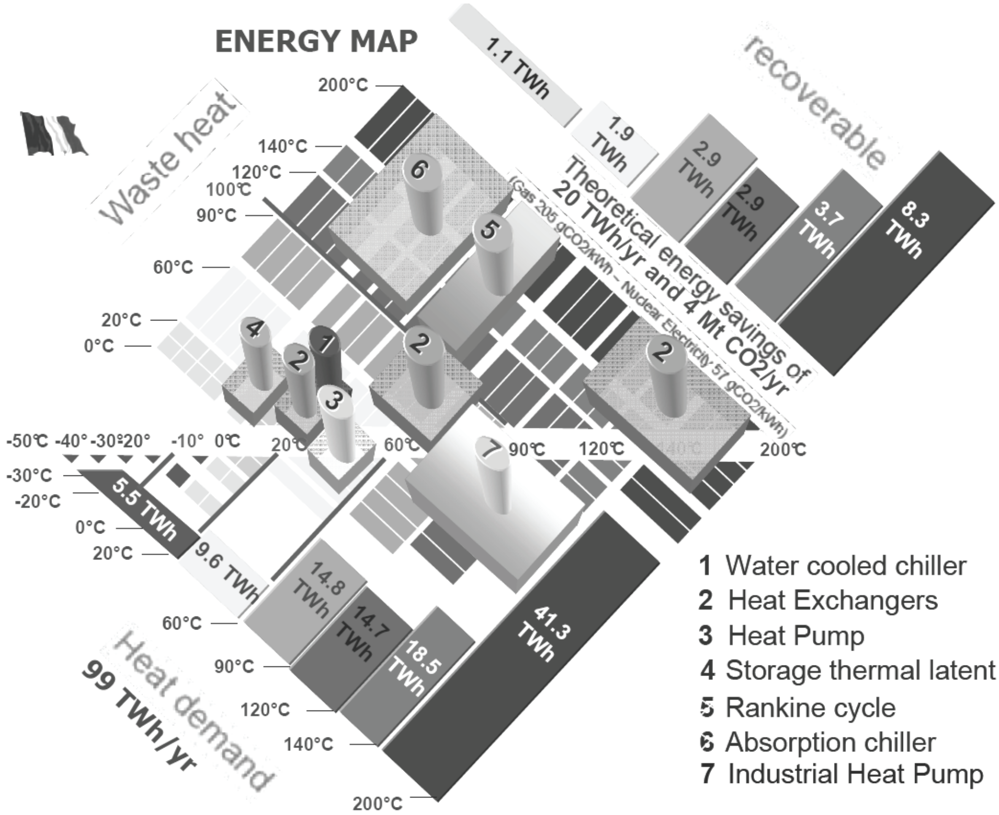

Figure 1. Technologies of conversion and transfer of energy [data from CEREN]

Traditional transports methods of thermal energy, which are usually based on sensible heat or the latent heat of water is limited to a small temperatures range (below 300°C) and distance (less 10 km).

For the low temperature thermal energy, new technologies have been developed and much research focuses on the long-distance transport of the residual heat energy for use in domestic heating or cooling / air conditioning and is currently concentrated on five main aspects.

These technologies include reversible chemical reactions, energy storage by phase change and transportation with vehicles or pipelines, absorbing alloys to hydrogen, the solid-gas chemical adsorptions, the liquid-gas absorption...etc.

3. MATERIALS, EQUIPMENTS AND SYSTEMS FOR THERMAL ENERGY STORAGE

3.1. Thermal Energy Storage by sensible heat

The Thermal energy storage by sensible heat consists to contacting a primary fluid with the storage medium, solid or fluid, which is at a distinct temperature from primary fluid, the result of this operation is then the increase in average temperature of the medium storing while the physical state of this medium is not modified by this change of temperature:

- Fluids: water, organic fluids and synthetic oils are potentially usable fluids;

- Solids: concrete, ceramics and carbon are also used in these processes.

The main thermo-physical properties to be considered to characterize these media and the performance parameters which are deduced from are summarized in Table 1.

Regarding liquids:
- The water is obviously the base material which is the most economic for the applications "low temperature" (10-90°C). Its implementation is varied;
- Synthetic oils or molten salts are relevant solutions for high temperatures (> 200°C) and for short storage periods (hourly to daily). Molten salts represent obviously a more complex solution of implementation for very high temperatures (> 400°C) in the case of concentrating solar power plants for electricity generation.

Regarding solids:
- The soil is a widely valued element for long-term storage (daily to monthly), although his limited temperature range (20/40°C). As aquifers or water storage in large volume, Germany has developed a remarkable expertise for the valorization of solar thermal energy at low temperature level;
- For high temperatures, ceramics, concrete and sand have been studied and implemented in few demonstrator projects and are the subject of particularly active research in Northern Europe.

3.2. Thermal Energy Storage by latent heat & Phase Change Material

The thermal energy storage by latent heat is related to change of state of body: solid-liquid, solid-gas, liquid-gas or solid-solid. These changes usually occur at constant temperature and pressure (for pure component) and have an interesting latent heat (>150 kJ/kg). Thus, compared to thermal energy storage by sensible heat, Thermal energy storage by latent heat can store larger amounts of energy with reduced masses and volumes. This storage method is based on the energy involved during a transition phase of matter (eg solid - liquid). The inverse transformation releases the stored energy as heat or cold.

Materials (organic or inorganic) used for storage must present an attractive cost, high enthalpy phase change and good thermal conductivity. The stability of these products, their Thermophysical properties and behavior during phase change (hysteresis effect...) are often poorly documented and are still being evaluated. Moreover, for the transport of heat and especially cold, the use of charged fluids with particles or biphasic coolants could be in a relatively distant future, an alternative to the heat transfer fluids or coolants, a technical response for the reduction of channeling diameter of the energy transport networks and finally a solution combining the features of storage/transport with the same fluid.

Table 1. Main Thermophysical properties and performance parameters to characterize the materials for thermal energy storage by sensible heat [1]

Thermophysical properties	Performance parameters of the medium	Impact on the design and sizing of the storage device
Liquid : freezing and vaporization temperature (at atmospheric pressure) **Solid** : liquefaction temperature	Minimal and maximal temperature of storage	
Specific heat capacity (J/kg/K)	Mass heat capacity of storage (kWh/kg or J/kg)	Volume and mass of storage device
Density (kg/m^3)	Volumetric heat capacity of storage (kWh/m^3 or J/m^3)	
Solid : Thermal conductivity, density, Specific heat capacity	Time of charging and discharging of heat	Dimensions of the elementary bricks of storage and the exchange surface fluid / material to meet the dynamics of production or use
Liquid : Thermal conductivity, kinematic viscosity, volumetric coefficient of expansion	Time of charging and discharging (heat transfer coefficient between the storage fluid and the transfer wall)	Dimensions and design of the storage device (tanks, heat exchangers) to meet the dynamics of production or use

Regarding the two-phase fluids (biphasic fluids) that can provide the function of storage and transport of heat and cold, various technological developments have been undertaken over the past fifteen years and have led (at better) at a first demonstrator or industrial pilot. Biphasic coolants are formed of a liquid phase containing solids particles in suspension which can change of phases by heat transfer. Several types are being studied to date:

<u>* Ice slurries:</u> are constituted of water or aqueous solutions containing ice particles;
<u>*Micro-emulsions:</u> are constituted of very fine particles (several micrometers in diameter or less) of PCM (Phase Change Material) obtained by dispersing and stabilized by surfactant molecules. This is usually paraffin micro-emulsions which are dispersed in water and stabilized by anionic or nonionic surfactants. It can include up to 50% of PCM, but the important viscosities lead at high pressure drop. Stability of micro-emulsions at long-term in the circuits is problematic. Finally note that the particles of PCM are generally small enough to cause a troublesome super-cooling;
<u>*Micro-encapsulation:</u> are constituted of PCM dispersed in an inert liquid, each being individualized drop this time by a hard plastic coating. Current technology allows obtaining capsules of 1 to 5 microns in diameter. The envelopes, with a thickness of 2 to 10 nm, do not exhibit high thermal resistance. The PCM often consists of paraffin having melting temperatures around room temperature. The simultaneous use of capsules containing different PCM and thus different melting temperatures is possible. One advantage compared to micro-

emulsions is that the pressure drop is comparable to that of water until a concentration of 30% of the capsules in the inert liquid;
*Clathrates: (hydrates) of gas are solids composed of gas molecules (CFCs, HCFCs, butane, propane ...) trapped in a "cage" of water molecules (guest molecule). The water and gas can be separated by heating beyond a certain temperature, the heat of reaction being much greater than that of the melting of ice. The mixture of solid particles and liquid water gives a fluid that can be perfectly transported in a pipeline;
* The gel ball: with a diameter of the order of 1 mm, are made of a polymer matrix containing 90% water. They are dispersed in an organic liquid to form a suspension that may flow if the mass fraction of ball does not exceed about 36%.

Regarding the storage or encapsulation in volumes "important" (of dozen liters at several liters) - unlike the previous case of micro-encapsulation or gel for biphasic fluids - of the phase change materials, various technologies have been implemented:

- Ice Tank: This is simply a tank containing water in direct contact with a battery (heat exchangers) in which circulates cold liquid that can be water or glycol refrigerant itself. Around this circuit it will form ice that can completely or partially filling the tank. The retrieval is performed either by pumping water at 0°C mixed with ice (external fusion processes) or by circulating hot liquid (external fusion processes);
- Encapsulated nodules: The principle of this storage is to use a PCM contained in sealed containers of small size (just a few cm3 at few liter). It suffices to cool in order to solidify their content and put them in contact with the hot load for the destocking. It exists thus, on the market, a number of products. They are made of bricks, pockets, plates which are removable. We note principally use of spherical nodules. These nodules fill a vessel which can be traversed by a heat transfer fluid such as brine (glycoled water);
- Heat Exchangers: The principle of encapsulation involves the use of traditional exchangers whose a part of the tubular circuits (or plates) is filled with a PCM while the other part of the circuits is used for circulation of fluids primary or secondary.

The main thermo-physical properties to be considered to characterize the Phase change Materials (PCM) and the performance parameters which are deduced from are summarized in Table 2.

Undoubtedly, associated technologies at PCM are complex to implement and only the technologies developed for low temperature (-40°C/0°C) are really mature and this for much targeted applications (isothermal transport and refrigeration, air conditioning for large buildings/Tertiary).

The innovative solutions developed over several years are promising but are still in pre-industrial and can’t easily be integrated into a demonstrator in the short term.

3.3. Thermal Energy Storage by Thermo-Chemical Reaction

Thermal energy storage by Thermo-chemical reaction is defined as a process involving two reactants A and B in a reversible transformation including a reaction exothermic and the reverse reaction is endothermic. For a use of heat, it is pertinent that the reaction A+B is exothermic whereas the dissociation of AB is endothermic and values the initial thermal rejection. The implementation of the reaction A + B is performed in the area of use after transport through pipes or tanks distinct of the two species A and B. Chemical reactions generally used are hydration processes of mineral salts and can reach heats of reaction of several hundreds or even thousands of kJ/kg.

Table 2. Main Thermophysical properties and performance parameters to characterize the materials for thermal energy storage by latent Heat [1]

Thermophysical properties	**Performance parameters of the medium**	**Impact on the design and sizing of the storage device**
Freezing and vaporization temperature (at atmospheric pressure); liquefaction temperature	Temperature of storage	
Specific heat capacity (J/kg /K)	Mass heat capacity of storage (kWh/kg or J/kg)	Volume and mass of storage device
Solid and liquid density (kg/m^3)	Volumetric heat capacity of storage (kWh/m^3 or J/m^3)	Take into account of changes in volume when switching solid-liquid to define cellular encapsulation
Solid : Thermal conductivity	Time of discharging of heat	Dimensions/Design of the elementary bricks of storage to meet the dynamics of use
Liquid : Thermal conductivity, kinematic viscosity,	Time of charging (heat transfer coefficient between the storage fluid and the transfer wall)	Dimensions and design of the storage device (tanks, heat exchangers) to meet the dynamics of source

A process very similar - well as abusively positioned in the thermo-chemical storage because as the physics nature - is that of water vapor adsorption on zeolites or salts which exhibits adsorption enthalpies (exothermic process) also significant (several hundred kJ/kg of adsorbent) and asks, for the reverse process of desorption(endothermic process), comparable enthalpies.

The interests of such processes are obvious: it presents a volumetric (and mass) storage capacity (relative to the mass or volume of reagent or adsorbent) much higher than the process previously described. Given the necessity of more complex infrastructure to these thermo-chemical and thermo-physical processes, the ratios of enthalpy to the total mass of storage (including infrastructure) are less differentiated than the ratios which only take into account that reagents or materials adsorbent. This solution presents the advantage of significantly reducing the risk of degradation of the storage with the time because storage is storage of species (or solid supports (adsorbent)) at room temperature. Only leaks or deterioration of reagents or air inlets in the reactor containing the adsorbent can reduce the performance of these devices.

These processes are reserved exclusively for the storage of heat. The storage of cold that could also be considered - requires a more complex device like 'sorption machine "- in order to convert the storage of species in cold production. We do not retain in this study.

3.4. Performance characteristics of storage devices

Evaluate the potential performances of technical solutions described above require the definition of performance criteria of devices integrating material / Implementation / integration into the storage volume and transfer mode with the carrier fluid. The criteria may first be associated with environmental constraints and security of such material or reagents in the heart of the storage process:

- Toxicity;
- Flammability and Explosivity;
- Environmental impact (eutrophication, ozone, greenhouse ...);
- Recyclability.

In connection with the above criteria, reglementary criteria can also be taken into account:

- Legislation: "Greenhouse Gases" "Ozone layer";
- ICPE for risk facilities (ICPE=Classified Installation for environmental protection);
- DESP for the constraints associated with tanks or exchange under pressure and temperature (DESP = Directive of the Under-Pressure equipment);
- REACH Directive in the case of chemical reagents or PCM.

More economic criteria (conditioned by including the previous settings) must obviously be integrated:

- Cost of materials and their implemented;
- Availability of materials.

4. CONCLUSION

We have indicated three modes of thermal energy storage which are: sensible heat, latent heat and thermo-chemical / thermo-physical.

Regarding technologies for sensible heat storage in liquid phase, among them only a few have been studied and developed for considered range of temperature in this study (100-250°C). They are:

- Molten salt tanks technology which is now well develop and usable for relatively high temperature levels, limited to their freezing point (T> 150°C);
- Technology of water tanks under pressure is now reliable with real maturity;
- The use of thermal oils technology is more technically affordable in this temperature range than the pressurized water.

Always in the same range of temperature(100-250°C), there is only a few technology for thermal energy storage with solid media (sensible heat), but projects using an high temperature concrete or technical ceramics give a promising future in terms of design price / performance ratio and operation. This is the case of the prototype developed by DLR (Deutsches zentrum für Luft- und Raumfahrt).

Then, by identifying the different PCM (Phase Change Materials) and their main implementation, we found that some of them are commercialized for a use within the range of temperatures of this study (> 100°C).

We mentioned too that the thermal energy storage by latent heat with phase change materials is technologically attractive especially for the quantity of energy stored and thermal performance achievable. However, for high temperature ranges (100°C - 400°C), industrial applications are practically nonexistent and still today at a stage of pilot for research studies. For a use of PCM above temperatures 100°C, it is a trouble to implement it and use encapsulation technology because of heat transfer control (flux draw off), low lifetime technology period and a too high price. In this context only solutions at low temperature applications are available for PCM (and therefore often applied for building thermal efficiency) with a good maturity. Research projects of DLR are promising but still under test.

The storage by sorption or thermo chemical is applicable offers in a wider range of temperature source (100-1000°C). Some works on these storage methods have been developed since several years, but none has reached the stage of industrial demonstrators. This lack of substantial results is mainly due to the choice of suitable enclosure materials, of the reactor design and the cost of complete devices. It's therefore too early to consider these solutions in a significant size for industrial demonstration.

Many important locks exist, including access to information only for having an idea of availability about technologies of storage. Nevertheless, we can already say that we have to go in this axis to improve energy efficiency by expanding the field of end users using the energy providing from thermal rejects. This will reduce greenhouse gases emission satisfying the growing need of building, housing and industry otherwise than using fossil energy.

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RASPRAVA OKO PRIHVATLJIVOSTI SKLADIŠTENJA TOPLINSKE ENERGIJE

Sažetak: *Potrošnja energije u stalnom je porastu i ograničeni primarni resursi mogli bi biti nedostatni da zadovolje potrebe budućih generacija. Učinkovito korištenje energije (energetska učinkovitost) i posvemašni razvoj obnovljivih izvora energije zbog suočenja s osiromašenjem fosilnih resursa, su vjerojatno, zajedno s pravilnim gospodarenjem svjetskim rezervama pitke vode, glavni izazovi 21. stoljeća. Nadalje, potrošnja energije je promjenjiva, sezonska i nestabilna, s periodima visoke vršne potrošnje i periodima smanjene potrošnje. Prava strategija za odgođenu uporabu je pohrana toplinske energije, ostavljajući tako mogućnost izbora boljeg cjenovnog razdoblja (tarife) korištenja energije, što je pravi alat za upravljanje energijom. U ovom radu, nakon izlaganja konteksta razvoja skladištenja energije slijedi razmatranje osnovnih elemenata skladištenja. Nakon toga opisani su materijali, oprema i sustavi pogodni za pohranu toplinske energije. Na kraju dan je pregled metoda vrednovanja potencijala korištenja pohrane toplinske energije za tehnička rješenja različitih područja uporabe.*

Ključne riječi: pohrana toplinske energije, transport toplinske energije, povratno korištenje energije, valorizacija energije, osjetni spremnik topline, latentni spremnih topline, materijal s promjenom faze, termo-kemijski spremnih toplinske energije, energetska učinkovitost

THE POSSIBILITY OF AN ADAPTIVE CONTROL OF COOLING-DEFROSTING CYCLE DEPENDING ON FROST CONDITIONS AT THE EVAPORATOR

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Abstract: *In the paper, an analysis of a refrigeration device operation under frost forming conditions has been performed. The results of mathematical modelling and numerical calculation of heat and mass transfer in the boundary layer have been used as a base for the calculation of an effective exchanged heat flux. Several cases with different operating conditions have been analysed and the resulting correlations for determining the optimal duration of the cooling cycle have been shown. The presented results could be used to control the device within the scope of maximising the cooling effect and reliability of a cooling energy supply. In the controlling algorithm hereunder, the starting moment of the defrosting cycle has been selected depending on real frosting conditions such as air temperature, humidity and velocity as well as temperature of the heat exchanger surface.*

Key words: fin-and-tube heat exchanger, defrosting process

1. INTRODUCTION

The frost layer, formed when an evaporator operates in moist air and when a fin surface has been cooled below 0°C, represents significant thermal resistance. Therefore, a defrosting process has to be performed, which consumes an additional amount of energy. Moreover, it causes interruptions in the cooling energy supply and leads to insertion of additional heat to the cooled space. Frost layer growth results with a reduction of mean exchanged heat flux, which can be significantly smaller than nominal heat flux exchanged on frost-free surfaces. Frost layer forming has an effect on the space cooling quality and the operating behaviour of the whole device (Sanders, 1974). For maximising the cooling efficiency it is necessary to control the device in an appropriate manner. Selection of the appropriate starting moment of the defrosting cycle is of a great importance.

Therefore, in the paper, a simulation and an analysis of the device operation during working cycles have been performed. During continuous operation the cooling cycle and defrosting cycle have been alternated in sequences. As a base for the simulation of the device operation under frost growth conditions, a detailed calculation of frost layer formation and exchanged heat flux has to be performed. The model mathematically describes the physical mechanism of frost layer forming, in which one part of the water vapour flux condenses and solidifies on a frost surface, thus increasing the frost layer thickness. The other part of the water vapour flux penetrates by diffusion into the frost layer and increases the frost density. The increase of the frost density caused by water vapour diffusion leads to augmentation of thermal conductivity and finally to reduction of thermal resistance of the frost layer. The mathematical model of heat and mass transfer during frost formation has been based on previous investigations (Lenic et al., 2008). Many authors analysed and mathematically described the frost formation process using different levels of a mathematical and numerical approach (Lenic et al., 2008; Hayarishi et al., 1977; Lee et al., 1997; Gall et al., 1997; Lenic, 2006). In the majority of the models, the frost layer is considered as a porous structure containing iced mesh and air gaps (Tao et al., 1993; Lee ae al., 2003). Some of the models use empirical correlations on the air-side (Lee et al., 1997; Jones and Parker, 1975; Sahin, 1995; Na and Weeb, 2004). The other group of models give some improvements and analyse the air flow using boundary layer equations and predict frost properties using empirical correlations (Sherif et al., 1990; Yang and Lee, 2005). The frost forming process has also been investigated experimentally by Cheng and Shiu (2002) and Na and Weeb (2004). The most sophisticated recent models include calculation of the boundary layer using governing equations, both for the air and frost side (Hayarishi et al., 1977; Tao et al., 1993; Lee et al., 2003). Some authors analyse frost formation in a turbulent flow (Yang et al., 2006) as well as behaviour of the whole heat exchanger under frosting conditions (Yang et al., 2006; Tso et al., 2006). As in recent investigations, in the presented paper it is assumed that the partial pressure of water vapour on the frost layer surface is larger than the partial pressure of water vapour for the temperature of frost layer surface, i.e. the air near the surface of frost layer is supersaturated (Lenic et al., 2008; Lenic, 2006; Na and Weeb, 2004; Mago and Sherif, 2005; Lee and Ro, 2005). The aim of this research presented in the paper is to provide a controlling algorithm for device operation to maximise the cooling effect and reliability of cooling energy supply. The control is based on real frosting conditions: air temperature, humidity and velocity as well as temperature of the heat exchanger surface.

2. MATHEMATICAL MODEL

For simulation of exchanged heat on a fin-and-tube heat exchanger, a specific mathematical model has been used and solved numerically. The domain of calculation has been extracted from the physical model of the fin-and-tube heat exchanger and includes a representative part of the heat exchanger i.e. one half of the space between fins, as presented on Fig. 1. Two different regions which need a different mathematical approach can be distinguished: the subdomain of the humid air and subdomain of the frost layer, which are delimited by the air-frost interface. According to earlier studies, it has been assumed that the frost layer subdomain is a porous medium.

A transient two-dimensional mathematical model of frost formation has been developed. The applied mathematical model has been defined using governing equations for the boundary layer near and inside the frost layer. Governing equations and boundary conditions for both regions have been presented on Fig. 2. The presented model calculates velocity and temperature fields of the boundary layer near the cooled fin in a humid air stream, as well as the temperature and density fields inside the frost layer. It predicts a frost layer growth rate as well as a change of the thermal conductivity of the frost layer.

The exchanged heat flux has been significantly influenced by the frost layer which has formed on heat exchanger surfaces. The frost layer growth rate depends on a water vapour transfer from an air stream into the frost layer, diffusion rate of the water vapour into the frost layer and thermal conduction inside the layer. Only one part of the water vapour flux which transfers from the air stream has been deposited on the frost surface and increases the frost thickness. The other part of the water vapour flux enters e the frost layer and thus increases its density.

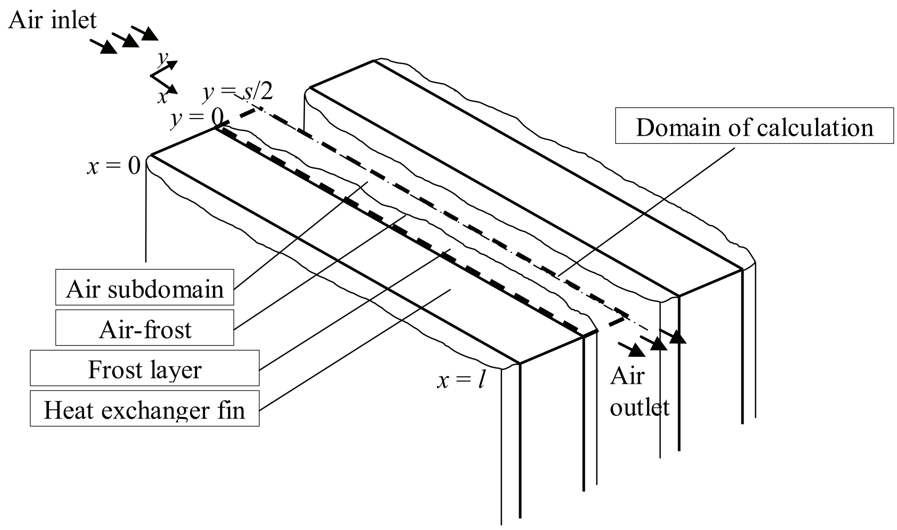


Figure 1. Domain of numerical calculation: half space between heat exchanger fins

$$\frac{\partial u_x}{\partial y}=0 \quad u_y=0 \quad \frac{\partial T_{\mathrm{a}}}{\partial y}=0 \quad \frac{\partial w}{\partial y}=0$$

Air inlet

$$u_x=u_{\mathrm{in}}, \quad u_y=0, \quad T_{\mathrm{a}}=T_{\mathrm{in}}, \quad w=w_{\mathrm{in}}$$

Air subdomain

$$\frac{\partial}{\partial x}(\rho_{\mathrm{a}}\, u_x)+\frac{\partial}{\partial y}(\rho_{\mathrm{a}}\, u_y)=0$$

$$\rho_{\mathrm{a}}\frac{\partial u_x}{\partial t}+\rho_{\mathrm{a}}\left(u_x\frac{\partial u_x}{\partial x}+u_y\frac{\partial u_x}{\partial y}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u_x}{\partial x^2}+\frac{\partial^2 u_x}{\partial y^2}\right)$$

$$\rho_{\mathrm{a}}\frac{\partial u_y}{\partial t}+\rho_{\mathrm{a}}\left(u_x\frac{\partial u_y}{\partial x}+u_y\frac{\partial u_y}{\partial y}\right)=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 u_y}{\partial x^2}+\frac{\partial^2 u_y}{\partial y^2}\right)$$

$$\rho_{\mathrm{a}}\frac{\partial T_{\mathrm{a}}}{\partial t}+\rho_{\mathrm{a}}\cdot\left(u_x\frac{\partial T_{\mathrm{a}}}{\partial x}+u_y\frac{\partial T_{\mathrm{a}}}{\partial y}\right)=\frac{k_{\mathrm{a}}}{c_{\mathrm{p,a}}}\left(\frac{\partial^2 T_{\mathrm{a}}}{\partial x^2}+\frac{\partial^2 T_{\mathrm{a}}}{\partial y^2}\right)$$

$$\rho_{\mathrm{a}}\frac{\partial w}{\partial t}+\rho_{\mathrm{a}}\cdot\left(u_x\frac{\partial w}{\partial x}+u_y\frac{\partial w}{\partial y}\right)=\rho_{\mathrm{a}}\cdot D\cdot\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}\right)$$

Air outlet

$$\frac{\partial u_x}{\partial x}=0, \quad \frac{\partial u_y}{\partial x}=0, \quad \frac{\partial T_{\mathrm{a}}}{\partial x}=0, \quad \frac{\partial w}{\partial x}=0$$

Air-frost interface

$$u_x=0 \qquad u_y=0 \qquad k_{\mathrm{a}}\frac{\partial T_{\mathrm{a}}}{\partial y}=k_{\mathrm{fl}}\frac{\partial T_{\mathrm{fl}}}{\partial y}+q_{\mathrm{sub}}\rho_{\mathrm{fl}}\frac{\mathrm{d}y_{\mathrm{fl}}}{\mathrm{d}t}$$

$$\frac{\partial \rho_{\mathrm{fl}}}{\partial y}=0 \qquad w_{\mathrm{fs}}=0.622\cdot\frac{(1+S)p_{\mathrm{v,sat}}}{p-(1+S_{\mathrm{v}})p_{\mathrm{v,sat}}}, \quad S=0.808\left(\frac{p_{\mathrm{v},\infty}}{p_{\mathrm{v,sat},\infty}}\right)\left(\frac{p_{\mathrm{v,sat,fs}}}{p_{\mathrm{v,sat},\infty}}\right)^{-0.657}-1$$

Frost layer

$$\frac{\partial T_{\mathrm{fl}}}{\partial x}=0, \quad \frac{\partial(\rho_{\mathrm{v}}/\rho_{\mathrm{a}})}{\partial x}=0$$

$$\rho_{\mathrm{fl}}\frac{\partial T_{\mathrm{fl}}}{\partial t}=\frac{\partial}{\partial x}\left(\frac{k_{\mathrm{fl}}}{c_{\mathrm{p,fl}}}\frac{\partial T_{\mathrm{fl}}}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{k_{\mathrm{fl}}}{c_{\mathrm{p,fl}}}\frac{\partial T_{\mathrm{fl}}}{\partial y}\right)+q_{\mathrm{sub}}\frac{\partial \rho_{\mathrm{fl}}}{\partial t}$$

$$\frac{\partial \rho_{\mathrm{fl}}}{\partial t}=\frac{\partial}{\partial x}\left(D_{\mathrm{eff}}\rho_{\mathrm{a}}\frac{\partial(\rho_{\mathrm{v}}/\rho_{\mathrm{a}})}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_{\mathrm{eff}}\rho_{\mathrm{a}}\frac{\partial(\rho_{\mathrm{v}}/\rho_{\mathrm{a}})}{\partial y}\right)$$

$$\frac{\partial T_{\mathrm{fl}}}{\partial x}=0, \quad \frac{\partial(\rho_{\mathrm{v}}/\rho_{a})}{\partial x}=0$$

Fin surface

$$T_{\mathrm{fl}}=T_{\mathrm{s}} \qquad \frac{\rho_{\mathrm{v}}}{\rho_{\mathrm{a}}}=\frac{\rho_{\mathrm{v}}(T_{\mathrm{s}})}{\rho_{\mathrm{a}}(T_{\mathrm{s}})}$$

Figure 2. Governing equations and boundary conditions on a domain of numerical calculation

The frost layer growth rate is defined as follows:

$$\frac{\mathrm{d}y_{\mathrm{fl}}}{\mathrm{d}t}=\frac{1}{\rho_{\mathrm{fl}}}\dot{m}_{\Delta\mathrm{y}}=\frac{1}{\rho_{\mathrm{fl}}}\left(\dot{m}_{\mathrm{a}}-\dot{m}_{\mathrm{dif}}\right) \tag{1}$$

The total mass flux of water vapour transferred from air to the frost layer surface and the mass flux which enters into frost layer by diffusion are defined respectively as follows:

$$\dot{m}_{\mathrm{a}}=\rho_{\mathrm{a}}\cdot D\cdot\frac{\mathrm{d}w}{\mathrm{d}y},\quad \dot{m}_{\mathrm{diff}}=-\rho_{\mathrm{a}}\cdot D_{\mathrm{eff}}\cdot\frac{\mathrm{d}\left(\rho_{\mathrm{v}}/\rho_{\mathrm{a}}\right)}{\mathrm{d}y} \tag{2}$$

The above-mentioned water vapour mass fluxes have been calculated for every time step, following the calculation of the velocity, humidity, temperature and density fields. These values of water mass fluxes are used to calculate the frost growth rate. Then the overall heat transfer coefficient and, consequently, the exchanged heat flux have been obtained.

The specific heat and effective thermal conductivity of the frost layer depend on frost density, porosity and effective diffusion coefficient. They have been calculated accordingly [8, 11, 12], using following terms:

$$k_{\mathrm{fl}}=0.132+3.13\cdot10^{-4}\rho_{\mathrm{fl}}+1.6\cdot10^{-7}\rho_{\mathrm{fl}}^{\;2} \tag{3}$$

$$c_{\mathrm{p,\,fl}}=\frac{1}{\rho_{\mathrm{fl}}}\left[\rho_{\mathrm{i}}(1-\varepsilon)c_{\mathrm{p,\,i}}+\rho_{\mathrm{a}}\varepsilon\, c_{\mathrm{p,a}}\right] \tag{4}$$

$$D_{\mathrm{eff}}=D\cdot\varepsilon\cdot\frac{1+\varepsilon}{2} \tag{5}$$

The overall heat transfer coefficient related to a segment of the fin-and-tube heat exchanger shown on Fig. 3, has been calculated using

$$U=\left[\frac{1}{U_{\mathrm{fin}}\left(\eta_{\mathrm{fin}}+\dfrac{\Delta A_{\mathrm{pipe}}}{\Delta A_{\mathrm{fin}}}\cdot\dfrac{U_{\mathrm{pipe}}}{U_{\mathrm{fin}}}\right)}+\frac{\Delta A_{\mathrm{pipe}}}{\Delta A_{\mathrm{R}}}\frac{a}{c_{\mathrm{p,\,a}}\cdot h_{\mathrm{R}}}\right]^{-1} \tag{6}$$

where U_{fin} and U_{pipe} denote overall heat transfer coefficients for the fin and pipe of the heat exchanger respectively and have been calculated using the following equations:

$$U_{\mathrm{fin}}=\frac{1}{\dfrac{\Delta A_{\mathrm{fin}}}{\Delta A_{\mathrm{fl,\,fin}}}\cdot\dfrac{1}{h_{\mathrm{a}}}+\dfrac{\Delta A_{\mathrm{fin}}}{\Delta\overline{A}_{\mathrm{fin}}}\cdot\overline{W}_{\mathrm{fl}}\dfrac{a}{c_{\mathrm{p,\,a}}}} \tag{7}$$

$$U_{\mathrm{pipe}}=\frac{1}{\dfrac{\Delta A_{\mathrm{pipe}}}{\Delta A_{\mathrm{fl,\,pipe}}}\cdot\dfrac{1}{h_{\mathrm{a}}}+\dfrac{\Delta A_{\mathrm{pipe}}}{\Delta\overline{A}_{\mathrm{pipe}}}\cdot\overline{W}_{\mathrm{fl}}\dfrac{a}{c_{\mathrm{p,\,a}}}} \tag{8}$$

The instantaneous exchanged heat flux on the total surface area of the heat exchanger has been calculated using

$$\dot{Q}=\frac{U}{c_{\mathrm{p,\,a}}}\frac{\left(h_{\mathrm{a,1}}-h_{\mathrm{sat},\,T_{\mathrm{R2}}}\right)-\left(h_{\mathrm{a,2}}-h_{\mathrm{sat},\,T_{\mathrm{R1}}}\right)}{\ln\dfrac{h_{\mathrm{a,1}}-h_{\mathrm{sat},\,T_{\mathrm{R2}}}}{h_{\mathrm{a,2}}-h_{\mathrm{sat},\,T_{\mathrm{R1}}}}}A_{\mathrm{fin,tot}} \tag{9}$$

For a limiting case, when the refrigerant temperature is assumed to be constant (approximating the evaporator) the expression for the instantaneous exchanged heat flux becomes

$$\dot{Q} = \frac{U}{c_{\mathrm{p,a}}} \left(\frac{h_{\mathrm{a,1}} - h_{\mathrm{a,2}}}{\ln \frac{h_{\mathrm{a,1}} - h_{\mathrm{sat},T_\mathrm{R}}}{h_{\mathrm{a,2}} - h_{\mathrm{sat},T_\mathrm{R}}}} \right) A_{\mathrm{lam,tot}} \tag{10}$$

A detailed description of the numerical approach has been given in previous works (Lenic et al. 2008.; Lenic, 2006).

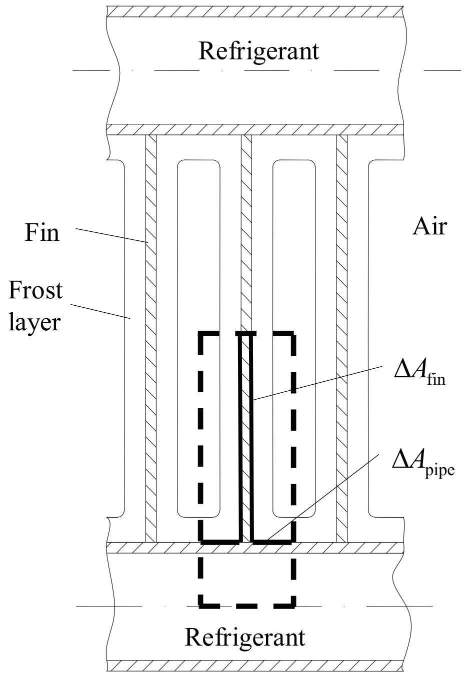


Figure 3. Elementary segment of fin-and-tube heat exchanger

A typical cycle of a chiller operation when working under frost formation conditions is shown on Fig 4. When the chiller operates under frost growth conditions, a reduction in the exchanged heat flux at the evaporator side occurs. After some time of device running, it is necessary to provide the defrosting process in order to restore the nominal exchanged heat flux. Defrosting is often very inconvenient, because long defrosting periods can result in undesirable condition changes in the cooled space. After a cooling time t_C, there follows the time used for defrosting t_D. In the presented analysis it is assumed that defrosting heat is supplied by a constant heat flux. The total duration of whole cool-defrost cycle t_{CD} is the sum of cooling and defrosting times. The nominal exchanged heat flux $\dot{Q}_0$ is provided only at the beginning of a cooling cycle, when there is no frost on the heat exchanger fins. The exchanged heat flux at the evaporator side decreases as a result of frost layer growth and increase of thermal resistance. The average exchanged heat flux during the cooling period has been calculated using

$$\bar{\dot{Q}}_\mathrm{C} = \frac{1}{t_\mathrm{C}} \int_{t_\mathrm{C}} \dot{Q}(t)\,\mathrm{d}t \tag{11}$$

During the defrosting process, it is necessary to provide a sufficient amount of heat for melting the whole frost layer. There are several types of defrosting techniques. The overview of defrosting types has been given in Table 1 according to Sanders (1977). Moreover, three types of control procedures have been used to control the defrosting process: Time-Initiated-

Time-Terminated, Time-Initiated-Temperature-Terminated and Time-Initiated-Pressure-Terminated defrosting control.

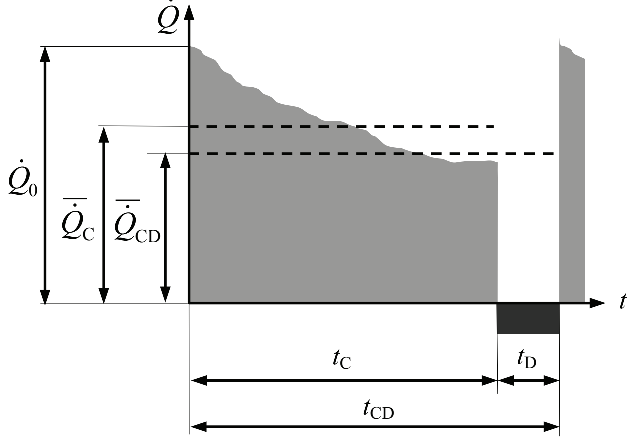


Figure 4. The typical cycle of a chiller operation during frost formation conditions

In the presented mathematical model, when modelling the defrosting process, it is assumed that the heat for defrosting is supplied from the refrigerant side i.e. from the fin side. It is also assumed that the process occurs with a constant defrosting heat flux. During the mathematical modelling the entire defrosting process is divided into two phases, which differ mainly by the heat transfer. In the first phase, the temperature of the frost layer and fins changes up to the melting temperature of water (0 °C). During the second phase, melting of the frost layer takes place. Through mathematical modelling of these two phases, the minimal heat for the defrosting process can be calculated. The minimal heat for defrosting in an ideal case, ignoring the thermal capacity of the heat exchanger, amounts:

$$Q_\mathrm{D} = Q_\mathrm{D,\,min} = \int_{t_\mathrm{D}} \dot{Q}_\mathrm{D}(t)\,\mathrm{d}t = m_\mathrm{fl} \cdot c_\mathrm{p,fl} \cdot T_\mathrm{D}^0 + m_\mathrm{fl} \cdot q_\mathrm{mt} \tag{12}$$

As the defrosting process consumes energy and influences the cooling supply continuity, it is important not to continue the defrosting longer than is absolutely necessary.
The effective cooling output has been significantly affected by air humidity i.e. frost growth rate. It has been significantly influenced by the defrosting process also. The calculation of the average exchanged heat flux therefore includes a period of cooling and a defrosting period. The average exchanged heat flux i.e. effective exchanged heat flux in the heat exchanger, during the whole cycle, has been defined as

$$\overline{\dot{Q}}_\mathrm{CD} = \frac{\int_{t_\mathrm{C}} \dot{Q}(t)\,\mathrm{d}t - \int_{t_\mathrm{D}} \dot{Q}_\mathrm{D}(t)\,\mathrm{d}t}{t_\mathrm{C} + t_\mathrm{D}} \tag{13}$$

3. NUMERICAL CALCULATION AND VERIFICATION

In order to determine the instantaneous exchanged heat flux, a detailed calculation of boundary layer has been performed. The governing equations which describe boundary layer, presented in Fig. 2, are discretised using the control volume method. To avoid a physically unrealistic pressure field in the air subdomain, staggered grids for velocity components have been used. The convection-diffusion terms have been discretised using a power-law scheme. An iterative procedure has been used to solve the resulting set of linearised discretised equations. For the time-stepping numerical treatment, a fully implicit method has been used. A SIMPLER algorithm for the velocity-pressure coupling has been applied (Patankar, 1980;

Versteeg and Malalasekera, 1995). After calculation of temperature and velocity fields as well as frost thickness, the overall heat transfer coefficient on the heat exchanger has been computed, according to equations (6)-(8). Subsequently, the instantaneous exchanged heat flux has been computed for every time step. The algorithm has been implemented in a self-written Fortran code and solved on a personal computer. When the calculation procedure reaches the end of the cooling period, the defrosting period has been simulated consequently. The calculation of heat needed for defrosting is based on the previously calculated amount of frost layer. The whole calculation procedure has been show in a block diagram on Fig. 5. The validation of the computational procedure has been performed by comparison of numerical results with experimental data. The validation has been performed by simulating several sets of experimental conditions. A detailed description of testing equipment and experimental validation has been given in (Lenic et al. 2008.; Lenic, 2006).

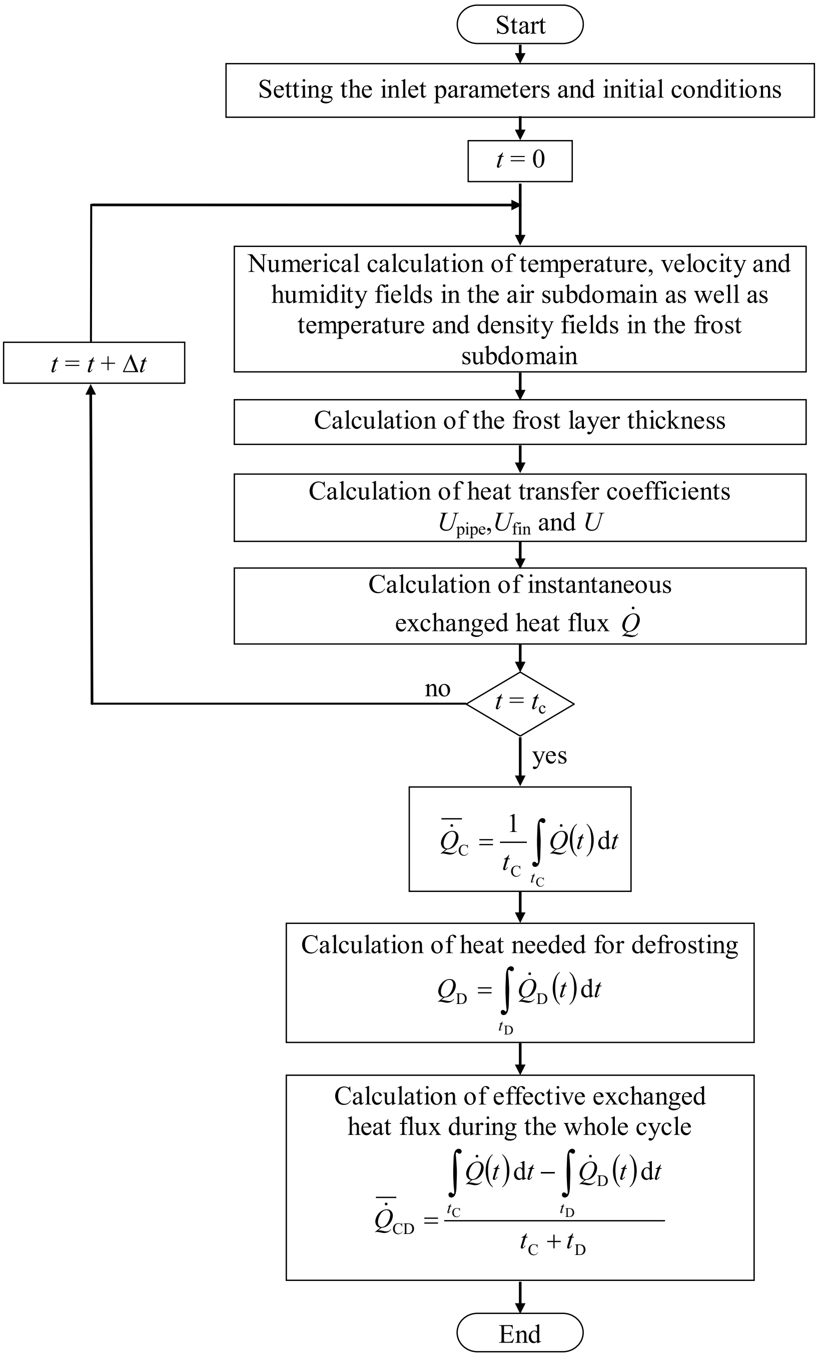


Figure 5. Block diagram for the calculation of the effective exchanged heat flux

Table 1. The overview of defrosting methods

Heat supply from refrigerant side (through the fins)				Heat supply from air side	
Hot gas refrigerant defrosting	Hot liquid refrigerant defrosting	Secondary pipe system	Electrical heating elements	Cold store air or hot air	Spraying with water or brine

4. CALCULATION RESULTS

4.1. Instantaneous exchanged heat flux

The calculation has been performed for the fin-and-tube heat exchanger with the following geometrical characteristics: fin thickness 0.001 m, space between fins 0.006 m, fin width 0.048 m, total number of pipes 189, total number of fins 210, heat exchanger surface 18 m^2, longitudinal pipe distance 0.016 m, transversal pipe distance 0.014 m, outer pipe diameter 0.01 m and inside pipe diameter 0.008 m. A set of numerical calculations has been performed in order to evaluate the influence of operating conditions on instantaneous exchanged heat flux. The results of many calculations have shown that the influence of air humidity on frost layer growth rate and thus on instantaneous exchanged heat flux is substantial. Time-wise variations of instantaneous and nominal heat flux ratio during frost formation for different inlet air humidities are shown on Fig. 6. Nominal heat flux is exchanged when all fins and pipes of the heat exchanger are clean, i.e. without any frost layer. If the heat exchanger operates in frost growth conditions, as a result of additional thermal resistance, the exchanged heat flux will be lower. Frost layer growth is more intensive under higher air humidities because of the higher gradient of air humidity near the frost surface in the boundary layer. Consequently, higher frost growth rates lead to an intensive decrease of the exchanged heat flux. For example, if the inlet air humidity is 2 g/kg, after three hours of operation, the exchanged heat flux is reduced by about 28 % regarding nominal heat flux. If the inlet air humidity is higher, for example 4 g/kg, 36 % heat flux reduction occurs.

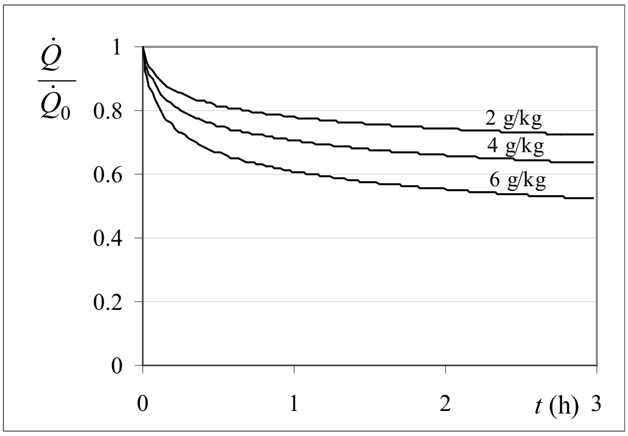
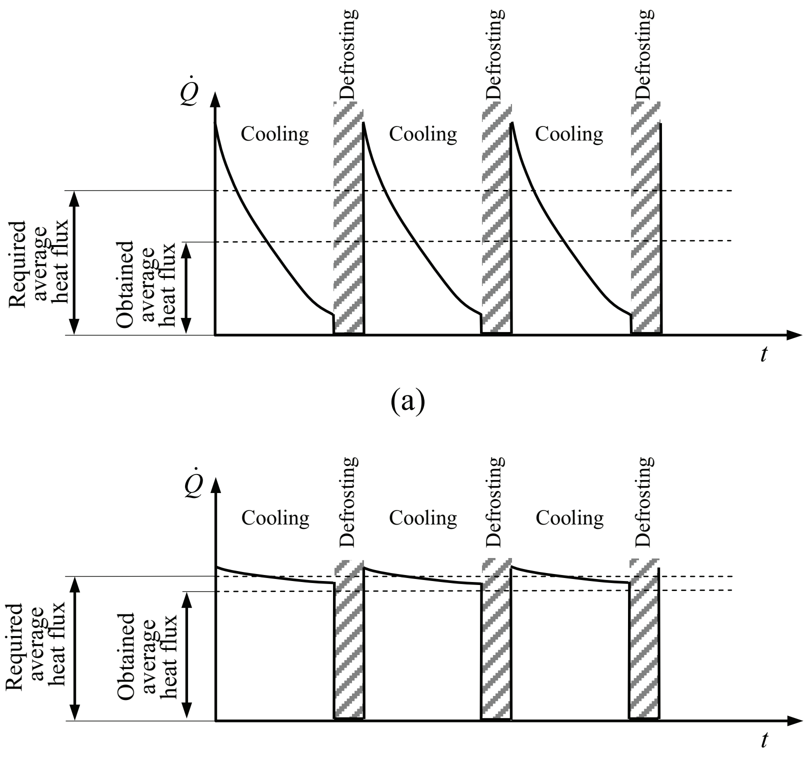


Figure 6. Time-wise variations of instantaneous and nominal heat flux ratio during frost formation for different air humidities ($T_{a,in}$ = 12 °C, $u_{x,in}$= 1 m/s, T_{fs} = -12 °C)

4.2. Different duration of the cooling period

It is not always easy to choose correctly the starting moment of the defrosting cycle. The defrosting process is an energy consumption process. Moreover, it causes the discontinuous

production of cooling energy since the device does not produce any cooling output during defrosting periods. Therefore, it is important to perform the defrosting process only when it is really necessary. The frequency of defrosting cycles is usually preset i.e. the device runs a defrosting cycle after some period of working time, regardless of the real frosting condition. During such an operating mode, some too large or too short cooling periods might be unwontedly obtained. The cooling period could have an inadequate duration, considering optimal energy consumption and adequate cooling power supply. If the device works under operating conditions which are favourable for frost layer growth, in some cases of intensive frost growth, too large cooling periods might be obtained. This leads to a decrease of the mean exchanged heat flux under the tolerable limit, Fig. 7a. From the other side, too short cooling periods lead to a decrease of the mean exchanged heat flux also, because in this case the defrosting cycles have been performed too frequently, Fig 7b. Furthermore, frequent performing of the defrosting cycle causes unwanted break-downs of the cooling supply.
For the above-mentioned reasons, the importance of selecting the optimal duration of a cooling period is evident. Optimal duration of a cooling period will provide the best possible cooling output considering, at the same time, rational energy consumption.
Bearing in mind this primary aim, the simulation of a heat exchanger acting as an evaporator has been investigated numerically. The operation of a heat exchanger has been simulated for different cycle durations, different heat fluxes supplied during the defrosting process and for a variety of operating conditions. Only part of the results has been presented. Variations of exchanged heat flux during operation under different operating conditions and for different cycle duration have been evaluated. The time-wise exchanged heat flux variations for different cycle durations of 1, 2 and 3 hours and for constant defrosting heat flux of 0.6 kW have been shown on Fig. 8. The defrosting heat flux has been denoted as a negative value on a vertical axis. For the presented operating conditions, when shorter cycles are applied, the average exchanged heat flux of cooling period and the average exchanged heat flux of whole cycle are higher in comparison with cases when longer cycles have been used.



(b)

Figure 7. Too large (a) and too short (b) cooling periods

4.3. Optimal duration of a cooling period

Some recent experimental investigations have shown that the overall efficiency of the refrigeration device could be changed for 10-15% by manual adjustments of various operating parameters relating to the defrosting cycle. One of the investigated parameter was the temperature of the refrigerant used for defrosting, which influences the defrosting duration. The second influencing parameter was defrosting frequency. The aim of the analysis presented in this paper is to provide a controlling algorithm where the defrosting frequency will be defined by actual frosting conditions instead of preset periods of working time. Results obtained just offer a possible solution to the problem. Using the developed computer program, it is possible to set optimal duration of the cooling cycle, depending on operating parameters such as air humidity, air temperature, fin temperature and air velocity. By analyses of several cases with different operating parameters, the analytical correlations have been obtained. The correlations can be used for prediction of necessary duration of the cooling period depending on required average heat flux during the cooling cycle. With such correlations it is possible to determine the starting moment of the defrosting cycle.

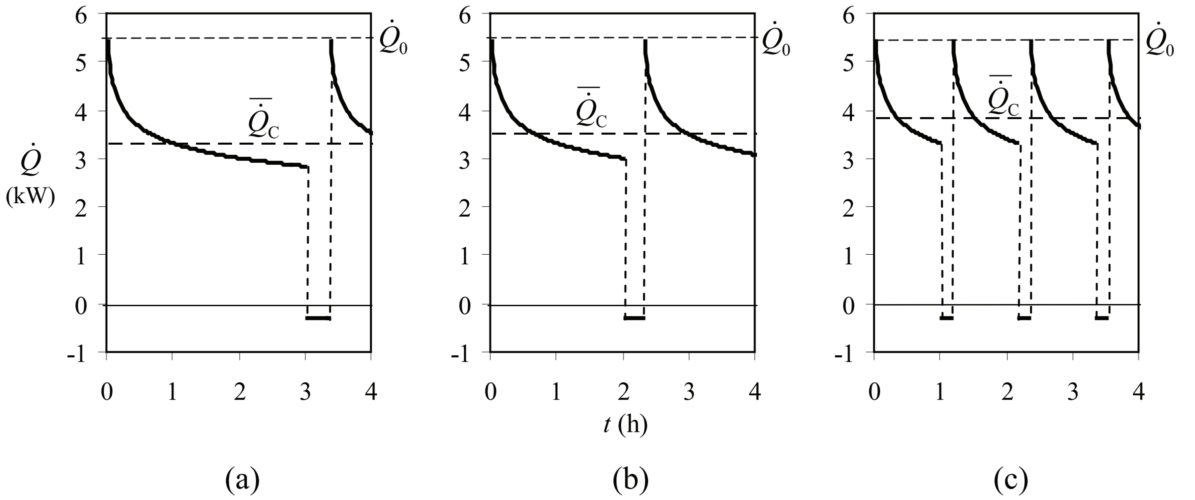


Figure 8. The time-wise exchanged heat flux variations during operation for different duration of the cooling cycle ($\dot{Q}_D = 0.6$ kW, $u_{x,in} = 1$ m/s, $T_{a,in} = 12$ °C, $T_{fs} = -12$ °C, $w_{in} = 6$ g/kg): (a) t_C=3 h; (b) t_C=2 h; (c) t_C=1 h

Hereafter, a few examples of implementation of the results have been presented in the form of diagrams. A diagram for the estimation of the maximally allowed duration of the cooling period depending on desired effective cooling output i.e. depending on the ratio of average and nominal exchanged heat flux, has been shown on Fig. 9. The results shown on the diagram have been calculated for different air humidities with defined values of air velocity, air temperature and fin temperature. For required average heat flux, the longest duration of cooling period can be determined, based on real frost growing conditions.

For example, if required average heat flux should amounts 70 % of the nominal heat flux, the period of cooling could last a maximum of 3 hours, when air humidity amounts 4 g/kg. If the air humidity is higher and amounts 6 g/kg, the period of cooling have to be shorter and the defrosting cycle should be applied after 1 hour of interrupted cooling operation. In this second case, the period of cooling should be shorter because higher air humidity causes intensive growth of frost layer as well as a reduction of the exchanged heat flux on a heat exchanger. Moreover, the defrosting cycles have to be performed more frequently.

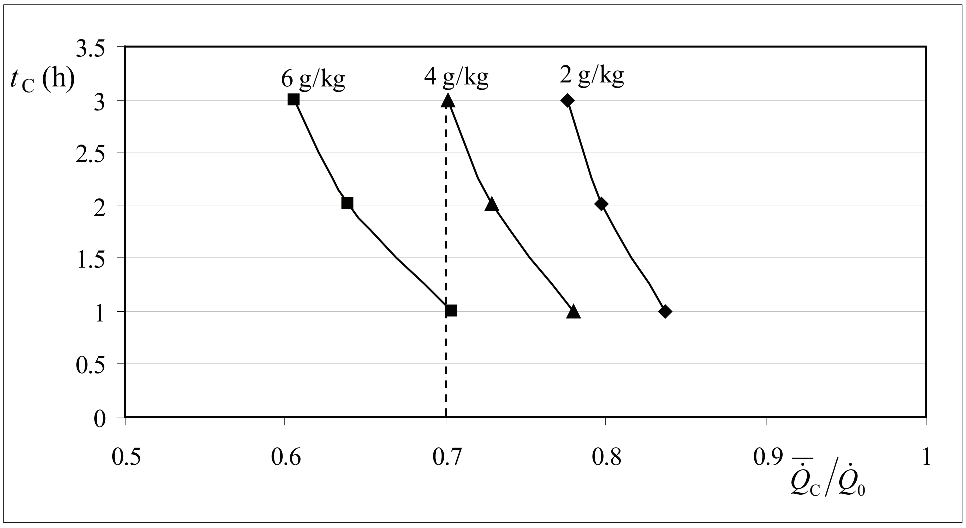


Figure 9. Maximally allowed duration of the cooling period depending on required ratio of average and nominal exchanged heat flux for different air humidities ($u_{x,in}$ = 1 m/s, $T_{a,in}$ = 12 °C)

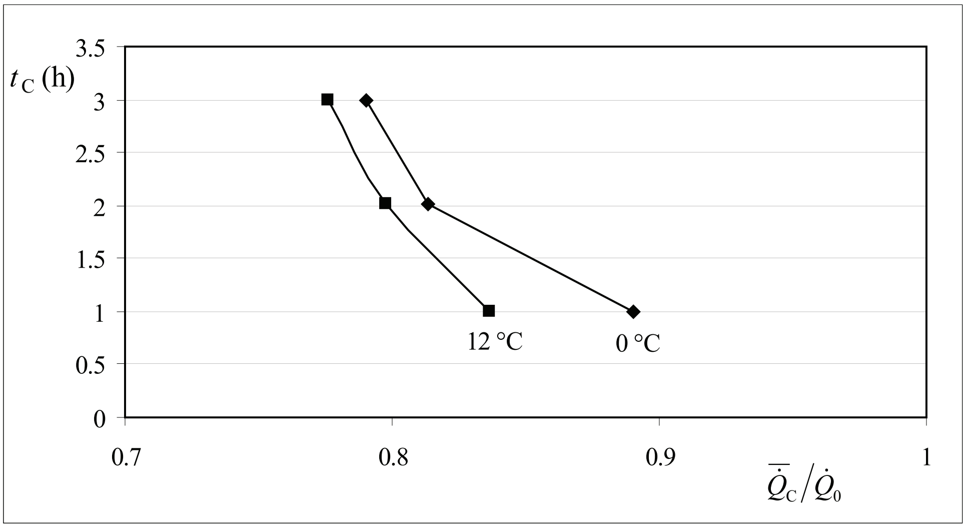


Figure 10. Maximally allowed duration of the cooling period depending on required ratio of average and nominal exchanged heat flux for different air temperatures ($u_{x,in}$ = 1 m/s, w_{in} = 2 g/kg)

The influence of air temperature has been also analysed. A diagram which can be used for selection of the maximally allowed duration of the cooling period for different air temperatures and for the air humidity of 2 g/kg has been presented on Fig. 10. The maximally allowed duration of the cooling period can be selected depending on required ratio of average and nominal exchanged heat flux. It can be noted that it is possible to obtain longer cooling periods under the lower air temperatures as opposed to the case with higher air temperatures. That is because the process of frost formation has been more intensive under operating conditions with higher air temperature, in the specific temperature range. If required average heat flux should amounts 80 % of the nominal heat flux, i.e. $\bar{\dot{Q}}_C / \dot{Q}_0 = 0.8$, the maximally allowed duration of cooling period is 2 hours with air temperature of 12 °C. If the air temperature is 0 °C, under the same other operating conditions, the allowed duration of cooling period can be 2.6 hours. Hence, in presented case, it is possible to obtain 0.6 hours longer cooling period if air temperature has been reduced by 12 degrees. This influence of air temperature on maximally allowed duration of cooling period is not as significant as the influence of the air humidity.

The influence of air velocity on maximally allowed duration of cooling period for given heat flux ratio has been shown on Fig. 11. The diagram has been given for operating conditions with air humidity 4 g/kg and inlet air temperature of 12 °C. For the analysed operating conditions, the influence of air velocity is practically insignificant.

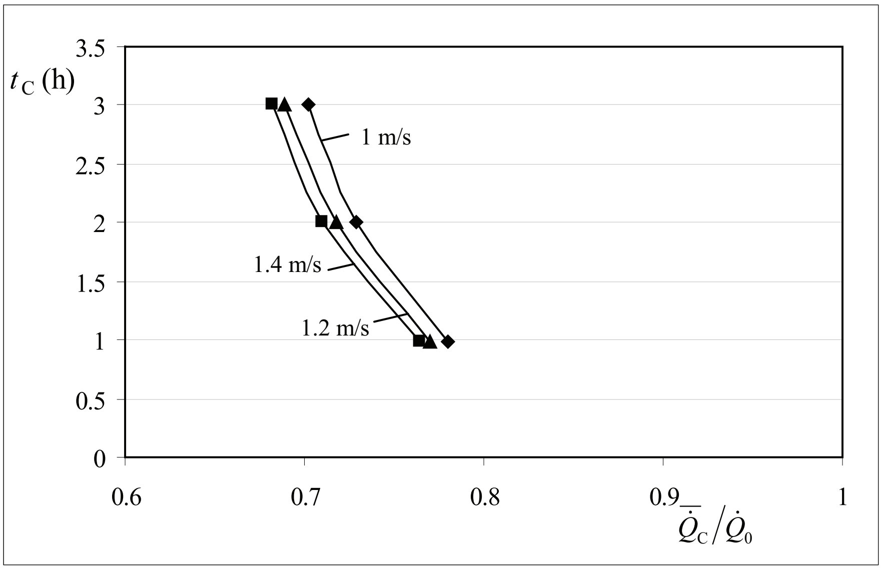


Figure 11. Maximally allowed duration of the cooling period depending on required ratio of average and nominal exchanged heat flux for different air velocities ($T_{a,in}$ = 12 °C, w_{in} = 4 g/kg)

5. CONCLUSIONS

Using an algorithm presented in the paper, it is possible to control the operating cycles of the device in an optimal manner by monitoring the operating conditions. The algorithm allows determining the optimal duration of the cooling cycle, depending on required average heat flux. Accordingly, unnecessary defrosting cycles can be avoided as opposed to the case with preset time-initiated defrosting control method. Moreover, cooling periods with unacceptable reduced exchanged heat flux, caused by thicker frost layer, can be avoided too. By monitoring the real operating conditions, which can be continuously measured, it is possible to control the operating process in the optimal way, considering the electrical energy consumption, quality and stability of delivered cooling or heating output.

For this purpose, a two-dimensional mathematical model of heat and mass transfer on a fin-and tube heat exchanger has been developed. The calculation of exchanged heat flux on a heat exchanger has been performed by detailed calculation of frost thickness and density, as well as air velocity, humidity and temperature in the boundary layer. Several cases with different operating conditions have been analysed and the results have been used to define the correlations for determining the optimal duration of the cooling cycle. The developed mathematical model and self-written computer program can successfully be used to predict the real behaviour of chillers operating under frost forming conditions.

6. LIST OF SYMBOLS

ΔA_{fin} fin surface area of the elementary segment (m^2)
$\Delta A_{\text{fl,fin}}$ air side fin surface area of the elementary segment (m^2)
$\Delta\overline{A}_{\text{fin}}$ average area (between ΔA_{fin} and $\Delta A_{\text{fl,fin}}$) at the middle of frost layer thickness (m^2)
ΔA_{pipe} pipe surface area of the elementary segment (m^2)
$\Delta A_{\text{fl,pipe}}$ air side pipe surface area of the elementary segment (m^2)
$\Delta\overline{A}_{\text{pipe}}$ average area (between ΔA_{pipe} and $\Delta A_{\text{fl,pipe}}$) at the middle of frost layer thickness (m^2)
ΔA_{R} refrigerant side pipe surface area (m^2)
a coefficient in linearised relationship of saturated air enthalpy and air temperature ($h_{\text{sat},T} = a \cdot T + b = 1.4204 \cdot T + 10.205$) (J kg^{-1} K^{-1})
c_{p} specific heat capacity under a constant pressure (J kg^{-1} K^{-1})
D mass diffusivity (m^2 s^{-1})
h convective heat transfer coefficient (W m^{-2} K^{-1})
k thermal conductivity (W m^{-1} K^{-1})
l length (m)
m mass (kg)
$\dot{m}$ water vapour mass flux (kg m^{-2} s^{-1})
$\dot{m}_{\text{a}}$ water vapour mass flux from air towards frost layer (kg m^{-2} s^{-1})
p pressure (Pa)
Q heat (J)
$\dot{Q}$ heat flux (W)
q specific heat (J kg^{-1})
S supersaturation degree
s distance between fins (m)
T temperature (°C)
t time (s)
U overall heat transfer coefficient (W m^{-2} K^{-1})
u_x x-velocity component (m s^{-1})
u_y y-velocity component (m s^{-1})
W specific thermal resistance (m^2 K W^{-1})
w mass fraction of water vapour in air (kg kg^{-1})
x coordinate (m)
y coordinate (m)

Greek symbols
ε porosity
η efficiency
μ dynamic viscosity (Pa s)
ρ density, kg m^{-3}

Subscripts
a air
C cooling period
CD cooling-defrosting period
D defrosting period
diff related to diffusion into frost layer
eff effective

fin	related to fin
fl	frost layer
fs	frost surface
i	ice
min	minimal
mt	melting
pipe	related to pipe
R	refrigerant side
s	fin surface
in	inlet
sat	saturated
sub	sublimation
tot	total
v	water vapour
Δy	related to layer thickness increasing
0	initial value, nominal value
1	inlet side
2	outlet side
∞	free air stream

Superscripts

^{0}	value at the beginning of the process
$\bar{}$	average value

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MOGUĆNOST ADAPTIVNOG UPRAVLJANJA PROCESOM HLAĐENJA I RAZLEĐIVANJA U OVISNOSTI O UVJETIMA NASTANKA LEDENOG SLOJA NA ISPARIVAČU

Sažetak: *U radu je provedena analiza rada uređaja u uvjetima nastanka ledenog sloja na isparivaču topline. Rezultati numeričkog rješavanja matematičkog modela izmjene topline i tvari u graničnom sloju, korišteni su kao temelj za proračun efektivnog izmijenjenog toplinskog toka u isparivaču. Analizirano je nekoliko slučajeva različitih ulaznih pogonskih parametara što je rezultiralo određivanjem korelacija kojima se može odrediti optimalno trajanje ciklusa hlađenja. Predstavljeni rezultati mogli bi se iskoristiti kao pomoć pri upravljanju uređaja u svrhu boljeg iskorištenja rashladnog učinka uređaja. U predloženom algoritmu, prilikom upravljanja uređajem, početni trenutak procesa razleđivanja određuje se temeljem trenutnih pogonskih uvjeta kao što su temperatura, vlažnost i brzina zraka te površinska temperatura isparivača.*

Ključne riječi: lamelni izmjenjivač topline, proces razleđivanja

ECONOMIC JUSTIFIABILITY OF THE APPLICATION OF THE TWO - STAGE HIGH TEMPERATURE HEAT PUMP

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Abstract: *The paper presents the possibilities of using geothermal energy for the purpose of long-distance heating of urban areas, giving a detailed description of the operation principles of a two-degree high-temperature heat pump. A computer programme was used to process the dependences of different evaporation temperatures regarding the heat flow, the heat pump strength and COP. An economic assessment of the investment into different heat pump designs at different evaporation temperatures of refrigerants was also conducted.*

Key Words: Heat transfer, high temperature heat pumps, economic analysis

1 INTRODUCTION

For a long time now, people have experienced the negative consequences of the greenhouse effect. The situation is alarming and that is why we are searching for the ways how to avoid the approaching natural catastrophy. It threatens to destroy mankind unless we do something immediately. At various conferences and forums scientists are establishing that the only possible method of reducing air pollution is the efficient use of energy together with the development of new technologies and systems, as well as the use of renewable energy sources.

The consequences of an intensive exploitation of energy and energy dependence refer decidedly to the countries with poor sources of energy and which are classified into a group of the most environmentally endangered countries in Europe. The complicated situation in these countries does not allow them to deal with energy issues by simply fulfilling demands and desires of energy consumers.

When it comes to the operation of an energy plant, there is often a dilemma how to improve specific consumption of energy in processes, how to increase efficiency, how to direct and convert energy more efficiently, how to use waste heat and replace combustion of liquid and gaseous fuels with other sources of energy.

Researches have come up with an innovative solution of using waste low-temperature water (45°C) for the purpose of long-distance heating of buildings at the temperature of 90/70°C. In this respect, the Faculty of Chemistry and Chemical Engineering of University of Maribor developed an innovative high-temperature heat pump (HP) made by a Japanese company named Mycom in 2010 [1, 2, 3]. This is the first example in the world and has unseen application possibilities in industry, which is confirmed by the Intergovernmental platform for R&D in Europe reward.

2 THE TWO-STAGE HIGH-TEMPERATURE HEAT PUMP WITH A FLASH EXPANDER

Heat pump is a process device which is used for heating. Its operation principles are based on the removal of low temperature from the environment, which is then given on a higher

temperature level. The sources for the removal of energy are air, water or ground. The operating principles of a one stage heat pump are shown in [4, 5].
The two-stage high-temperature heat pump with a flash expander includes two compressors and two expansion valves. The two stages of compression are necessary due to the reduction of a high ratio of pressures, which has negative effects on the performances of the compressor (energy consumption, cooling...). Middle stage of compression is separated by the flash expander, and the same refrigerant is used for heat transfer in both stages. Two- stage heat pump with a flash – expander is presented on Fig. 1.
Due to the two sages of compression there is a possibility of using lower temperature sources (10 to 30°C) for heating. In such implementation it is important which refrigerant will be used, because it has to have good thermo - physical characteristics as well as properly determined pressure.

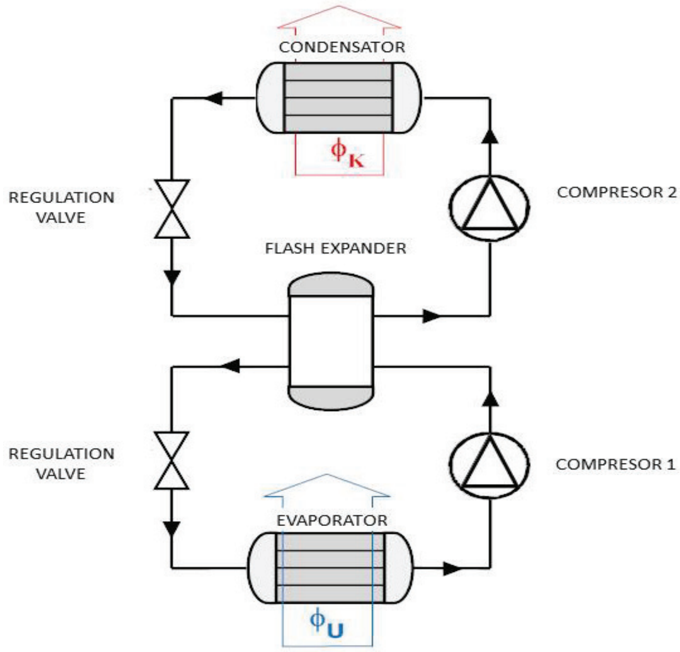

Figure 1. Two-stage high-temperature heat pump with a flash expander (HP – FE)

2.1 Equations for the Calculation

When performing calculation for the two-stage high temperature heat pump with a flash expander it is important to determine correctly the intermediate pressure of the refrigerant, between the first and the second stage, which is equal to the following according to the general equation:

$$p_M = \sqrt{p_{S,1} \cdot p_{T,2}} \text{ (Pa)} \tag{2.1}$$

where:

$p_{S,1}$ - vapour pressure of the refrigerant on the inlet side of the first stage of compression (Pa)

$p_{T,2}$ - vapour pressure of the refrigerant on the delivery side of the second stage of compression (Pa)

Intermediate temperature T_M, which for the first stage of compression of the refrigerant it is the condensation temperature $T_{K,1}$, and for the second stage of compression it is the temperature of evaporation $T_{U,2}$ is calculated using the following equation:

$$T_M = \left[\frac{-B \pm \sqrt{B^2 - 4 \cdot A \cdot (C - \log\left(\frac{p_M}{[Pa]}\right)}}{2 \cdot A} \right]^{-1} \text{ (K)} \quad (2.2)$$

Heat flows, of the first stage $\Phi_{HP,1}$ and of the second stage $\Phi_{HP,2}$ are calculated using the equations:

$$\Phi_{HP,1} = q_{m,S_1} \cdot (h_{g,2} - h_{l,3}) \text{ (W)} \quad (2.3)$$

$$\Phi_{HP,2} = q_{m,S_2} \cdot (h_{g,6} - h_{l,7}) \text{ (W)} \quad (2.4)$$

where:

$h_{g,6}$ - specific enthalpy of refrigerant vapour on the delivery side of the compressor of the second stage of the heat pump (J/kg·K)

$h_{l,3}$ - specific enthalpy of the liquid refrigerant in the condenser of the second stage of the heat pump (J/kg·K)

The heat number of the two - stage heat pump with a flash expander is calculated using the following equation:

$$COP = \frac{\Phi_{HP,2}}{P_{K,1} + P_{K,2}} \text{ (/)} \quad (2.5)$$

Other parameters of the high-temperature heat pump with a flash expander and the dimensions of the compressor for both stages are calculated according to the same principle as for one-stage high-temperature heat pumps [6, 7].

2.2 Calculation results

The calculations of the two-stage high-temperature heat pump with a flash expander for refrigerants R-600a, R-290, R245fa and R-134a were conducted at temperature of condensation (t_K = 70°C, t_k = 80°C). Results are shown in Fig. 2 and Fig. 3 shows the dependences between COP and heat flow of evaporation temperature.

The main objective of the implementation of the two - stage heat pump with a flash expander is to try to reduce the strength which is necessary for the compressor to operate in order to reduce the ratio between pressures and increase the useful heat flow of the condensation part of the pump.

When conducting the calculation, the fact that the compressors in both stages are equal, was taken into consideration. The compressors were piston compressors WBH chosen from the catalogue of the manufacturer called MYCOM [8]. The volume flow of the compressor q_v = 637 m^3/h, maximum operating pressure $p_{max.}$ = 2,0MPa and maximum power of the compressor $P_{K\,max.}$ = 145,0 kW.

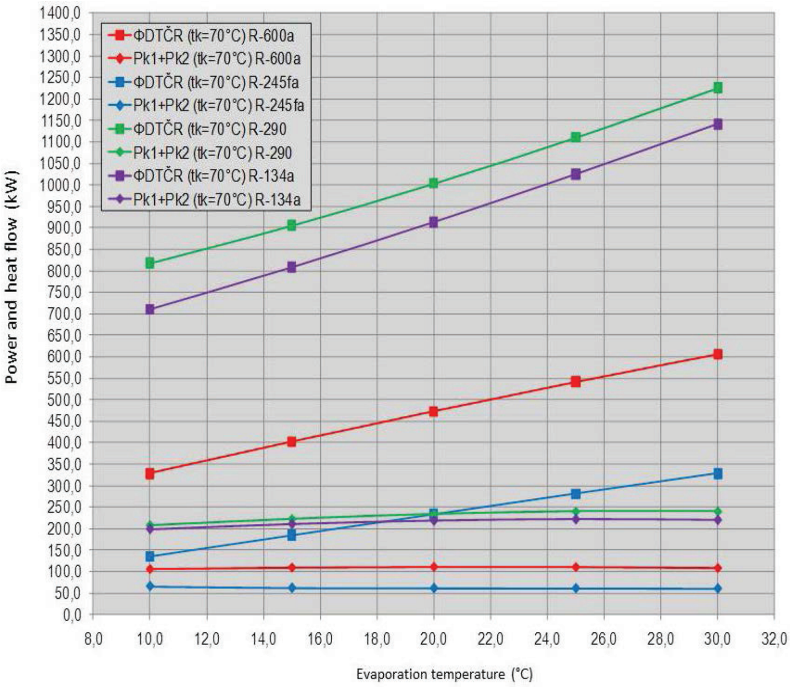

Figure 2.The two-stage high-temperature heat pump with a flash expander at the condensation temperature of the refrigerant of t_K = 70°C

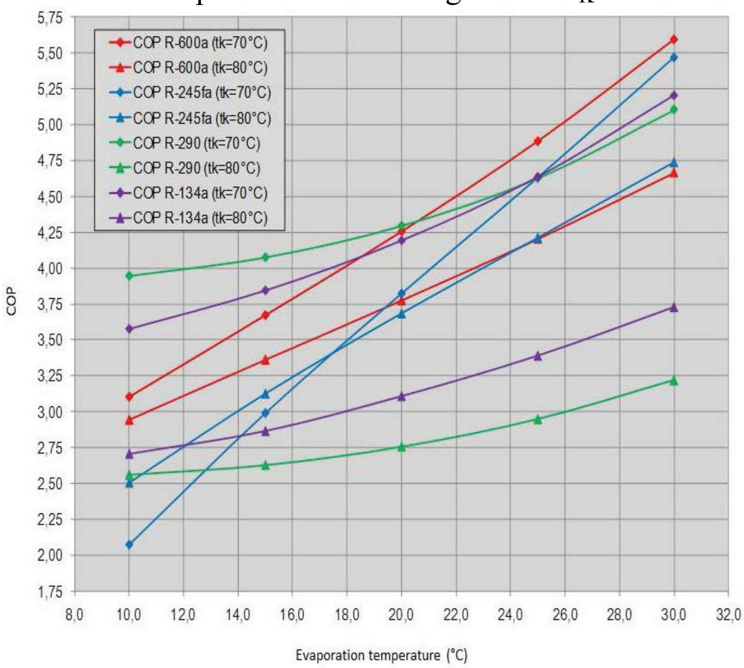

Figure 3. Heat number of the two-stage heat pump

The diagram shows that using refrigerants R-290 and R-134a we achieve high values of heat flow, but for the proposed temperatures the consumption of energy necessary for the operation of the compressor is to high in relation to the chosen compressor. Refrigerant R-245fa gives low values of the heat flow as well as the low consumption of energy. For the refrigerant R-245fa the compressor is oversized. The most suitable characteristic parameters of the two-stage heat pump with a flash expander were obtained using the refrigerant R-600a, which enables a wide scope of operation and, on the other hand, conditions for optimal operation of the compressor are in accordance with the instructions from the manufacturer.

3 THE TWO-STAGE HEAT PUMP WITH A HEAT EXCHANGER

The two-stage heat pump with a heat exchanger consists of two one-stage heat pumps. The stages are separated by the heat exchanger, which serves as the condenser for the first stage and as evaporator for the second stage. The stages are separated in such way that refrigerants are not in contact. This means that each stage has its own refrigerant. The heat pump diagram is shown in Fig. 4. [11].

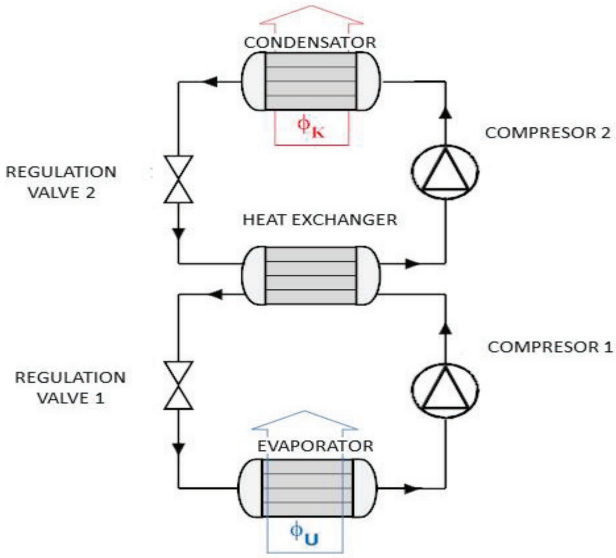

Figure 4. The two-stage heat pump with a heat exchanger (HP – HE)

3.1 Equations for the calculation

Calculation of the characteristic parameters of the operation of the two-stage heat pump with a heat exchanger is more simply conducted according to the principle of the two one-stage pumps, where it is assumed that the heat flow of the condensation of the first stage $\Phi_{C,1}$, is equal to the heat flow of boiling of the second stage $\Phi_{B,2}$. It holds that:

$$\Phi_{C,1} = q_{m,S,1} \cdot (h_{g,2} - h_{l,3}) \text{(W)} \tag{3.1}$$

$$\Phi_{C,1} = \Phi_{B,2} \text{(W)} \tag{3.2}$$

It follows that the mass flow of the refrigerant on the inlet side of the compressor of the second stage of the heat pump is equal:

$$q_{m,2} = \frac{\Phi_{B,2}}{(h_{g,5} - h_{l,8})} \text{(kg/s)} \tag{3.3}$$

where:

$h_{g,5}$ - specific enthalpy of the refrigerant which enters the compressor in the second stage of the heat pump (J/kg·K)

$h_{l,8}$ - specific enthalpy of the liquid refrigerant which enters the evaporator in the second stage of the heat pump (J/kg·K)

Heat number of the two-stage heat pump with a heat exchanger is calculated:

$$COP = \frac{\Phi_{HP,2}}{P_{K,1} + P_{K,2}} \ (/) \tag{3.4}$$

Condensation temperature of the first stage $T_{K,1}$ and the boiling temperature of the second stage $T_{U,2}$ of the refrigerant are calculated using the method of the average value between the temperatures of boiling of the first stage $T_{U,1}$ and the temperature of the condensation of the second stage $T_{K,2}$.

$$T_M = \frac{T_{U,1} + T_{K,2}}{2} \ (\mathrm{K}) \tag{3.5}$$

The possibility of using refrigerant in both stages requires that we determine the characteristics of the compressor for each stage separately according to the same principle as for the one-stage heat pump. [7, 8, 9].

3.2 Calculation Results

Calculation of characteristic parameters was conducted for the following refrigerants:

- R-407c in the first stage and R-600a in the second stage,
- R-717 in the first stage and R-600a in the second stage,
- R-290 in the first stage and R-600a in the second stage.

The results are given in Fig. 5 and Fig. 6, which show the power which is necessary for the operation of the compressor and the heat flow of the heat pump. Calculations were conducted for different temperatures (t_U) of the refrigerant: from 5,0°C to 25,0°C and the constant temperature of condensation t_K = 70°C.

The values of COP of the two-stage heat pump with a heat exchanger were calculated for the condensation temperatures of the refrigerant t_K = 60°C and t_K = 80°C. Fig. 7 shows the dependence between the COP and the refrigerant boiling temperature.

For the calculation of all suggested combinations of refrigerants the compressors chosen were: a piston compressor with the flow of 300 m^3/h for the first stage and a piston compressor with the flow of 700 m^3/h for the second stage.

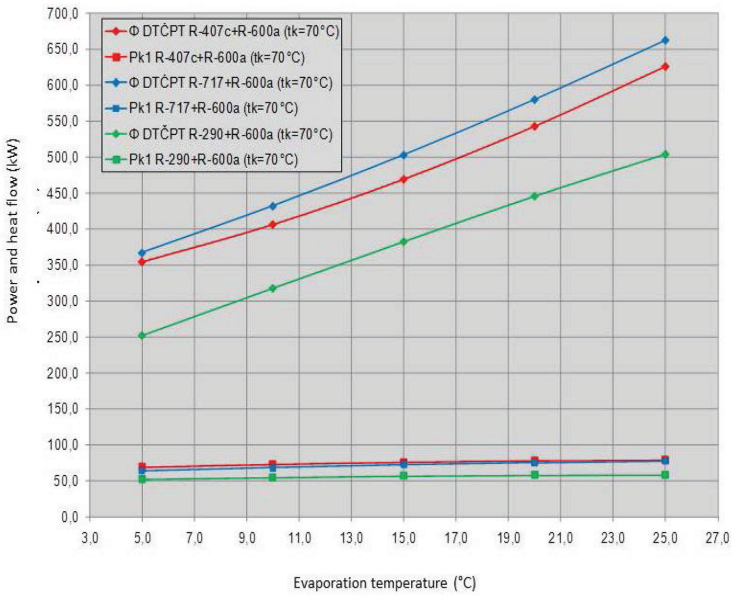

Figure 5. The first stage of the two-stage heat pump with the heat exchanger

The following combinations of refrigerants are optimal for the operation of the two-stage heat pump with a heat exchanger:

- R-717 in the first stage and R-600a in the second stage,
- R-407c in the first stage and R-600a in the second stage.

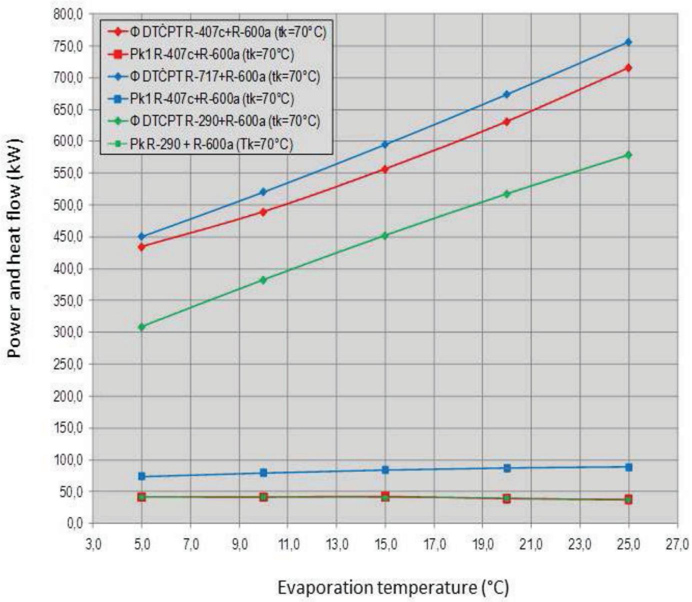

Figure 6. The second stage of the two-stage heat pump with a heat exchanger

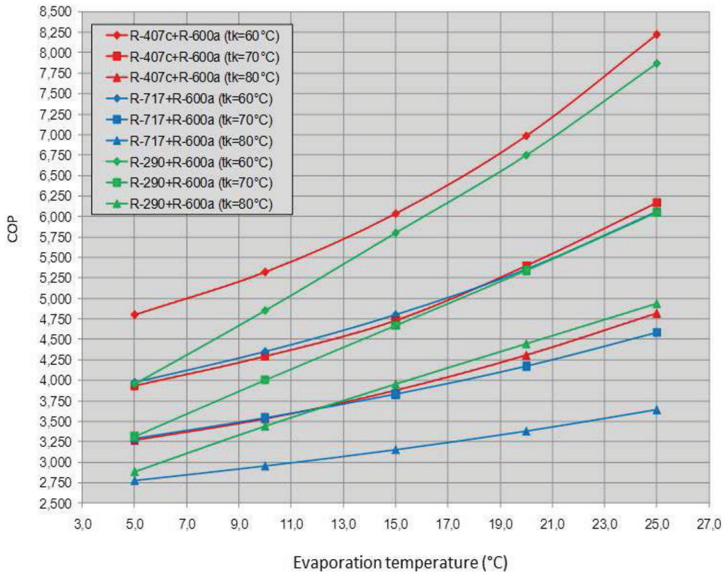

Figure 7.COP of the two-stage heat pump with a heat exchanger

4 ECONOMICAL ANALYSIS

The decision on the investment is much easier and simpler if it is based on the calculated parameters for individual implementations of heat pumps [10]. The calculation included the models with most suitable refrigerants. The economic analysis stated that the costs of the investment are covered from personal sources and from loans in 30% to 70% ratio. The present value of the investment costs C_{INV} je was calculated according to the equation;

$$C_{INV} = C_0 + \sum_{j=0}^{N} \frac{a_n \cdot C_{HP}}{(1+r)^j} \text{ (EUR/year)} \tag{4.1}$$

where:

C_0 - own funds (EUR)

C_{HP} - the cost of the heat pump (EUR)

r - discount rate (/)

N - lifetime of the system (years)

Annuity factor a_n is calculated using the equation:

$$a_n = \frac{r_a \cdot (1+r_a)^{n_1}}{(1+r_a)^{n_1} - 1} \text{ (/)} \tag{4.2}$$

where:

r_a - discount stage annuity (/)

n_1 - time of return annuity (/)

Maintenance costs of the heat pump were evaluated at 2 % of the purchase price. Net present value of expenses with inflation rate included was calculated using the equation:

$$C_S = \sum_{j=0}^{N} \frac{0.02 \cdot C_{HP} \cdot (1+r_j)^j}{(1+r_j+r)^j} \text{ (EUR/year)} \tag{4.3}$$

Net present value of electric power costs for the operation of the compressor of the pump were calculated using the equation:

$$C_{PS} = \sum_{j=0}^{N} \frac{C_E \cdot P_K \cdot t_1 \cdot t_2 \cdot (1+r_j)^j}{(1+r_j+r)^j} \text{ (EUR/year)} \tag{4.4}$$

Net present value of the income from the heat produced considering the inflation rate is calculated using the equation:

$$C_P = \sum_{j=0}^{N} \frac{C_T \cdot \Phi_{HP} \cdot t_1 \cdot t_2 \cdot (1+r_j)^j}{(1+r_j+r)^j} \text{ (EUR/year)} \tag{4.5}$$

Net present value of the heat income, considering the investment costs and maintenance costs , as well as the consumption of electric energy for the operation of the compressor is calculated using the equation:

$$C = C_P - (C_{INV} + C_S + C_{PS}) \quad \text{(EUR/year)} \tag{4.6}$$

where :

r_j - inflation rate (/)

C_E - electric power cost (EUR/kWh)

C_T -the cost of heat for heating (EUR/kWh)

t_1 - operation time per day (h/day)

t_2 - operation time per year (days/year)

Table 1 contains data for the calculation of different implementations of heat pumps. It shows NPV at different temperatures of boiling of refrigerants, and at a constant condensation temperature t_K=70°C.

Table 1: Data for the calculation of the economic analysis of different implementations of the two –stage heat pump (HP)

Implementation of the two – stage heat pump	HP - FE	HP - HE	HP - HE
Refrigerant	R-600a	R-717/R-600a	R-407c/R-600a
Temperature of boiling (t_U) [°C]	20,0	20,0	20,0
Temperature of condensation(t_K) [°C]	70,0	70,0	70,0
Heat flow of the heat pump (Φ_{HP}) [kW]	473,0	674,2	631,1
Compressor strength (P_K) [kW]	111,1	161,6	116,9
Operation time per day (t_1) [h/day]	18	18	18
Operation time per year (t_2) [days/year]	120	120	120
Heat pump lifetime (N) [year]	20	20	20
Own funds (C_o) [EUR]	28.200	31.800	31.800
Cost of the heat pump (C_{HP}) [EUR]	94.000	106.000	106.000
Electric power costs (C_E) [EUR/kWh]	0,07	0,07	0,07
Cost of heat for heating (C_T) [EUR/kWh]	0,0325	0,0325	0,0325
Discount rate (r) [%]	7,00	7,00	7,00
Inflation rate (r_j) [%]	1,20	1,20	1,20

5 CONCLUSION

With a two-stage heat pump with a flash expander, the best operating conditions are with the refrigerant R-600a. For the proposed implementation of the heat pump, the ratio between the pressures of the compressed refrigerants decreases. Boiling of the refrigerant at the temperature of t_U = 20°C is economical. The condensation temperature is t_K = 70°C. Then the heat flow is 408,0 kW, the consumption of energy for the operation of both compressors is 111,1 kW. It is suggested to use the same compressor in the first and the second stage as with the one-stage pump.

The two-stage heat pump with a heat exchanger consists of two one-stage pumps. Its advantage is that we can use, in each stage, different refrigerants [11].

The analysis of thermo-physical properties of refrigerants established that the operation of a two-stage heat pump with a heat exchanger is the cheapest using refrigerants R-407c in the first stage and R-600a in the second stage of the heat pump. If the condensation temperature of the refrigerant in the second stage is t_K=70°C, the operation of the heat pump of the first stage is economically justifiable at the boiling temperature of t_U = 10°C. In the first stage, the type of the compressor which is recommended is WA or WBH, in the second stage only WBH. The heat flow of the two-stage heat pump with a heat exchanger in that case is 489,4 kW, the total consumption of energy for the operation of both compressors is 113,9 kW.

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EKONOMSKA OPRAVDANOST PRIMJENE DVOSTUPANJSKE VISOKO TEMPERATURNE DIZALICE TOPLINE

Sažetak: *U radu je analizirana mogućnost korištenja geotermalnih voda za daljinsko gradsko grijanje. Rad daje detaljan opis primjene dvostupanjske visoko temperaturne toplinske crpke. Numeričkim modeliranjem ukazano je na vezu između zazličitih temperatura isparivanja i protočne količine radnog medija, učina i COP-a. Ekonomska opravdanost primjene dvostupanjske visoko temperaturne toplinske crpka za različite konstrukcije toplinskih crpki i različite temperature isparivanja radne tvari.*

Ključne riječi: *toplinska crpka*, visoko temperaturne toplinske crpke, ekonomska analiza

ANALYSIS OF DIFFERENT REFRIGERATING AGENTS IN SINGLE PHASE HIGH TEMPERATURE HEATING PUMP

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Abstract: *The following text presents the way of choosing the most adequate agent for refrigerating for the sake of adiabatic circular process for various usages. The choice is based on the lessening of the harmful effects on nature, thermo-physical characteristics of the agent as well as the characteristics of the used compressors. Simulation model of determination the optimal concentration of mixture of R-600 and R-290 for single phase heating pump working is presented. Simulation of the determination of the optimal mixture of all agents is done in the GAMS programme package.*

Key Words: Heat transmission, high temperature heat pump, refrigerating agents, effect simulation

1 INTRODUCTION

According to the scientific research, it is known that the atmosphere has been rapidly warming since the mid-20th century. A lot of changes in almost each part of the world make us perceive the global warming. Most of the studies show that the man is the one who is guilty for the global warming. He and his unthinking actions (industry, traffic…) destroy the balance of nature. This is the reason why we have to prevent further warming by reducing gas emission. We also have to find new technological solutions in the fields of process and heating techniques.

According to Kyoto agreement, the gas emission that causes the greenhouse effects has to be reduced by EU in comparison to the 1990 emission in the same area. These gases include- CO_2, CH_4, N_2O, and anthropogenic F- gases. Substances that also make the ozone layer deplete include CFC, partly halogenated carbon hydrates and halons.

Having in mind the accepted agreements for reaching certain goals in the field of energy, we should get down to development of getting and using cheap energy and energy, based on low carbon technologies, that is acceptable for the nature.

The choice of refrigerating agent is based on physical- chemical characteristics of the existing agent and the ability of certain technological solutions that enable the wanted parameters of the operating heat pumps.

2 REFRIGERATING AGENT

These are functional liquids in heating pumps that absorb heat in lower temperature levels and transmit it to higher temperature levels. Functioning of the heating pumps is very dependent on the choice of refrigerating means.

It is proved that agents like CHCs and HCFC destroy the ozone layer. Other anthropogenic fluorinated gasses cause global warming. This is why the usage of CHC and CHFC in heating pumps is forbidden. As a current solution various fluorinated carbon hydrates are used, but they still have the negative effects. Developing new technologies and improving the

pumps, organic means, which don't have harmful effects on environment, are increasingly used. The development of refrigerating agent is shown in Fig. 1.
The influence of the agent on depleting of the ozone layer is estimated by ODP index "Ozone Depleting Potential", which is determined for each agent separately and it is compared to the CFC 11 means, whose ODP is 1.

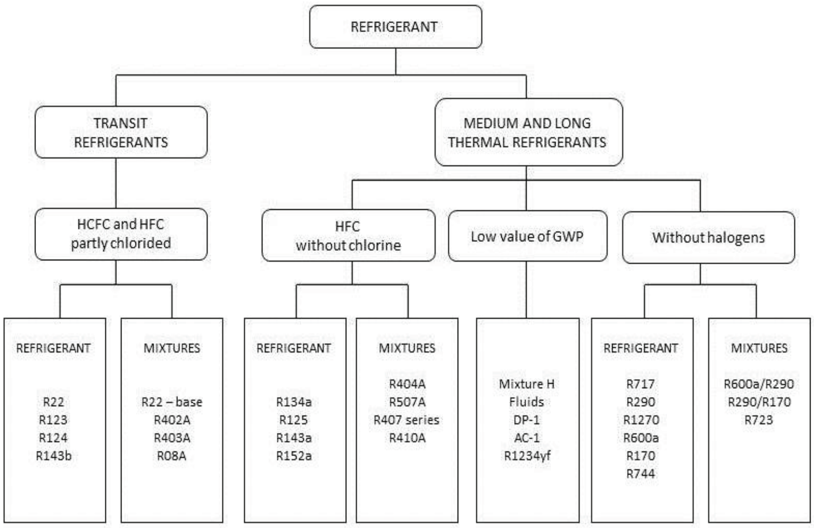

Figure 1. Directions of the refrigerating agent development

The lower ODP is, the less ozone depleting is. Gases are also harmful for the ozone, that's why the ozone layer depleting is related to the process of global environment changing. GWP "Global Warming Potential" for each harmful gas shows the effect of the molecules of that gas on global warming and it is compared to molecule CO_2, whose value is 1. The effect of certain agent on ozone and global warming is shown in table 1 [1].

Table 1: The effect of certain agent on ozone and global warming

Agentsign	Chemical formula	ODP	GWP
R-12	CCl_2F_2	1.00	8100
R-22	$CHClF_2$	0.055	1500
R-32	CH_2F_2	0.0	550
R-125	CHF_2CF_3	0.0	3400
R-134a	CF_3CH_2F	0.0	1100
R-143a	CF_3CH_3	0.0	4300
R-245fa	$CF_3CH_2CHF_2$	0.0	950
R-407c	R-32/R-125/R134a	0.0	1548.5

2.2 Physical and chemical characteristics of the means

While the heating pump operates, the agent is exposed to great changes in pressure and temperature. This is why the physical and chemical characteristics of the agents are very important.
For good heat transmission it is good if the heating transmission and transfer coefficient between the refrigerator and the metal part is as bigger as it is possible, because it influences the size of the heat exchanger. Crystallization temperature has to be lower than the lowest possible temperature in the heating pump. Critical pressure and the temperature have to be as

higher as possible above the operating zone of the device. The proportion among compressor pressures have to be as low as possible, which agent that the condensation pressure has to be as low as possible, while the steaming pressure has to be as high as possible. In order to have the minimum waste while passing through pipes, vents and heat exchangers, the viscosity has to be as low as possible.

The quantity of water in the agent has to be as low as possible, due to the lifetime of the pump. Chemical structure can be stable without other gases presence. Table 2 and 3 shows some important physical and chemical characteristics of the refrigerating agent that are important when planning the process.

Table 2: Basic chemical and physical characteristics of the agent [3, 4]

Means	Chemical formula	Mol. weight (g/mol)	Boiling T (°C)	Crystallization T (°C)	Critical T (°C)	Critical p (kPa)	Critical V (L/kg)
R-134a	CF_3CH_2F	102.30	-26.16	-96.6	101.1	4067	1.81
R-290	$CH_3CH_2CH_3$	44.10	-42.09	-187.7	96.70	4248	4.53
R-407c	mixture	86.20	-43.79	/	86.1	4635	1.98
R-600a	$CH(CH_3)_3$	58.13	-11.73	-160.0	135.0	3645	4.526
R-717	NH_3	17.03	-33.3	-77.7	1330.0	11417	4.245

Table 3: Other chemical and physical characteristics of the means

Means	R-22	R-134a	R-245fa	R-290	R-407c	R-600a	R-717
Form	gas	gas	Liq.. gas	gas	Liq. gas	gas	gas
Colour	colourless	colourless	colourless	colourless	colourless	colourless	colourless
Smell	Ether	Ether	Weak	Considerable	Ether	Sweet	Ammoniac
Temperature of burning	Non-flammable	> 750 °C	/	470 °C	Non-flammable	450 °C	630 °C
Explosion danger	No.	No	No.	Yes .	No	yes.	yes.
Explosion limits upper / lower In the air	/	/	/	2.1 / 9.5 vol%	/	1.3 / 8.5 vol %	15 / 30 vol %
Density (kg/l) 0°C, p=1.013 bar	1,194	1,21	1.226	1.56	1.136	2.0	0.6
Solubility in water 20 °C	3.0 g/l	0.15 wt % mg/100g	0.13 g/l	75 mg/l	unimportant	5.4 mg/l	Hydrolyzed

3 SINGLE PHASE HIGH TEMPERATURE HEATING PUMP

Single phase high temperature heating pump is, basically, a common heating pump, where we can achieve the wanted temperature difference between the condensation temperature (t_k) and the cooking temperature (t_u) of 35°C to 50°C if we choose the adequate refrigerating agent and compressor. The scheme of the single phase heating pump used for heating is shown in Fig. 2. In order to function the single phase heating pump needs a relatively high heat source with the temperature range from 20°C to 40°C. The weak side of the pump is the fact that we cannot maximally use the energy source and its advantage is relatively small investment.

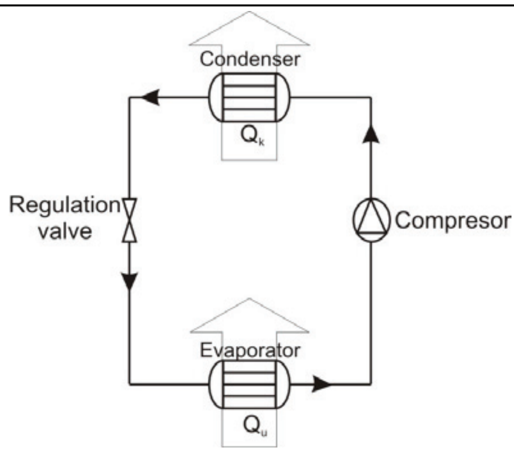

Figure 2. Single phase heating pump

3.1 Mathematical model

Developing a maths model for calculating the process characteristics of the pump and simulation of the refrigerating agent mixture is done on the base of known thermo physical data. For each agent, certain linear or quadratic equation for calculating the steam pressure, density and specific enthalpy is determined, based on the wanted functioning temperature.
The equation for calculating the steam pressure depending on temperature looks like this:

$$p = 10^{\left[A\cdot\left(\frac{1}{T}\right)^2 + B\cdot\left(\frac{1}{T}\right) + C\right]} \text{(Pa)} \tag{3.1}$$

where:
A, B, C are the constants for calculating the steam pressure depending on temperature

Equation for calculating the density of liquid ρ_l and density of steam ρ_g of the agent depending on temperature are:

$$\rho_l = \left[a_l \cdot T^2 + b_l \cdot T + c_l\right] \text{(kg/m}^3\text{)} \tag{3.2}$$

$$\rho_g = \left[a_g \cdot T^2 + b_g \cdot T + c_g\right] \text{(kg/m}^3\text{)} \tag{3.3}$$

where:
a_l, b_l, c_l - are constants for calculating the density of the liquid depending of temperature
a_g, b_g, c_g - are constants for calculating the density of the steam depending on temperature

Equation for calculating the specific enthalpy of the liquid h_l and specific steam enthalpy h_g of the agent depending on the temperature are:

$$h_l = \left[x_l \cdot T^2 + y_l \cdot T + z_l\right] \text{(J/kg)} \tag{3.4}$$

$$h_g = \left[x_g \cdot T^2 + y_g \cdot T + z_g\right] \text{(J/kg)} \tag{3.5}$$

where:
x_l, y_l, z_l - are constants for calculating the specific enthalpy of the liquid depending on temperature
x_g, y_g, z_g - are constants for calculating the specific enthalpy of the steam depending on temperature

Based on the above mentioned equations, using the MathCAD programme, the programme for calculating the functioning characteristics of the heating pump was created. In the programme package GAMS, the programme for simulation of the determining of the optimal proportion between the two agents in the mixture under the chosen conditions, was created [5, 6].
Heating flow of the single phase heating pump $\Phi_{TČ}$ and refrigerating device Φ_{HN} are calculated from the following:

$$\Phi_{TČ} = q_{m,T} \cdot (h_{g,2} - h_{l,3})\,(\mathrm{W}) \tag{3.6}$$

$$\Phi_{HN} = q_{m,S} \cdot (h_{g,1} - h_{l,4})\,(\mathrm{W}) \tag{3.7}$$

Where:
$h_{g,1}$ - specific enthalpy of the steam at the entrance into the compressor (J/kg·K)
$h_{g,2}$ - specific enthalpy of the steam at the pressure side of the compressor (J/kg·K)
$h_{l,3}$ - specific enthalpy of the liquid agent in condensator (J/kg·K)
$h_{l,4}$ -specific enthalpy of the liquid agent that enters the stove (J/kg·K)

Heating number of the heating pump (HP)

$$COP = \frac{\Phi_{HP}}{P_K}\,(\,/\,) \tag{3.8}$$

Refrigerating number of the refrigerating device

$$COP_H = \frac{\Phi_{HN}}{P_K}\,(\,/\,) \tag{3.9}$$

Compressor characteristics have to be precisely calculated in order to correctly dimension the heating pump or the refrigerating device capacity. Having in mind the calculated data and standard dimensions of the compressor, we determine the capacity of the heating pump or the refrigerator device in theory [7, 8, and 9].
Refrigerating device temperature on the pressure side of the compressor

$$T_T = T_S \cdot r_K^{\left(\frac{\chi-1}{\chi}\right)}\,(\mathrm{K}) \tag{3.10}$$

The proportion of the compressor pressure is:

$$r_K = \frac{p_T}{p_S}\,(\,/\,) \tag{3.11}$$

where :
T_S - Temperature of the agents at the entrance side of the compressor (K)
χ - Pressure factor of the agent (/)
p_T - Steam pressure of the agent at the pressure side of the compressor (Pa)
p_S - Agent steam pressure at the suction side of compressor (Pa)

The power needed for compressor functioning P_K at adiabatic agents compressed in the heating pump or refrigerating device is calculated by the following equation:

$$P_K = \frac{P_{ad}}{\eta_K} = \frac{\frac{\chi}{\chi - 1} \cdot p_S \cdot V_K \cdot \left[r_K^{(\frac{\chi-1}{\chi})} - 1 \right]}{\eta_K} \text{ (W)} \tag{3.12}$$

Where:

P_{ad} - adiabatic power of agent compression (W)

η_K - usefulness of compressor (/)

Level of filling the compressor cylinder λ is determined this way:

$$\lambda = 1 - \varepsilon_o \cdot \left[r_K^{(\frac{1}{\chi})} - 1 \right] (/) \tag{3.13}$$

The real cubic flow of compressor:

$$q_{V_K dej.} = q_{V_K} \cdot \lambda \text{ (m}^3\text{/s)} \tag{3.14}$$

Volume flow of the refrigerating device in the compressor:

$$q_H = q_{V_K dej.} \cdot \frac{\rho_{g,S}}{\rho_{g,T}} \text{ (m}^3\text{/s)} \tag{3.15}$$

Mass flow of the refrigerating agents at the suction side of the compressor :

$$q_{m,S} = q_{V_K dej.} \cdot \rho_{g,S} \text{ (kg/s)} \tag{3.16}$$

Mass flow of the refrigerating agents at the pressure side of the compressor:

$$q_{m,T} = q_H \cdot \rho_{g,T} \text{ (kg/s)} \tag{3.17}$$

where:

ε_o - harmful area (/)

q_{V_K} - comrpessor volume flow (m^3/s)

$\rho_{g,S}$ - agent steam density at the suction side of the compressor (kg/m^3)

$\rho_{g,T}$ - agent steam density ustina at the pressure side of the compressor (kg/m^3)

3.2 Determining the optimal proportion in the two refrigerating agent mixture

Programme GAMS (*General Algebraic Modelling System*) is used for simulating of the determining the optimal proportion in the two refrigerating agent mixture. Simulating in the above mentioned programme determines the mixture of the two refrigerating agents, where the maximum efficiency for them can be achieved when the heating pump is functioning.

Optimal proportion of the mixture is determined by Z function, for the heating flow value of the heating pump:

$$\max Z = q_{m,S} \cdot (h_{g,1} - h_{l,4}) \cdot 1000 \text{ (kW)} \quad (3.18)$$

Optimal proportion of the two agents in the mixture is determined for the agent share (X_1) and agent share (X_2), which means that:

$$X_1 + X_2 = 1 \text{ (\%)} \quad (3.19)$$

When simulating, we have in mind the basic characteristics of the compressor (functioning power, maximum pressure and pressure proportion), which are determined with the computer programme.

3.3 Simulation results

The main condition for mixing the refrigerating agents to be used in the heating pump is their capability to mix them physically without chemical reaction. That is confirmed for R-600a and R-290.

The aim of the optimal proportion simulation of the mixture is to determine the maximum capacity usage of the compressor and the maximum usage of the high temperature heating pump heating flow.

The limiting conditions for the efficacious simulation are determined:

- volume compressor flow is constant and equals q_{Vk} = 637 m^3/h,
- upper limit of the compressor power type WBH is P_K = 116 kW, which is 80 % of the maximum power of the compressor and equals 145 kW,
- upper limit of the allowed pressure of the agent mixture is 1,7133 MPa, which is 85,6 % of the maximum allowed pressure of the refrigerating agent which is 2,0 MPa,
- the proportion between the pressures is higher than 3
- the temperature of steaming t_U = from 15 to 35°C,
- The temperature of condensation t_K = from 60 to 80°C.

The results of the simulation are presented as a graphic in Fig. 3, where we can see the heating flow, the compressor power and single component shares. Fig. 4 shows refrigerating number values for the single phase heating pump.

The simulation shows that the power for the three functioning conditions is equal P_k= 116,0 kW. The heating flow of the steaming part of the single phase high temperature heating pump is lower if the condensation temperature t_K is higher. The diagram also shows the share of both agents X_1 and X_2, at different condensation temperatures.

The results of calculating functioning characteristics of the heating pump using R-290 agent show that the needed power of the compressor is too high. The heating flow of the heating pump with R-290 agent is high.

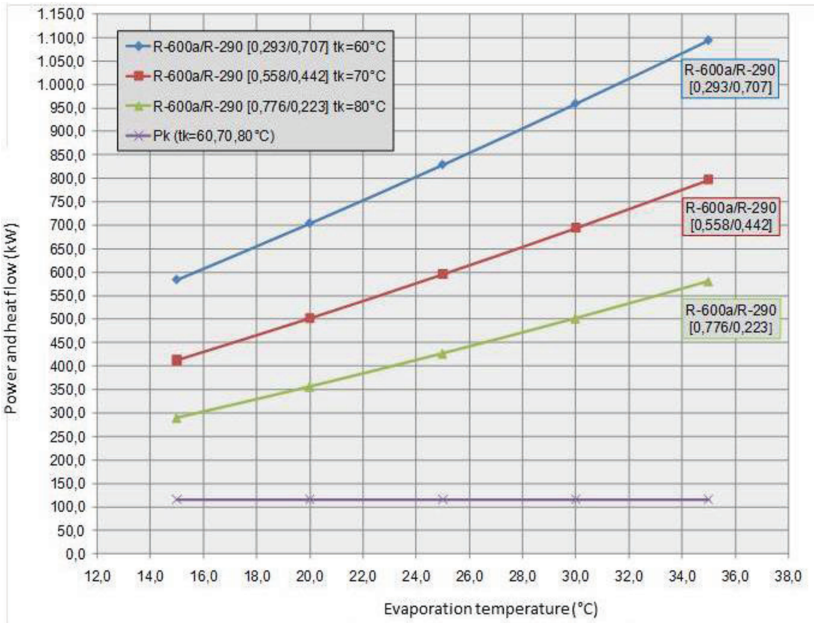

Figure 3. Single phase heating pump with the optimal proportion of R-600a and R-290 in the mixture.

If we compare the values of the heating flow and compressor energy consumption with R- 600a agent, we are reserved when we talk about the usage of the compressor power having in mind the above mentioned things.

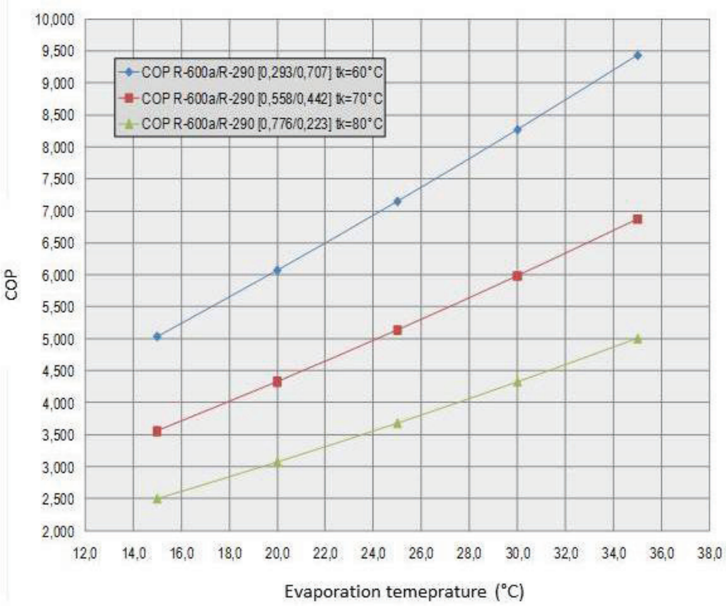

Figure 4. COP of the single phase heating pump with the optimal mixture proportion of R-600a and R-290

R-600a andR-290 mixture achieves the maximum, having in mind the maximum achieved by the compressor and the heating pump heating flow. There are some restrictions with some agents, and because of the thermo limitations the process is not possible to be taken out at all. Fig. 5 shows the dependence of the heating pump heating flow on the component share 1 (R -600a) in R-600a and R-290 agent mixture, at the constant temperature of steaming t_U = 20°C and at different condensation temperatures. The compressor power in each form is the same, P_K = 116,0 kW, the maximum pressure of condensation equals p_{mTk} = 1,7133 MPa.

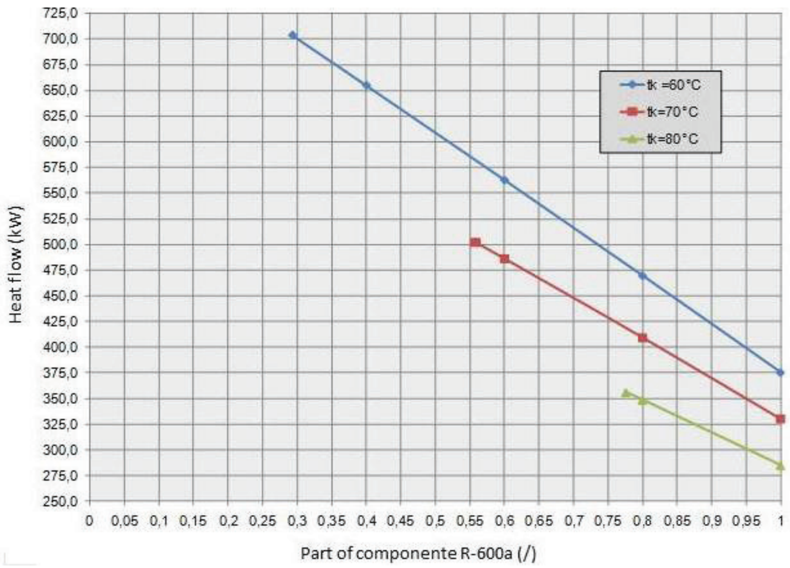

Figure 5. Heating flow of the cooking part of the heating pump depending on the share

The results of calculating heating flow depending on agent (R-600) share in two-agent mixture (R-600a/R-290) show that the share of (R-600a) increases if the temperature is getting higher. The simulation proves that functioning of the heating pump with R-290 is impossible because of the high pressures and great compressor power consumption, despite the great values of the heating flow. The optimal usage of the high temperature heating pump and the compressor is achieved when the mixture is R-600a/R-290 (0.558/0.442), at condensation temperature t_K = 70°C.

4 CONCLUSION

The way of choosing the most adequate refrigerating agent for adiabatic circular process functioning for various usages is presented in the text. The choice is based on reducing negative effects on the environment and on thermo dynamic characteristics [7]. Compressor characteristics also have to be considered. The article includes the detailed presentation of the optimal choice of the agents for heating pump functioning, which is used for central heating.

Simulation model for determining adequate agent R-600a and R-290 mixture for the most efficacious functioning of the pump is presented. With maximum heating flow and considering the determined limiting conditions, it is proven that the optimal mixture of the two agents at crystallization temperature t_K = 70°C equals R-600a/R-290 = 0,558/0,442. Process functioning conditions limit the way of using the mixture.

For heating households, three different pump types are suggested:

- Single phased high temperature heating pump
- Double phase high temperature heating pump
- Double phase high temperature heating pump with heat exchanger.

Each pump type has a programme written in MathCAD Professional, which enables calculating characteristic features of the heating pump and compressor. The calculating is done at different temperatures of steaming and condensation. The results are presented as graphics, which enables easier reading and choosing the adequate compressor.

The main aim of the simulation is determining the maximum heating flow and determining the usage of compressor. When doing this, we have to consider all the limitations that can appear when functioning. The simulation of determining of the optimal mixture is done by GAMS programme.

According to these data, using R-600a agent and MYCOM, type WBH compressor is recommended when using single phase heating pump. The heating pump functioning is reasonable at steaming temperature t_U = 25°C and condensation temperature t_K = 70°C. Heating flow of the single phase heating pump is, in such a case, 357,9 kW, and compressor energy consumption 82,0 kW.

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ANALIZA RAZLIČITIH RASHLADNIH MEDIJA U JEDNOFAZNOJ VISOKO TEMPERATURNOJ DIZALICI TOPLINE

Sažetak: *Ovaj rad predstavlja metodu izbora najprikladnijeg rashladnog medija za adijabatske kružne procese za razne upotrebe. Izbor medija je baziran na utjecaju na okoliš određenog medija, njegova termo-fizička svojstva, kao I prema karakteristikama korištenih kompresora. Predstavljen je simulacijski model za određivanje optimalnih udjela smjese R-600 I R-290 za jednofazne dizalice topline. Simulacija u svrhu određivanja optimalne smjese svih medija je napravljena pomoću GAMS programskog paketa.*

Ključne riječi: Prijenos topline, visoko temperaturna dizalica topline, rashladni mediji, simulacija

UČINKOVITO KORIŠTENJE ENERGIJE U PROMETU

EFFICIENT USE OF ENERGY IN TRANSPORT

NAČINI I MJERE ZA SMANJENJE KLIMATSKIH PROMJENA IZ PROMETA

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Sažetak: *Održiv razvoj u sebi obuhvaća i održiv promet koji podrazumijeva racionalnu upotrebu vozila svih vidova prometa. U zemljama EU, najveće povećanje emisija stakleničkih plinova u posljednjih 30-ak godina potječe od prometa. Od 1990.-2009. godine* CO_2 *povećale su se za 70%, pri čemu ukupni promet sudjeluje s 26%, a od toga na osobna vozila otpada 12%. Smanjenje emisija* CO_2 *iz cestovnog prometa pokušava se postići na razne načine: od propisivanja zakonskih odredbi, optimizacija pojedinih dijelova i sustava motora, uporabom alternativnih goriva kao i eko-vožnjom. Smatra se da je cestovni promet dio energetskog sektora u kojemu će biti najteže postići željene ciljeve, ali i područje u kojemu će svako djelovanje usmjereno k racionalnom korištenju obnovljivih izvora energije polučiti najveće rezultate u pogledu smanjenja* CO_2*. Osim cestovnog prometa, mora se uzeti u obzir i rast zračnog prometa. Kako su emisije* CO_2 *izravno proporcionalne utrošenom gorivu, te emisije će se također povećati za oko 57% do kraja 2015. godine. Utjecaj zračnog prometa na klimatske promjene primarno se očituje u izgaranju na visinama leta od 8-12km, sloj troposfere, tropopauze i donji slojevi stratosfere gdje su zrakoplovi jedini antropogeni zagađivači. Primjeri razvoja efikasnijih motora, optimizacija putanja leta, trgovanje dopuštenim kvotama štetnih plinova, ekotakse i sl. su samo neke od mjera uštede goriva u zračnom prometu. Željeznica troši 3% fosilne energije, a daljnje uštede su moguće smanjenjem mase vlaka, regenerativnim kočenjem i sl. čime se omogućuje povrat energije i do 30%. U radu se obrađuju mjere i načini smanjenja emisija stakleničkih plinova u sektoru prometa, gdje se ističu takva nastojanja razvojem održivog transporta, tehnološkim razvojem i primjenom* CO_2 *neutralnih goriva.*

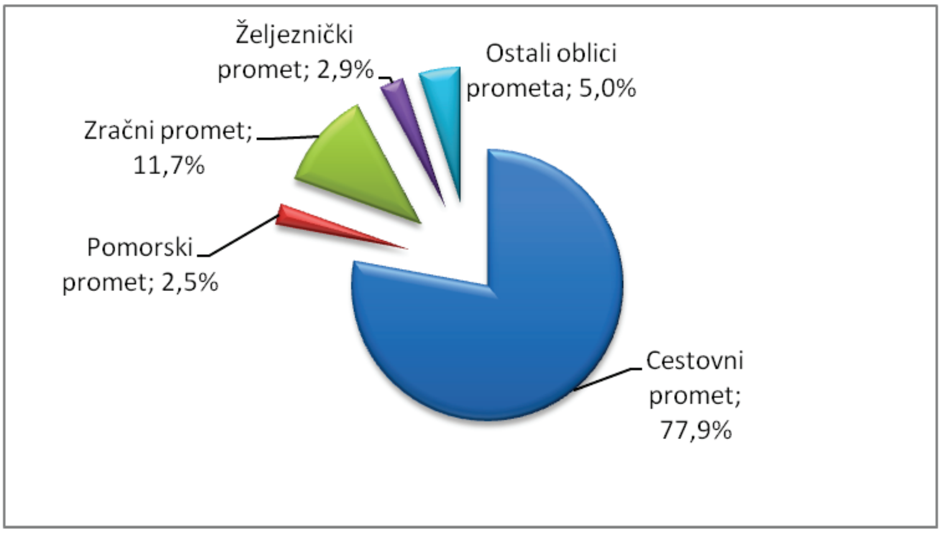
Ključne riječi: klimatske promjene, emisije CO_2 iz prometa, mjere za smanjenje emisija

1. UVOD

Promet, a osobito cestovni, je ekonomski ogranak koji doprinosi promjeni klime više od bilo kojeg drugog, čiji štetni utjecaji i dalje rastu, bez obzira što je mnogo učinjeno na problematici zaštite od onečišćenja zraka, vode i tla. Danas ne postoji niti jedan ekosustav na koji nije čovjek utjecao na bilo koji način, ili ga svojim djelatnostima izmijenio. Za očekivati je da će današnji sukob između tehnološkog razvitka i očuvanja okoliša biti pokretačka snaga koja će korigirati postojeće tehnologije i koja će uvesti nove tehnologije koje će manje zagađivati okoliš. Prema nekim autorima korištenje fosilne energije samo je kratka epizoda u povijesti čovječanstva koja dijeli „prvu solarnu civilizaciju do godine 1850." od druge moderne solarne civilizacije nakon godine 2050. Svjetsko gospodarstvo koje se temelji na solarnoj energiji postat će po nobelovcu H. Scheer-u (1999.) strategija ekološke moderne u 21. stoljeću. Samo uporabom obnovljivih energija i sirovina može se očuvati ekosfera, osigurati budućnost čovječanstva, poboljšati položaj zemalja u razvoju i spriječiti predvidljive ratne sukobe oko posljednjih ostataka fosilne energije. Različite vrste prometa imaju različite veličine djelovanja na okoliš – na globalnom, regionalnom i lokalnom planu. Od 1970. godine do 2009. godine emisija CO_2 je povećana za 70%, u čemu promet sudjeluje s 26%, a samo osobna vozila s oko 12%. Osim cestovnog prometa mora se uzeti u obzir porast zračnog prometa. Procjene su da će do 2050. godine avijacija pridonositi sa 66% svih CO_2 emisija u Europi. /2/ Iako cestovni i zračni promet svojim rastom predstavljaju opasnost za okoliš, svi oblici prometa moraju poboljšati svoje performanse u odnosu na okoliš. Smanjenje emisije štetnih plinova i ugljičnog dioksida pokušava se postići na razne načine kao npr. poboljšanjem radnog procesa motora i optimizacijom pojedinih dijelova i sustava motora, uporabom alternativnih goriva kao i ekonomskim i regulatornim mjerama. Smanjenje potrošnje energije i zagađenja zraka u sektoru prometa ne zasniva se na ideji niže proizvodnje nego na traženju novih, učinkovitijih načina uporabe fosilne energije i njenog postupnog nadomjeska drugim obnovljivim izvorima energije. Pitanje nije dostupnost te energije već tehnologije koja je može obraditi. U radu ćemo dati pregled najvažnijih mjera i načina smanjenja klimatskih promjena iz prometa kojima se utječe na održiv sustav uporabe energije koji je pak sastavni dio održivog razvoja.

2. MJERE ZA SMANJENJE STAKLENIČKIH PLINOVA IZ CESTOVNOG PROMETA

Najvažniji staklenički plinovi su vodena para (H_2O), ugljik (IV) oksid, (CO_2), metan (CH_4), dušik (II)oksid (N_2O), kluorofluorougljici (freoni – CHC itd), ozon u troposferi (O_3) itd. Smatra se da je u atmosferi ostalo oko 50% CO_2 koji je emitiran ljudskom djelatnošću. Od svih vidova prometa, cestovni promet je najveći potrošač energije (90%) i najveći proizvođač CO_2, stoga su mjere za racionalnijim korištenjem energije te uporaba obnovljivih izvora energije usmjerene upravo na promet cestovnih vozila. Na slici 1. vidi se porijeklo CO_2 emisija iz pojedinih prometnih grana, gdje najveći udio otpada na cestovni promet – 77.9%.[12] Budući da je ukupni promet odgovoran za više od 26% emisija CO_2 (samo osobna vozila više od 12%) i budući da se smatra da je promet dio energetskog sektora u kojem će biti najteže postići željene ciljeve, počele su se poduzimati hitne mjere regulatorne, ekonomske i tehnološke naravi u cilju minimiziranja štetnog utjecaja cestovnog prometa na okoliš. Ako je riječ samo o smanjenju CO_2 iz cestovnog prometa, postoje tri glavne opcije za državne vlade: oporezivanje goriva i vozila, inicijativa za promociju najboljih dostupnih tehnologija, primjena alternativnih goriva.

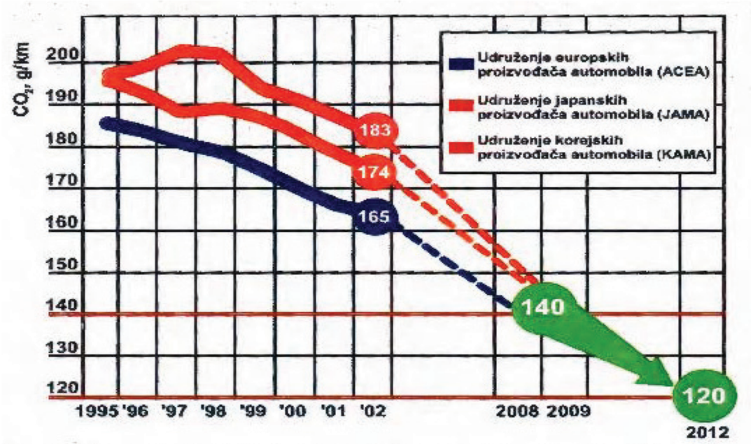


Slika 1. Porijeklo CO_2 emisija iz pojedinih prometnih grana [12]

2.1. Zakonodavne (regulatorne) mjere

Razvoj brige za okoliš u 80-tim doveo je do intenzivnijih aktivnosti vezanih za emisijske standarde u EU. Do 1992. godine fokus je bio usmjeren na poboljšanje tehnoloških karakteristika vozila, čime bi se došlo do smanjenja emisija, međutim Auto/Oil programom (inicijativa koju čine Europska komisija, automobilska industrija i naftna industrija) ispitivale su se i druge opcije kao što su: kvaliteta goriva, kontrola hlapivih tvari, programi nadgledanja i održavanja, porezna politika te korištenje javnog gradskog prijevoza. Prema podacima Europske agencije za okoliš EEA (European Environment Agency) udio emisija EU 2003. godine iznosio je 14% ukupne globalne emisije stakleničkih plinova, a u državama EU-15 je 2005. godine 19% ukupne emisije stakleničkih plinova dolazilo od prometa. Europska komisija je predstavila 14. ožujka 2007. godine novu sveobuhvatnu strategiju smanjenja CO_2 novih automobilskih i teretnih vozila koji se prodaju u EU. Cilj je do 2012. godine ostvariti redukciju CO_2 od 25% u odnosu na razinu iz 2007. godine tj. svesti emisiju na 120g/km. Cijeli projekt počiva na namjeri da predložene mjere budu od koristi za sve zainteresirane strane. Naime, efikasnije korištenje goriva će dovesti do značajnih ušteda kod vozača, a otvara se perspektiva automobilskoj industriji EU-e da svoju konkurentnost u svjetskim razmjerima temelji upravo na razvijanju tehnologija efikasnije upotrebe energije umjesto da svoj razvoj temelji na staroj paradigmi veličine i snage automobila. Smatra se da bi ovakav pristup otvorio prostor inovacijama i jeftinijim vozilima, uštedi energije i reduciranju CO_2 emisija na način približavanju standardima Kyota. Zabrinjava podatak da je između 1990. i 2004. EU smanjila emisiju stakleničkih plinova za skoro 5%, ali se u istom razdoblju emisija CO_2 kao posljedica cestovnog prometa povećala za 26%. Zato prijedlog Europske komisije još iz 1995. godine se temelji na jačanju već postojeće strategije kroz tri stupa (slika 2.). [11] Prvi je dragovoljna obveza japanskih, europskih u južno korejskih automobilskih industrija o smanjenju CO_2 na 140g/km na tržištu EU-a do 2008. godine za europske proizvođače ili 2009. za azijske. Drugi stup se sastoji od porasta svijesti među potrošačima tako da se na svakom novom automobilu stavi oznaka potrošnje goriva i CO_2. Treći stup nastoji promicati novu vrst automobila kroz fiskalne mjere – prijedlog komisije je da se zakonski uredi uključenje elementa CO_2 u nacionalne poreze na aute. Budući da u razdoblju od 1995.-2004. godine došlo je do nedovoljnog smanjenja emisija CO_2 sa 186g/km na 163g/km, donosi se novi paket mjera. Namjera je novim automobilima smanjiti stupanj emisije na željenu razinu od 120g/km, a teretnim vozilima dugoročno na 160g/km do 2015. godine. Kanada, SAD, Japan, Koreja, Kina i Australija imaju zakonske ili dobrovoljne pristupe ovom pitanju, a sa europskim standardom se može mjeriti samo Japan. Ohrabruju primjeri Kalifornije i drugih država koje su donijele mjere za smanjenje emisije stakleničkih plinova za 30% do 2016. godine na području cestovnog prometa. Proizvođači automobila će do 2015. godine morati smanjiti prosječne emisije CO_2 na maksimalno 130g/km plus dodatnih 10g/km korištenjem biogoriva. 65% novih automobila će morati zadovoljavati postavljeni kriterij do 2012. godine, 75% do 2013. godine, 80% do 2014. godine i 100% do 2015. godine. Svako registrirano vozilo koje emitira manje od 50g/km CO_2, dobit će koeficijente koji će biti tretirani kao višestruki broj vozila u proračunu prosjeka. Tako će u 2012. i 2013. godini ovakva vozila dobiti koeficijent 3,5 u 2014. godini koeficijent 2,5, a nakon toga koeficijent se ispušta. Isto tako, za svako prekoračenje do 1g/km uslijedit će sankcije (penali) od 5 eura, do 2g/km od 15 eura, a sve preko 3g/km čak i do 95 eura. Čak i da EU ostvari svoj cilj do 2012. godine, to će biti tek jedan manji dio nastojanja koji se imao poduzeti prema sporazumu iz Kyota.

Naime, njime do 2012. godine treba doći do smanjenja emisija stakleničkih plinova za 8%, uodnosu na početnu (referentnu) godinu, 1990. Vijeće za okoliš EU podržava cilj kojim se porast globalne temperature ograničava na maksimalno 2°C u odnosu na 1990. godinu, a jedanaest zemalja članica EU propisuje već pristojbe za osobna vozila koja su ili djelomično ili potpuno vezana za CO_2 emisiju ili potrošnju goriva. Osim zakonodavnih mjera, ekološki i gospodarski razlozi su temeljni zbog kojih komisija za biogoriva EU u posljednje vrijeme radi na razvoju novih tehnologija i unapređenju postojećih pri proizvodnji biogoriva i njihove upotrebe u prometu



Slika 2. Ciljevi automobilske industrije u smanjenju emisije CO_2 [11]

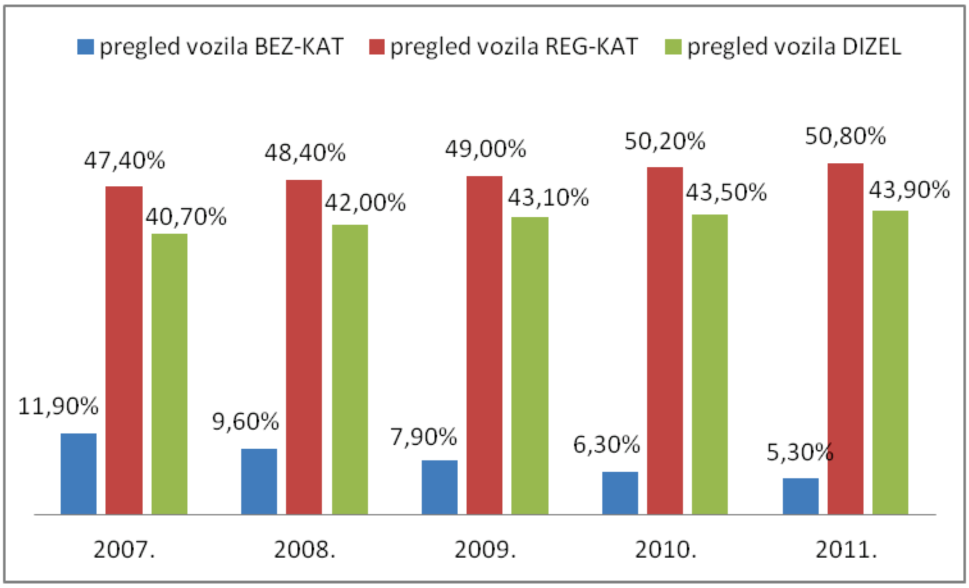
2.2. Primjena alternativnih goriva

U alternativna goriva koja se danas nalaze u primjeni za pogon motora s unutarnjim izgaranjem spadaju: alkoholna goriva (metanol i etanol), ukapljeni naftni plin (LPG), prirodni plin, biogoriva i vodik. Sva navedena alternativna goriva, zbog jednostavnije kemijske strukture u odnosu na benzinsko ili dizelsko gorivo imaju potencijal za smanjenje emisije štetnih ispušnih plinova. Zbog manjeg sadržaja atoma ugljika, alternativna goriva pri izgaranju proizvode manju količinu CO_2, a u slučaju uporabe vodika emisija CO_2 potječe isključivo od izgaranja ulja za podmazivanje. Za cestovni prijevozni sektor vrlo važnu i prije svega obvezujuću smjernicu Europskog parlamenta predstavlja smjernica o unapređenju i uporabi biogoriva ili drugih obnovljivih goriva za prijevozni sektor iz 2003. godine. U okviru ove smjernice upućuju se sve članice EU da odgovarajućim mjerama osiguraju zamjenu benzina i dizelskog goriva do kraja 2005. godine s 2%, odnosno do kraja 2010. godine 5,75% goriva iz obnovljivih izvora, mjereno po njihovom energetskom sadržaju. Provođenjem ove smjernice EU očekuje, pored djelomičnog smanjivanja ovisnosti o uvozu skupih fosilnih goriva, smanjenje emisije CO_2 kao stakleničkog plina. Iako je područje biogoriva posljednjih 15-ak godina vrlo dinamično, može se konstatirati da se za svaku vrst motora iskristaliziralo po jedan glavni predstavnik: biodizel za Dizelove motore i bioetanol za Ottove motore. Glavna njihova prednost je što pridonose rješavanju triju problema kao: rješavanje viška poljoprivredne proizvodnje u razvijenim zemljama, smanjenje onečišćenja okoliša i obnovljivost izvora.

Prednost biodizela u odnosu na mineralno (standardno) dizelsko gorivo s ekološkog aspekta prije svega proizlazi iz povoljnije bilance ugljičnog dioksida. Osnova za proizvodnju biodizela je plod biljke, a poznato je da biljke za svoj rast troše određenu količinu CO_2. Pri uzgoju biljaka upotrebljavaju se razni poljoprivredni strojevi koji svojim radom proizvode CO_2, a također pri procesu proizvodnje i izgaranja biodizela nastaje CO_2. Slično je pri izgaranju i proizvodnji i sa dizelskim gorivom jer i tu nastaje CO_2. Međutim, razlika jest u tome što se za daljnji uzgoj repice iz atmosfere preuzima dio CO_2 nastalog izgaranjem biodizela, dok se kod standardnog dizelskog goriva nastali ugljični dioksid samo akumulira u atmosferi. Uzgojem repice, proizvodnjom goriva, njegovim izgaranjem te ponovnim uzgojem stvara se djelomično zatvoren i ekološki povoljan lanac nastajanja i potrošnje CO_2. Potencijali smanjenja emisija CO_2 biogorivima u odnosu na klasična fosilna goriva su: za prvu generaciju do 60% (biodizel, bioetanol), za drugu generaciju do 90% (otpaci biljnog i životinjskog porijekla). [12] Zbog povećanja mobilnosti (unatoč povećanju učinkovitosti novih vozila), konstantno se bilježi porast broja cestovnih vozila, pa stoga i porast emisija CO_2 iz cestovnog prometa. Iako emisija CO_2 od željeznice vrlo malo utječe na ukupnu emisiju CO2 u sektoru prometa, a to nije spriječilo i ne treba sprečavati istraživanja o primjeni biogoriva u tračničkim vozilima. Bez smanjenja trošarina na biogorivo i stimuliranju proizvodnje iz biomase. neće se moći potaknuti upotreba biogoriva.

2.3. Tehnološke mjere

Kontinuiranim poboljšanjem procesa izgaranja u cilindru motora, sustavima direktnog ubrizgavanja goriva, poboljšanjem postojećih ili razvojem novih sustava za pročišćavanje ispušnih plinova te optimiranjem upravljanja radom motora i vozila u cjelini postižu se znatna smanjenja potrošnje energije i štetnih tvari. Kvaliteta goriva također je jedan od bitnih čimbenika potrebnih za zadovoljavanje strogih zahtjeva. Digitalno upravljanje motorom – MOTRONIC, elektronički sklop sa setom čipova i procesorom koji kontrolira sve uređaje bitne za rad motora osigurava malu potrošnju goriva i smanjenu emisiju CO_2 i do 15%. Tu je i „START-STOP" sustav koji preko inteligentnog elektronskog sustava isključuje motor kada vozilo miruje, čime se učinkovito doprinosi smanjenju potrošnje goriva i emisije CO_2. Smanjenju utjecaja stakleničkih plinova iz cestovnog prometa također može doprinijeti EKO-test i EKO vožnja. Održavanje vozila u ispravnom stanju, pravovremeno otklanjanje svih neispravnosti na njemu uz redovito servisiranje vozila, predstavlja učinkovit način za održavanje emisija štetnih i neštetnih plinova na niskoj razini, a to pokazuju rezultati EKO-testa i u RH. Na slici 3. dat je udio pojedinih vrsta vozila u ukupnom broju vozila podvrgnutih EKO-testu od 2007.-2011. u RH, gdje se vidi linearno povećanje broja REG-KAT u odnosu na smanjenje broja vozila BEZ-KAT.[6] Eko – vožnja je najpogodniji način vožnje za motore modernih tehnologija (npr. prebacivanje u viši stupanj prijenosa u području od 2000-2500 okretaja u minuti, češće provjeravati tlak u gumama , smanjiti nepotreban teret u vozilu, ne uključivati nepotrebno rashladne uređaje, ne ostavljati vozilo da radi u neutralnom hodu), čime se postižu uštede u potrošnji goriva i do 30%. Osim već spomenutih alternativnih goriva, prvenstveno biogoriva, inženjeri iz razvojnih centara koriste sva znanja koja su im na raspolaganju prije svega za poboljšanje radnog procesa motora, za optimizaciju pojedinih dijelova i sustava motora čime je moguće postizati smanjenje emisija stakleničkih plinova.



Slika 3. Udio pojedinih vrsta vozila, s obzirom na vrstu motora i način ispuha, u ukupnom broju vozila podvrgnutih EKO testu, u periodu 2007-2011. godine [6]

3. MJERE ZA SMANJENJE STAKLENIČKIH PLINOVA IZ ZRAČNOG PROMETA

Zrakoplovi emitiraju plinove i čestice izravno u gornji dio troposfere i donji dio stratosfere, što se očituje u sjevernim, umjerenim geografskim širinama, gdje zrakoplovi utječu na sastav atmosfere. Letovi zrakoplova godišnje proizvode 628 miliona tona CO_2. [2] Trenutni utjecaj zračenja ugljičnog dioksida proizvedenog izgaranjem u motoru zrakoplova tijekom leta manji je od učinka kondenzacijskih tragova, ali CO_2 ostaje u atmosferi znatno duže (10 do 300 godina.) čime se na vremenskoj skali utjecaj zračenja produljuje. Iako zračni promet ima mali udio u ukupnoj emisiji stakleničkih plinova u atmosferu (oko3%), izrazito se brzo razvija i raste za 5% godišnje. Kako su emisije CO_2 izrazito proporcionalne utrošenom gorivu (3,15 tone CO_2 po toni utrošenog goriva), te emisije će se također povećati za 57 posto do kraja 2015. godine. [7]
Mnogo je opcija za smanjenje zrakoplovnih emisija, uključujući promjene u tehnologiji zrakoplova i motora, gorivu, operativnim praksama, regulatornim i ekonomskim mjerama.

3.1. Zakonodavne i ekonomske mjere

Dok su neke države već nametnule poreze na gorivo za domaće zračne usluge i nekoliko zračnih luka u Europi koristi pristojbe u vezi s NO_x, ICAO[1] je proučavao opseg tržišnih mjera, uključujući poreze, pristojbe i trgovanje emisijama, kako bi ispitao potencijal za dodatne redukcije emisija CO_2. Postoji velik broj ugovora koji otežavaju primjenu politike zračnog prometa no zadnjih godina dogodila su se dva važna događaja: uvođenje jedinstvenog europskog zrakoplovnog tržišta i Direktiva o energetskim proizvodima (2003/96 EC). Razvitak SES-a (Single European Sky) ili „jedinstvenog europskog neba“ ključan je element rješavanju sadašnjih i budućih izazova europske zrakoplovne zajednice – prognoza povećanog rasta zračnog prometa i održavanje jednake razine sigurnosti i zaštite okoliša. Time članice EU dobivaju veću mogućnost kontrole europske aviopolitike, a samim tim da poduzmu

[1] ICAO – International Civil Aviation Organization – Međunarodna organizacija civilnog zrakoplovstva

konkretne korake u vezi s klimatskim promjenama. Želi se postići cilj – a to je ne dozvoliti povećanje temperature veće od 2°C a to će dugoročno zahtijevati smanjenje CO_2 emisija za minimalno 70% (neke zemlje kao Švedska, Velika Britanija, Francuska su na putu smanjenja CO_2 za 60% do 2050.) Daljnji zahvat u vezi smanjenja CO_2 je „trgovanje emisijama ispušnih plinova" (Emissions Trading System) koji je kao europski odgovor na sporazum iz Kyota obvezao sve zemlje svijeta na globalnu zaštitu. Još značajniji korak je oporezivanje goriva na smanjenje emisija. Prema prvoj opciji oporezivanja (sve rute od EU uključujući i unutarnje) rezultiralo bi se najviše smanjenjem CO_2 – 9,6% po pitanju EU operativcima i 2% pitanju ukupnih operativaca, a to bi značilo godišnje manje 14,7 miliona tona CO_2 [10]. Oporezivanje goriva samo po sebi, nije jednostavan potez, niti politički, ni zakonski ni administrativno a i nepopularna je mjera unutar zračne industrije. Analiza preuzeta unutar CAEP-a[2] između 2001. i 2004. podvukla je skup istaknutih dvojbi, zakonskih i praktičnih problema a glede upotrebe naknada za CO_2 emisije za zračni promet. ICAO je predviđao da bi prihodi od naknada za CO_2 mogli biti korišteni samo za financiranje mjera koje specifično umanjuju bilo koju štetu vezano za klimatske promjene uzrokovane zrakoplovstvom. Od inicijalnih mjera za smanjenje emisija stakleničkih plinova od strane kompanija, zračnih luka, proizvođača i pružatelja usluge kontrole leta izdvajaju se tri prioritetna cilja:

- unapređenje učinkovite potrošnje goriva, prosječno 1,5% godišnje do 2020. godine
- zadržati emisiju nakon 2020. godine s nultim rastom ugljika
- do 2050. smanjiti emisiju na pola u usporedbi s 2005. godinom.

Zadnjih godina IATA[3] provodi tzv. FEGA (Fuel Efficiency Gap Analysis) posjete aviokompanijama gdje daje analizu postupaka i mjesta gdje je moguće ostvariti uštede. Pokazalo se da svaka kompanija mora razviti svoj podsustav i prilagoditi mjere sebi svojim operacijama. Primjerice, nije preporučljivo uvijek raditi tankiranje goriva za oba smjera, ali to se mora ponekad učiniti zbog nedostatka goriva na odredištu ili zbog iznimno loše kvalitete goriva na odredištu. Kod ne-tehnoloških mjera najveći problem je podizanje svijesti da gorivo nije isključivo potrošna roba u procesu, te je potrebno uspostaviti sustav mjerenja rezultata potrošnje po zrakoplovu i po letu tj. po elementima koji su kompaniji od interesa.

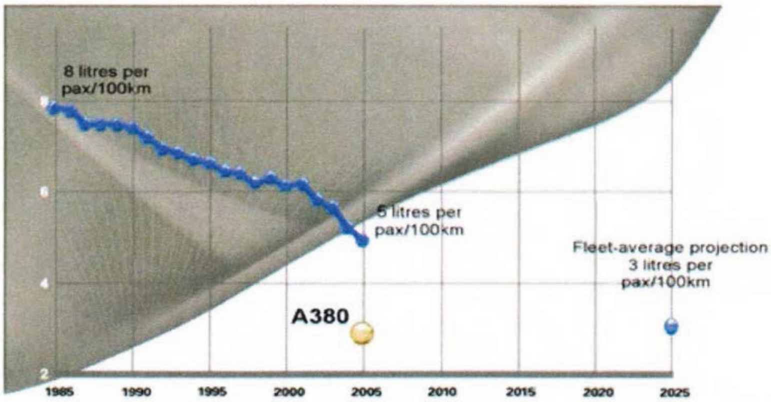
3.2. Tehnološke mjere

Način uštede goriva u operacijama zrakoplova moguć je na dva načina: efikasnijim motorima i optimizacijom putanja leta. Primjer razvoja efikasnijih motora predstavlja Evropski istraživački projekt – Clean Sky JTI (eng. Joint Technology Intiative) koji zajednički financiraju Europska komisija i zrakoplovna industrija (54 tvrtke)s primarnim ciljem uvođenja radikalno novih tehnologija koje se odnose na ekološki prihvatljiviji sustav zračnog prometa. Projekt Clean Sky nudi ubrzani razvojni proces koji predstavlja priliku za korištenje naprednih tehnologija u kratkom vremenu a ciljevi bi bili do 2020. godine i smanjenje emisije CO_2 po putničkom km za 50% na način da se smanji potrošnja goriva (20-25% od ukupnog smanjenja emisija odnosi se na poboljšanja na zrakoplovu, 15-20% na smanjenu specifičnu potrošnju motora i 5-10% na operativna poboljšanja u eksploataciji zrakoplova i zračnog prostora). Optimizacija putanja leta zrakoplova zahtjeva znatna ulaganja u sustav upravljanja zračnim prometom (eng. Air Traffic Management – ATM), a koja se trenutno provode u sklopu projekta SESAR (Single European Sky ATM Research project) i sukladno Europskoj komisiji tim načinom, moguće je smanjiti potrošnju goriva od 6-12%. Analize pokazuju da modreni zrakoplovi sa istom količinom goriva prelete i do tri puta veću udaljenost nego

[2] Committe on Aviation Environmental Protection – Odbor za zaštitu okoliša u zračnom prometu

[3] IATA – International Air Transport Association (Međunarodno udruženje zračnih prijevoznika). Osnovano 1945. godine i okuplja nacionalne zrakoplovne kompanije

zrakoplovi od prije 40 godina, što je 75% poboljšanje efikasnosti po ptkm. Slika 4 pokazuje svjetsku potrošnju goriva u zračnom prometu, gdje se vidi poboljšanje u efikasnosti potrošnje goriva za 20%. [10]



Slika 4. Svjetska potrošnja goriva u zračnom prometu (litra po putniku na 100km) [10]

Ukupno smanjenje od 50% emisije CO_2 potrebno je ostvariti kroz, poboljšanu konstrukciju, motore i procedure letenja. Budući da je emisija CO_2 direktno vezana s potrošnjom goriva, najveća ušteda postiže se kroz kvalitetna aerodinamična rješenja, smanjenu masu i učinkovitije motore i sustave aviona. Smanjivanjem težine konstrukcije uvelike se štedi gorivo. Jedan od načina je korištenje tehnologije lijepljenja kao i spajanja dijelova zrakoplova čime se smanjuje težina i za nekoliko stotina kg. Smanjivanje težine postiže se korištenjem novih metalnih legura na bazi aluminija i litija, te korištenjem kompozitnih materijala kao npr. staklena vlakna, ugljična vlakna, keramika. Motori zrakoplova unatoč svom velikom tehnološkom napretku u sagorijevanju goriva i ukupnoj učinkovitosti i dalje predstavljaju najveći izazov u tehnologiji. Za postizanje značajnije redukcije emisije CO_2 potrebno je još više povećati bypas ratio (omjer volumena usisanog zraka i zraka koji prolazi kroz jezgru motora) kod turbofan motora. Nove tehnologije motora kao što su otvoreni rotor (open rotor, poznat i kao propfan) omogućuju značajno smanjenje emisije CO_2 i buke. IATA filozofija uštede goriva i smanjenja emisija stakleničkih plinova ističe od pravila „četiri stupa", kao prvi stup tehnologiju – uporabom inovacija, izmjenama flote, motora i razvojem biogoriva predviđa se smanjenje CO_2 emisija do 21%. Postotno gledajući, očekuje se da će inovacijama u korištenju lakših materijala u izradbi zrakoplova, te re-enginingom postići učinak smanjenja emisija od 7-18%, dok novim dizajnom zrakoplova (prije 2020. godine) te turbofan motorima s višestupanjskom transmisijom i motorima s otvorenim rotorom, laminarnijom konstrukcijom krila učinak bi bio i do 35%.[11].

4. MJERE ZA SMANJENJE STAKLENIČKIH PLINOVA IZ ŽELJEZNIČKOG PROMETA

Željeznica ima značajnu ulogu u energetskoj efikasnosti pri prijevozu robe i putnika te zaštitite okoliša u odnosu na druge oblike prijevoza. To proizlazi iz tehničkih i tehnoloških specifičnosti prijevoza željeznicom te činjenice da se u Europi oko 80% prijevoza prometa na željeznici odvija električnom vučom. U preostalom dijelu dizelske vuče mora se dodatno smanjiti specifična potrošnja goriva i emisija štetnih tvari što se naročito naglašava uvođenjem novih propisa. Poznati proizvođač tračničkih vozila Bombardier Transportation nastoji dati doprinos očuvanju okoliša i uštedi energije što pokazuje i kroz program ECO4 (Eco4= Energy, Efficency, Economy, Ecology). Program podrazumijeva optimiranje korištenja energije, smanjenje potrošnje energije, smanjenje emisije CO_2 na najmanju mjeru,

višu ekonomičnost i ukupno povećanje performansi. Za motorne vagone operateri postavljaju vrlo visoke zahtjeve. Pored ekonomičnog pogona traži se velika raspoloživost te niski troškovi održavanja te niska nabavna cijena, a kako je sve više naglasak i na zaštiti okoliša, to predstavlja posebni izazov za proizvođače. Primjena biogoriva za pogon transportnih sredstava započela je u motorima osobnih vozila, potom je nastavljena u autobusima i kamionima da bi krajem prošlog i početkom ovog stoljeća nastavljena bila i na željeznici kako za putničke tako i za teretne vlakove.
Od 1990. do 2005. europske željezničke uprave (zbirno gledano) smanjile su emisiju CO_2 prosječno za 21% odnosno 14% po putničkom km i 28% po tonskom km [5]. Smanjenje emisije CO_2 posljedica je konstrukcije dizelskih lokomotiva i vlakova s učinkovitim prijenosom energije i elektrificiranim prugama. U pogledu uporabe biodizela na europskim željeznicama, očekuje se potrošnja biodizela veća od 5% [8] zbog niže energetske vrijednosti litre toga goriva u usporedbi s dizelom. Centar za razvoj transporta u Kanadi pokrenuo je projekt kojim bi vrednovao mogućnosti biodizela ili udjela biodizela u mješavini s dizelom kao zamjensko gorivo za dizelski motor na lokomotivama koje se koriste na kanadskim željeznicama. Primarno što se želi postići je daljnje smanjenje emisije stakleničkih plinova na godišnjoj razini te da se pripreme za moguću primjenu biodizela u svom sektoru kao djela gospodarstva Kanade. Također, željezničkim prugama u Indiji već prometuju vlakovi koji za pogon koriste mješavine biogoriva B5 i B10, a plan je nastaviti istraživanje na svim mješavinama do B20 (tj. 20% biodizel, a 80% naftni dizel), te za svaku željezničku zonu odrediti tip mješavine, postavljanje pokusnih pogona za proizvodnju biodizela od različitih sirovina (uljarice, otpadna biljna ulja, životinjske masti) te daljnji razvoj industrije za proizvodnju biodizela. Koja je mješavina prikladna za koji tip motora u voznom parku nacionalnih željeznica, trebala bi odrediti sama željeznička uprava temeljem vlastitih istraživanja, istraživanja uz pomoć lokalnih znanstvenoistraživačkih institucija ili korištenjem pozitivnih iskustava za pojedine tipove dizelskih motora u lokomotivama, pri čemu se ne smiju zaboraviti klimatske karakteristike područja kojim vlak prometuje. Željeznica bi korištenjem biogoriva mogla održat status „eko-povoljnog" vida transporta.

5. ZAKLJUČAK

U gospodarskom sektoru najveći proizvođač ugljičnog dioksida je promet, a unutar njega je cestovni promet (oko80%). Porast emisije stakleničkih plinova najteže je suzbiti u prometu budući da implementacija mjera sporo djeluje, a one se pored ekonomskih i zakonodavnih, najviše odnose na napredak u tehničkim značajkama vozila. Kako zadatak smanjenja emisije i štetnih tvari i stakleničkih plinova nije nimalo jednostavan, inženjeri iz razvojnih centara raznih proizvođača motora koriste sva „oružja" koga su im na raspolaganju. Pri tome se prioritetno pokušava poboljšati radni proces motora optimalizacijom dijelova i sustava motora, a drugi pristup problemu je uporaba alternativnih goriva, koja bi s današnjim ili novo razvijenim motorima trebala davati bolje rezultate u vezi emisija ugljičnog dioksida i štetnih plinova. Zbog ograničenja fosilnih goriva, jedan od scenarija energetske budućnosti, uz Sunčevu energiju, je da će glavni nosilac energije biti biološki obnovljiva goriva. Biodizel za dizel motore i bioetanol za ottove, su se nametnuli jer pridonose istodobno rješavanju triju problema a to su: rješavanje viška poljoprivredne proizvodnje u razvijenim zemljama, smanjenju onečišćenja i obnovljivosti izvora. Zrakoplovstvu će najveći izazov biti udovoljavanje zahtjevu rastu zračnog i uspješno rukovođenje nad ekološkim zahtjevima. Rezultati koji su do sada postignuti uvođenjem restriktivnih i ekonomskih mjera, ali poglavito, uvođenjem novih tehnologija – primjenom novih lakših materijala izradbe novih generacija zrakoplova, korištenjem alternativnih goriva, novim dizajnom i turbofan motorima s višestupanjskom transmisijom dobar su pokazatelj da zrakoplovstvo ide ka održivom razvoju. Održiv sustav uporabe energije obuhvaća i održivi promet koji podrazumijeva racionalnu upotrebu vozila svih vidova prometa, pa tako i racionalnu upotrebu vozila kopnenog prijevoza – cestom i željeznicom. Niska razina emisije CO_2 (u usporedbi s emisijom od cestovnih vozila) nije spriječila istraživanja o primjeni biogoriva u motorima tračničkih vozila u EU i svijetu, pa bi trebala i u Hrvatskoj. Ako tome dodamo podatak da željeznički promet troši oko 3% energije i da su moguće dalje uštede kroz smanjenje mase vlaka, regenerativnim kočenjem čime se omogućuje povrat energije i do 30%, onda to govori u prilog željeznice kao ekološki najefikasnijeg prometnih sredstava. Tehnološkim razvojem i inovacijama, primjenom CO_2 neutralnih goriva, regulatornim, operativnim i ekonomskim mjerama promet može biti održiv. Projekti i tehnologije za pravilno korištenje prirodnih resursa postoje, tako da pitanje nije dostupnost te energije već tehnologije koja je može obraditi također i u prometu.

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METHODS AND MEASURES TO REDUCE CLIMATE CHANGES DUE TO TRAFFIC

***Abstract**: Sustainable development includes also the sustainable transport which understands rational use of vehicles of all transport modes. In the EU countries the biggest increase in the emission of greenhouse gases in the last thirty years has been generated by traffic. From 1990 to 2009 the emissions of CO_2 increased by 70%, with the total transport accounting for 26%, and out of this 12% was accounted for by personal cars. There are various ways of attempting to reduce CO_2 emissions generated by road traffic: from stipulating legal provisions, optimizations of certain parts and systems of the engine, using alternative fuels as well as with eco-driving. Road traffic is considered as part of the energy sector in which the desired goals will be most difficult to achieve, but also an area in which every action directed to rational usage of renewable sources of energy will yield the highest results regarding the reduction of CO_2. Apart from road traffic, one has to take into consideration the growth of air traffic as well. Since CO_2 emissions are directly proportional to the consumed fuel, these emissions will also have increased by about 57% by the end of 2015. The impact of air traffic on the climate changes is primarily shown in the combustion at the flying altitudes of 8-12km, in the layer of troposphere, tropopause and the lower layers of stratosphere where the aircraft are the only anthropogenic polluters. The examples of the development of more efficient engines, optimization of the flying route, trading with permitted quotas of harmful gases, eco-taxes, etc. are only some of the measures for saving fuel in air traffic. The railways consume 3% of energy, and further savings are possible by reducing the train mass, regenerative braking, etc., thus enabling energy return of even up to 30%. The paper analyses the measures and methods of reducing greenhouse gases emissions in the transport and traffic sector, where attempts are highlighted, such as sustainable transport development, technological development and implementation of CO_2 neutral fuels.*

Key words: climate changes, CO_2 emissions from traffic, measures for emission reduction

COUPLED OPTIMIZATION OF ENERGY CONSUMPTION AND EXHAUST EMISSIONS OF HYBRID POWER TRAINS – APPLICATION OF MECHANISTIC SYSTEM LEVEL SIMULATIONS

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Abstract: *The paper presents a mechanistic system level simulation model for modeling hybrid and conventional vehicle topologies. The paper addresses the dynamic interaction between different domains: internal combustion engine, exhaust aftertreatment devices, electric components, mechanical drive train, cooling circuit system and corresponding control units. To achieve a good ratio between accuracy, predictability and computational speed of the model it is necessary to adequately develop the model by considering the characteristic time scales of the domains and the nature of their interaction. The applicability and versatility of the mechanistic system level simulations model is presented through analyses of transient phenomena caused by the high interdependency of the domains. Results reveal that reduction in fuel consumption and emissions of the* CO_2 *might adversely influence the NOx emissions, which call for adaptations in the exhaust gas aftertreatment devices. Coupled interaction of the domains reasons the application of system level simulation tools in the early development stages, since cross influences of different domains have to be considered in initial development stages to fulfill large variety of objectives.*

Key words: Hybrid-electric powertrain, simulation, transient operation

1. INTRODUCTION

Global concerns on sustainable energy use and environmental protection call for innovative power train technologies. Among the alternative power trains being investigated, the HEVs consisting of an internal combustion engine (ICE) and an electric machine (EM) are considered as a viable short to mid-term solution due to the use of a smaller battery pack and due to their similarities with the conventional vehicles. HEVs incorporate multiple energy sources and multiple energy converters featuring many available patterns of combining the power flows to meet given load requirements.

For such complex systems, the application of system simulations is indispensable during the early development phase. It allows a cost and time efficient identification of the most promising solutions and therefore it helps reducing the amount of expensive experimental validation on test benches. To efficiently support the development during early concept and design phases it is required that simulation models feature a high level of predictability and high computational speed. Especially the predictability strongly influences the potential of system simulations to support the development of power trains in very early development stages where measurements are not yet (fully) available. The application of predictive approaches also significantly reduces the time needed to set up the models, since potentially only a limited number of physically based parameters needs to be adjusted reducing the workload compared to the effort required to populate map based models and to train surrogate models. Moreover, physically based models also ensure adequacy of results when optimizing power trains, since a mechanistic modeling basis enables adequate response to changed parameters of individual components and adequate interaction between the components on the system level.

Recently, many commercial and non-commercial system level simulation models and modeling approaches for modeling hybrid and plug-in hybrid vehicles have been presented, e.g. [1-6]. The models in the cited studies differ in the level of details of components models and also in the overall model structure, however a common approach of all cited studies is that they do not rely on mechanistic engine models. Such models might have significant limitations when applied to transient conditions that are far from steady-state [1,2]. This influences their accuracy during the transient drive cycles and their predictability if modifying control strategies and particularly if scaling the components.

To expose applicability of the mechanistic models for modelling complex interaction between driveline components, electrical components, internal combustion engine, exhaust aftertreatment devices, cooling circuit components and controls the paper presents the analysis of the performance and emission of a hybrid electric and conventional vehicle. Mechanistic system level approach requires a careful selection of the physical depth of the models used to describe phenomena in particular domains with the aim to harmonize their accuracies, which enables optimizing the performance of the overall model. Moreover, the characteristic time scales of the addressed domains differ significantly, which typically results in a stiff system of equations, e.g. [7]. Therefore the performance of the model is further enhanced if the applied solver is capable of considering different time scales of sub-systems, i.e. domains, within the overall system.

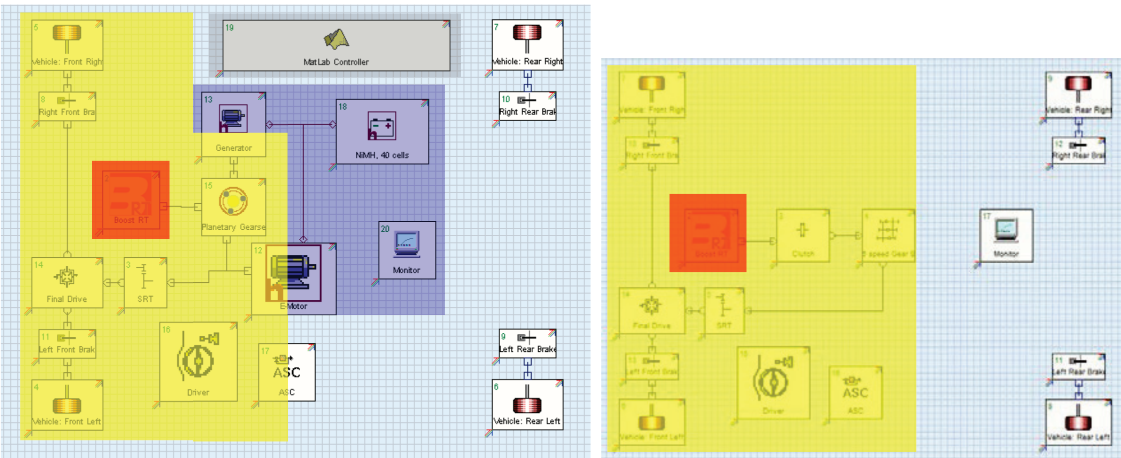

Figure 1. Schematics of the (a) HEV and (b) conventional vehicle models analysed in the present study with indicated domains; yellow – mechanical system, blue – electrical system, grey – external Matlab/Simulink HEV controller and red – internal combustion engine shown in Figure 2.

2. INTERACTION OF THE DOMAINS

To enhance the performance of the overall hybrid vehicle model it is necessary to analyze the characteristic time scales of different domains and the nature of their interaction.

2.1. Mechanical System

The vehicle and the driveline can be seen as a mechanical multi-body system represented mainly by the rotational degree of freedom. According to [8] such systems can be represented by

$$\begin{pmatrix} \mathbf{M} & \mathbf{B} \\ \mathbf{C} & \mathbf{D} \end{pmatrix} \cdot \begin{pmatrix} \mathbf{a} \\ \mathbf{m} \end{pmatrix} = \begin{pmatrix} 0 \\ \mathbf{F} \end{pmatrix} \qquad (1)$$

where $\mathbf{M}$ is the diagonal mass matrix, $\mathbf{B}$ describes the acting of the moments between the components on the components, $\mathbf{C}$ describes the constraints between the mechanical parts and $\mathbf{D}$ is the relation between the moments. $\mathbf{a}$ represents accelerations, $\mathbf{m}$ describes moments in the system and $\mathbf{F}$ covers the moments calculated in the components which act on the mechanic system. If explicit time schemes are used, which is the case in the presented analysis, time step lengths in the order of 1 ms are commonly used to integrated the mechanical system [8].

2.2. Electrical System

In hybrid electric powertrains, the electrical and mechanical systems are strongly coupled (see Figure 1). However, typically electrical system responds much faster compared to the mechanical system [8]. Following Kirchoff's law and the bond-graph approach all currents in the nodes sum up to zero. As discussed by [8] the applied electric system consists of resistors and capacities that typically depend on current, voltage but also on the mechanical state of attached mechanical components. On the system level, inductivities might be neglected [8], which enables by introducing the voltage as an additional variable to reformulate the governing equations of the electric system to yield an index of one [8].

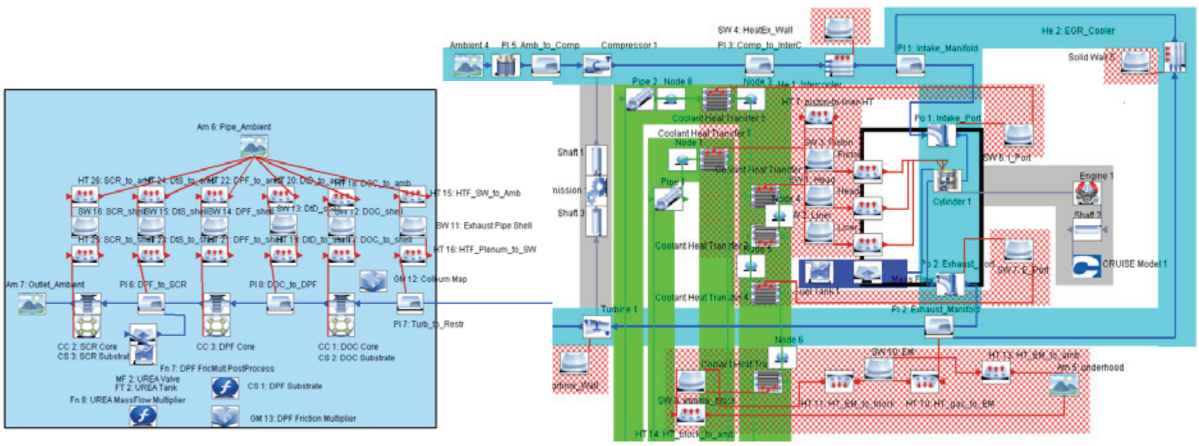

Figure 2. Topology of the CI engine model with the exhaust aftertreatment with indicated domains and different transfer paths; cyan – gas path of the engine, dark blue – fuelling, grey – mechanical part, red crossed – heat transfer functionality, green – liquid cooling circuits, light blue – exhaust aftertreatment, red – vehicle model shown in Figure 1.

2.3. Internal Combustion Engine

Internal combustion engines (Figure 2) typically feature three different characteristic time scales. The shortest time scale is associated with the in-cylinder phenomena, wave dynamics in the engine manifold and torque oscillations at the engine shaft. A larger time scale is associated with filling and emptying the engine manifolds during transient operation of turbocharged engines or during changed throttle position. Third, the largest time scale is associated with the thermal response of the engine.

The highest accuracy of the model would certainly be achieved if the complete engine will be modeled considering the shortest time scale. However, this will lead to computational times that are characteristic for 1D cycle simulation engine models, which typically amount to approximately 100 times the physical time for complex multi-cylinder high speed engine topologies, e.g. [9].

In the present analysis the complete hybrid vehicle model considering all domains targets to run close to or even faster than real-time. Therefore the engine model is subjected to further optimization regarding computational speed. This is done by optimizing the code but also by reducing the level of detail of the model. The engine model therefore consists of a crank angle resolved cylinder model embedded in a mean value based gas path description (Figure 3). Mean value modeling of engine manifolds does not consider wave dynamics. This is an acceptable simplification for modeling engines that do not exhibit significant enhancements of volumetric efficiency due to wave dynamics as will be shown later in the paper for a passenger car turbocharged diesel engine. Typical integration steps of explicit solvers that ensure stable results of the mean value gas path models are in the range from 1 ms for passenger car engine up to 5 ms or even more for certain commercial vehicle engines. This is also in agreement with the data published in [10,11]. As discernable from Figure 3, the mean value model covers the interaction of the gas path with the turbocharger dynamics and also describes EGR on a mechanistic basis. This is crucial for simulating transient engine operation [12].

To ensure a high level of predictability and accuracy during transient engine simulations it is necessary to model the cylinder with mechanistic models on a crank angle basis [12,13]. Such an approach enables an adequate interaction of the cylinder with the intake and exhaust manifold, since the exchange of mass, enthalpy and species masses is based on the physical models. Additionally, heat transfer and mass transfer due to fuel injection are also modeled on the crank angle basis. This is also beneficial for the adequacy of transient results, since variations in temperature of the solid structure and arbitrary injection strategies are captured. In Figure 3, the black rectangle indicates elements that exchange crank angle resolved fluxes with the cylinder. Moreover, since cylinders are calculated in a different time domain than other engine components, the components marked by the black rectangle exchange with the surrounding cycle average fluxes that are evaluated based on the crank angle resolved data.

An even bigger challenge compared to modeling engine performance is modeling engine emission. During the gas exchange phase a set of transient 0D single zone equations is solved [13], whereas during the combustion, balance equations for a generic two zone model are used [14,15]. The two zone approach serves as a basis for evaluating a burned zone temperature, which is together with species concentrations and the pressure used to model a kinetically driven NOx, CO and soot formation [15].

Mean value engine models are generally based on the bond-graph approach as presented in [13]. The transient variation of the state in a single storage (volume) component can be expressed by

$$\mathbf{B} \cdot \frac{\mathrm{d}\mathbf{\Phi}}{\mathrm{d}t} = +\sum \dot{\mathbf{F}}_{\mathrm{k}} \tag{2}$$

where $\mathbf{B}$ is the capacity matrix, $\mathbf{\Phi}$ is the state vector and $\dot{\mathbf{F}}_{\mathrm{k}}$ represents the flux vector related to the k'th attached bond (transfer component). Focusing on the description of the air path, the state and flux vectors comprise the conservation variables for mass, energy and species. This can be expressed by

$$\mathbf{\Phi} = \left[m, u, \mathbf{w}_{\mathrm{A}}, \mathbf{w}_{\mathrm{P}}\right]^{\mathrm{T}}, \tag{3}$$

$$\dot{\mathbf{F}} = \left[\dot{m}, \dot{H}, \dot{\mathbf{W}}_{\mathrm{A}}, \dot{\mathbf{W}}_{\mathrm{P}}\right]^{\mathrm{T}}, \tag{4}$$

where m is the mass and u is the specific internal energy. $\mathbf{w}_{\mathrm{A}}$ and $\mathbf{w}_{\mathrm{P}}$ represent vectors holding the mass fraction of active and passive species, respectively. In analogy, the elements of the flux vector are the mass flow $\dot{m}$, the enthalpy flow $\dot{H}$ and two species flow vectors $\dot{\mathbf{W}}_{\mathrm{A}}$ and $\dot{\mathbf{W}}_{\mathrm{P}}$. More details on the gas path models and on the cylinder and emission production models are given in [12-16].

If the cylinders are integrated based on the crank angle, the integration time steps typically range from approximately 10 to 100 μs for automotive engines. This is at least an order of magnitude smaller that the time steps required by the mechanical network as addressed above. If the analysis does not cover vibrational modes of the drive train, as it is common in system level simulations aimed at optimizing performance and emissions of the vehicle, it is possible to exchange the data between the engine and the mechanical system with the frequency of the integration of the mechanical system or even with the frequency of engine cycles.

2.4. Catalytic Converters

Transient 1D models can be seen as a reasonable compromise to describe with sufficient accuracy single catalysts or also entire exhaust lines (Figure 2) of lean operating engine as presented in this paper. Transient 1D balance equations for the gas phase and the solid substrate can be applied under the common assumption that radial variations (e.g. flow velocity, species fractions, temperature) within a single channel and also within the entire catalyst brick are negligible. The model equations (described in detail in [14-16]) cover the effects of convection in the gas phase, heat conduction in the substrate and heat mass transfer between the two phases. Chemical reactions comprising conversion and storage reactions take place at active sites within the washcoat.

Many of the chemical reactions taking place in catalysts feature an exponential temperature dependency. Therefore adaptive step size solvers are mandatory to efficiently solve balance equations of catalytic converters. To optimize the overall computational time gas path and catalytic converter equations are not solved in a fully coupled system. Instead, an independent time domain of the catalytic solver allows depending on the problem, either smaller or even bigger integration time steps compared to the gas path solver. The dynamic interaction of the gas path and chemical reaction time scales thus optimizes the performance of the overall model.

2.5. Heat Transfer

The heat transfer in the vehicle power train can generally be categorized in heat transfer between components of a particular domain, heat transfer between particular domains and the cooling circuit domain and heat transfer between the domains and the surrounding as shown in Figures 3 and 4.

Heat is always transferred via the solid structure (Figure 2). The time scale related to the thermal inertia of the solid structure is generally much larger compared to the integration time steps of the coupled mechanical/electrical solver, or of the catalytic converters solver, or of the cylinder and of the gas path solver. Therefore, the stability of governing equations of the solid structure does not represent a limitation in terms of the overall stability of the model, which provides a good basis for interaction of domains with different time constants.

2.6. Coupled overall system

The different domains described above are modeled by equations representing different characteristics. For an efficient and coupled solution they can be transformed into a similar form. Thus, the second order mechanical system is transformed into a first order system of doubled size. This is given by

$$\begin{aligned} &\mathbf{M}\cdot\frac{d\omega}{dt}=\tau(\omega,\varphi) \\ &\frac{d\varphi}{dt}=\omega \end{aligned} \tag{5}$$

where the system inertias represented by the mass matrix $\mathbf{M}$ times the rotational acceleration equals all momentums. The angular position φ itself is also described by first order ODEs depending on the angular velocity ω.

The gas path equations (Eq. 2) already follow the above derived form of first order ODEs representing the mechanical system. The mechanical system typically features additional linear constraints which can be substituted into the system. Additional remaining constrains are given by the electrical circuits.

All different states can be merged into a common state vector of unknowns x. Its time derivate multiplied with the system matrix $\mathbf{S}$ equals a right-hand-side function depending on x and time t. This coupled system of ODEs, as it is combined with algebraic constrain functions $g(x)$, leads to an overall semi-implicit Differential Algebraic Equation (DAE) system

$$\begin{aligned} &\mathbf{S}\cdot\frac{\mathrm{d}x}{\mathrm{d}t}=f(x,t) \\ &0=g(x) \end{aligned} \tag{6}$$

where the system matrix $\mathbf{S}$ may additionally depend on the state x. Due to the special nature of the electrical system the index of the overall DAE system is one. This allows an efficient solution of the coupled problem.

Besides controllers that are already available in the software a hybrid vehicle XCU and a conventional vehicle ECU that mimics operation of the real series production controllers were developed in Matlab/Simulink. These controllers steer vehicle components and thus influence system matrix in eq. (6).

3. SIMULATION MODEL AND ITS VALIDATION

The simulations of the hybrid electric vehicle are based on the 2004 Toyota Prius model (Figure 1). The model uses realistic data of the vehicle, tires, mechanical driveline components and electric components. For the purpose of the presented analysis the original gasoline engine was replaced by a turbocharged diesel engine as diesel and lean-gasoline engines potentially have substantial fuel economy benefits over the conventional gasoline engines and thus there is a growing interest in the use of lean-burn engines in hybrid and plug-in hybrid vehicles [1,2]. It was assumed that the new engine is compatible with the vehicle body.

Results of the hybrid electric vehicle were compared against the results of the conventional vehicle powered by the same engine. The conventional vehicle is equipped with a 6-speed manual transmission. To enable a valid comparison between the hybrid and the conventional vehicle, a vehicle model featuring the same geometric characteristics and tires was used for simulating the conventional vehicle. However, the mass of the conventional vehicle is 140 kg less than the mass of the hybrid vehicle to account for the mass of the electric components.

A 1.4 liter high speed direct injection turbocharged diesel engine with EGR was used in the simulations (Figure 2). The validation of the engine model is presented in [12,14]. Ref. [14] additionally presents good agreement between measured and simulated NO_x emissions for full load operation and selected part load operation points, which is important for the purpose of the presented analysis. The validation of the models of catalytic converters is presented in [14,16], whereas details on applied exhaust gas aftertreatment devices are given in [16].

The capability of the overall vehicle and power train model to adequately simulate transient vehicle operation was presented in [12], where chassis-dynamometer measurements were compared to the simulated results of the conventional internal combustion engine powered vehicle equipped with a 6-speed manual transmission.

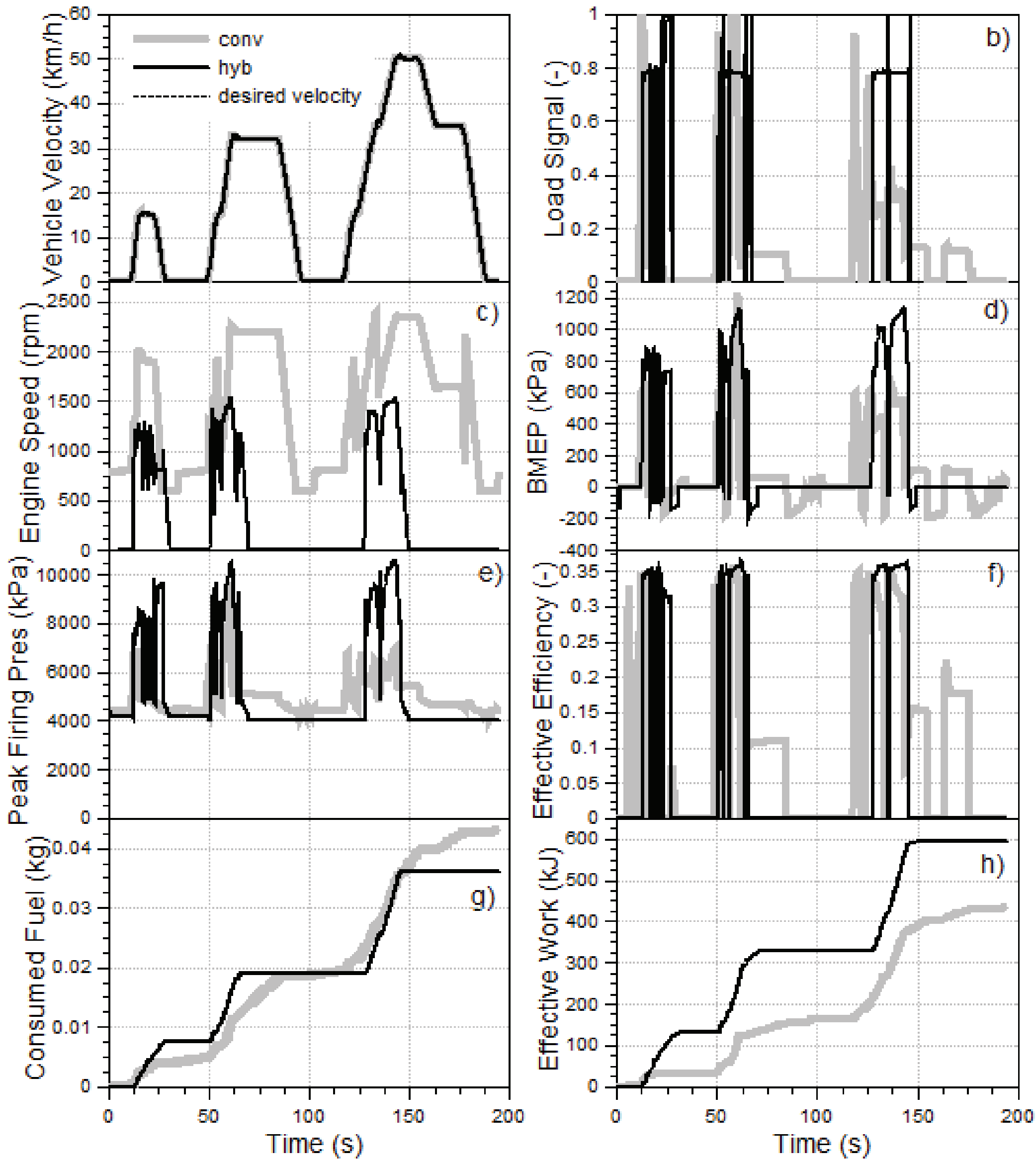

Figure 3. Comparison of engine and vehicle parameters for the UDC.

4. RESULTS

Results of the hybrid vehicle (denoted "hyb") and of the conventional vehicle with (denoted "conv") are presented and analyzed in this section.

The results are shown for the UDC driving cycle. Due to the fact that for a cold start of the first UDC cycle the catalysts do not feature any significant conversion efficiency for all vehicles, since light off temperature is not yet reached, all vehicles were run for four consecutive UDC cycles. The results are shown only for the last UDC to preserve readability of the figures. The hybrid vehicle was operated with the neutral SOC of the batteries and thus its fuel consumption reflects adequately its energy consumption.

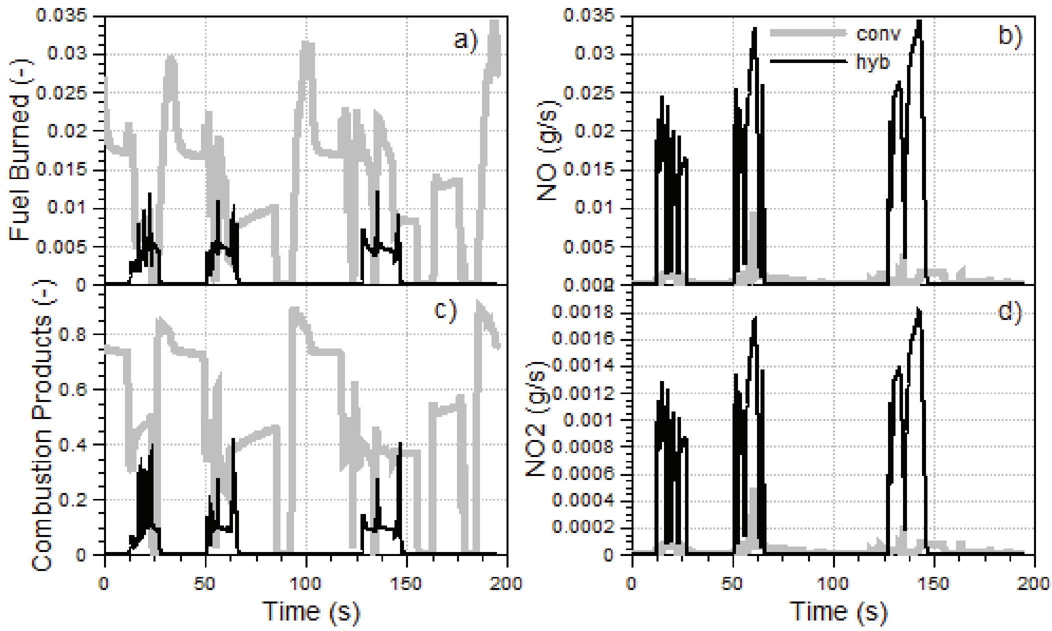

Figure 4. Comparison of fuel burned (a)) and combustion products concentrations (c)) together with the engine out NO (b)) and NO2 (d)) emissions.

In the presented analysis the aim was not to fully optimize performance and emissions of all vehicles but to show the interaction of the domains that are described by the mechanistic system level models while simulation driving performance of realistic vehicles. Therefore the controller of the hybrid vehicle was also not fully optimized, since the main aim was to operate the engine in the hybrid vehicle at low speeds and high loads to enhance its efficiency.

Figure 3 a) confirms that all vehicles adequately follow the UDC velocity trace. From Figure 3 c) it is discernible that in the hybrid vehicle, the engine is turned on mainly only during vehicle acceleration and thus for a much shorter period compared to both conventional vehicles. Moreover, in the hybrid vehicle, the engine is coupled to the wheels over a planetary gear box, which enables operating the engine at much lower engine speeds. However, this results in larger values of the load signal (Figure 3 b)) and therefore in higher values of BMEP (Figure 3 d)). Both obviously results in higher values of the peak cylinder pressure (Figure 3 e)) – here it might be noted that during engine off periods, the peak firing pressure is not calculated and thus the value from the last operating cycle is plotted. The operation of the engine in hybrid vehicle at lower speed and high loads results in high effective efficiency that is most of the time above 35% (Figure 3 f)). As a result, the hybrid vehicle consumes less fuel than both conventional vehicles (Figure 3 g)). At this place it is interesting to note that the effective work (Figure 3 h)) produced by the engine in the hybrid vehicle exceeds over the entire cycle those of the conventional vehicles. The values in Figure 3 h) were obtained by integrating engine power over the entire cycle whereby only non-negative values were considered. This is justified by the fact that in the conventional vehicles the engine also frequently absorbs power during vehicle decelerations and it is thus not adequate to consider such operation when evaluating effective work produced by the engine. The effective work of the engine in the hybrid vehicle is larger mainly due to two facts. First, the hybrid vehicle features larger mass and thus more work is needed for its propulsion. Second, the transformation between mechanical and electrical energy, and transport and storage of electric energy is associated with larger losses than transport of mechanical energy. If regenerative braking is not capable of compensating for all these losses, additional energy produced by the engine is needed to cover them if the hybrid vehicle is operated with neutral SOC (more details on the energy conversion phenomena in hybrid electric vehicle can be found in [17]).

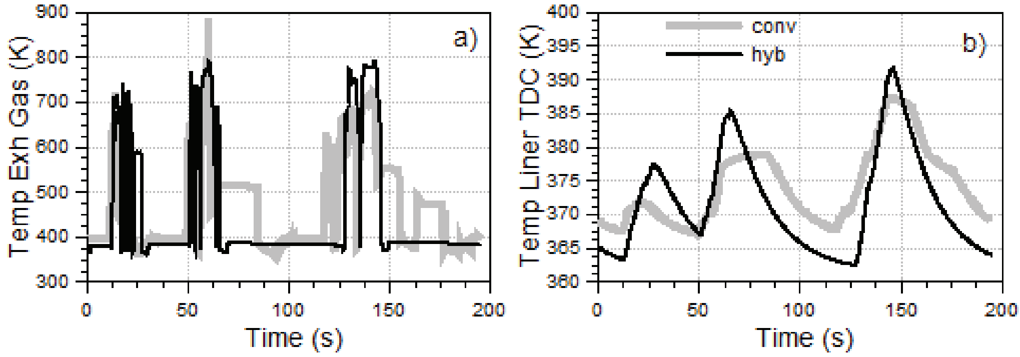

Figure 5. Comparison of temperatures of the exhaust gasses in the exhaust manifold (a)) and temperatures of the liner at TDC.

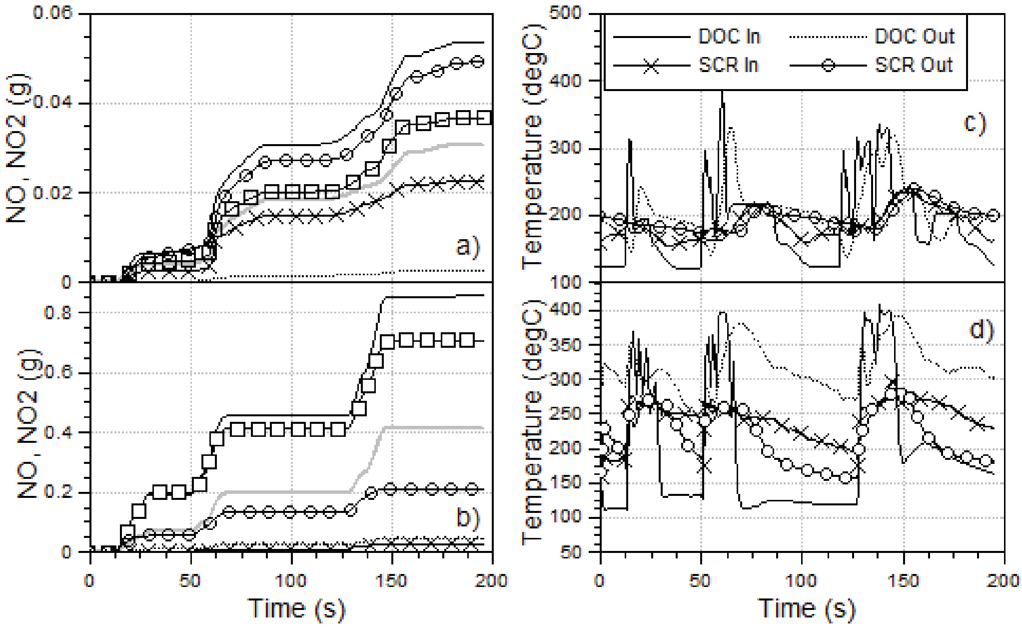

Figure 6. Comparison of NO and NO_2 emissions for conventional a) and hybrid b) vehicle and temperatures of substrates of catalytic converters at the inlet and the outlet for conventional c) and hybrid d) vehicle.

It can be observed that conventional vehicle is characterized by low engine loads and thus low BMEP during steady-state cruising at relatively low vehicle speed. Thus results in low effective efficiency of the engine being the main reason for its worse fuel economy.

The operation of the engine at high loads is clearly favored if the fuel economy is the main objective. However, operating the engine constantly at high loads as is the case for the engine in hybrid vehicle (Figure 3 b)) results in very low EGR rates (Figure 4 a) and c)), since sufficient amount of oxygen should enter the cylinders to allow for compete combustion and sufficiently low soot emissions. Figure 4 a) gives the concentration of the combustion products in the intake manifold, where for the lean operating engines it is also necessary to consider the concentration of the burned fuel, since it gives the information on the oxygen availability in the exhaust gasses. Due to the operation of the engine in the hybrid vehicle at high loads, i.e. high cyclic fuel deliveries, and with low EGR rates, the temperature of the burned zone is significantly larger than the ones in the conventional vehicles leading to significantly higher engine out NO and NO_2 emissions (Figure 4 b) and d)).

Due to the operation at higher loads, the engine in the hybrid vehicle also feature higher exhaust gas temperatures (Figure 5 a)), which will positively influence the NO and NO_2 conversion efficiency in the catalysts. From Figure 5 b) it can be seen that liner temperature at the TDC is not significantly higher for the engine in the hybrid vehicle due to longer engine off periods.

Figure 6 shows cumulative emission across the exhaust aftertreatment devices and temperature of the DOC and the SCR substrates. In Figures 6 c) and d) it can be seen that relatively large thermal inertia of the exhaust line significantly damps temperature peaks from the DOC to the SCR. This fact importantly influences the conversion efficiency of the SCR. In the case of the conventional vehicle SCR is not heated above the light-off temperature during operation of the engine at higher loads, i.e. vehicle accelerations (Figure 6 c)). As already indicated by Figure 4 b) and d) it can be seen that engine in the hybrid vehicle produces much larger engine out NO and NO_2 emissions (very similar to DOC inlet emissions Figures 6 a)-b)).

The DOC is the first aftertreatment device and it thus features sufficiently high temperature allowing significant oxidation of NO to NO_2. Conversion from NO to NO_2 is more pronounced for the hybrid case due to higher exhaust gas temperatures. Again, the DOC out emissions are very similar to SCR inlet emissions and thus these results are not shown to preserve readability of the figures. Due to a sufficiently high SCR temperature, high NO_2 and sufficient NH_3 concentrations it can be observed that NO is very efficiently removed in the SCR of the hybrid vehicle. In the SCR, NO_2 is mainly removed in the reactions with NO and NH_3. Due to its high inlet concentration the hybrid case, NO_2 is removed less efficiently than the NO due to slower rate of the reaction between NO_2 and NH_3. Unlike, it can be observed that for the conventional vehicle, the temperature of the SCR is too low to enable notable NO_x reduction. Instead only partial oxidation of NO to NO_2 is observed. Overall it can be concluded that the total NO_x emissions of the hybrid vehicle are higher compared to the conventional one despite much higher NO_x conversion efficiency in the aftertreatment line, since it cannot compensate for much higher engine out emissions.

Here it might be noted that controllers of the hybrid power train might be optimized to reduce engine out emissions as presented in [2], however this was not the scope of the presented analysis.

4. CONCLUSION

A comprehensive mechanistic system level simulation model of a hybrid vehicle was presented in the paper. The model comprises all relevant domains, which are necessary to adequately model performance and emissions of the vehicle. It was shown in the paper that mechanistic modeling approach provides a good basis for development and optimization of hybrid and conventional power trains. This is justified by their high level of predictability and their adequacy in modeling the interaction of different domains during transient operation of the components. Moreover, mechanistic models are unlike map based models also able to cover highly transient operating regimes that significantly deviate from the steady-state regimes.

An adequate coupling of the domains is crucial for achieving a good ratio between accuracy, predictability and computational speed. An efficient modeling approach considering the characteristic times of different domains and the nature of their interaction is presented in the paper. Thereby it is possible to achieve very short computational times considering the mechanistic basis of the model. The overall real-time factor measured for an offline UDC simulation on a standard PC is in the range of 1.6 for the conventional and 1.7 for the hybrid power train, whereas real-time factors decrease below 0.9 if chemical reactions in the catalysts are not considered.

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OPTIMIZACIJA POTROŠNJE GORIVA I ISPUŠNIH EMISIJA HIBRIDNIH POGONA – PRIMJENA SIMULACIJA NA MEHANISTIČKOM NIVOU

Sažetak: *U radu je predstavljen simulacijski model na razini mehanističkog sustava za modeliranje hibridnih i konvencionalnih tipova vozila. Rad se bavi dinamičkom interakcijom između različitih domena: motora s unutarnjim izgaranjem, uređaja za naknadnu obradu na ispuhu, električnih komponenti, mehaničkog pogona, rashladog kruga i odgovarajućih upravljačkih jedinica. Da bi se postigao dobar omjer točnosti, predvidljivosti i računalne brzine modela, potrebno je adekvatno razviti model s obzirom na karakteristične vremenske skale domena i prirodu njihove interakcije. Primjenjivost i svestranost simulacijskog modela na razini mehanističkog sustava prikazana je kroz analizu prijelaznih pojava uzrokovanih visokim međuovisnostima domena. Rezultati pokazuju da smanjenje potrošnje goriva i emisije* CO_2 *može negativno utjecati na emisije* NO_x*, koji upućuju na potrebne prilagodbe u uređaju za naknadnu obradu ispušnih plinova. Zajednička interakcija domena opravdava primjenu alata za simulaciju na razini sustava, i to u ranim fazama razvoja, budući da međuovisni utjecaji različitih domena moraju biti uzeti u obzir kako bi se ispunio veliki broj zahtjeva.*

Ključne riječi: hibridno-elekrtični pogon, simulacija

DIZEL GORIVA IZ BIOMASE

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Sažetak: *Biomasa može biti sirovina za proizvodnju cijelog niza različitih tipova dizel goriva. Prema vrsti biomase iz koje potječu, dizel goriva iz biomase se mogu podjeliti na prvu, drugu, treću i četvrtvu generaciju, dok se vrste primjenjenih tehnoloških procesa proizvodnje mogu podijeliti na izravnu ekstrakciju, biokemijsku konverziju i termokemijsku konverziju. Iz biomase proizvedena dizel goriva su čista biljna ulja, mikroemulzije biljnih ulja s alkoholima, produkti nastali pirolizom biljnih ulja, biodizel, NExBTL dizel, FT dizel, dimetileter, dizel gorivo iz biljnih ugljikovodika i ugljikovodika mikroorganizama, te HTU dizel. Sva ova goriva mogu se proizvesti iz sirovina prve, druge, treće i četvrte generacije. Nadomjestak naftnom dizelu mogu biti biodizel, NExBTL dizel, FT dizel i HTU dizel. U zdravstvenom, i ekološkom pogledu ta su goriva prihvatljivija od naftnog dizela, međutim njihova proizvodnja iz biomase prve i druge generacije nije održiva.*

Ključne riječi: dizel goriva, biomasa, biogoriva, konverzija

1. UVOD

Dizel motori se uvelike koriste u industriji i transportu za pogon automobila, kamiona, traktora, brodova, pumpi, generatora, strojeva u rudarstvu, graditeljstvu i poljoprivredi. Dizel gorivo se korištenjem pokazalo kao najpogodnije transportno gorivo, a potrošnja dizel goriva raste brže od ostalih transportnih goriva [1]. Najčešće korišteno i najbolje dizel gorivo je naftni dizel koje se proizvodi atmosferskom destilacijom sirove nafte i sakupljanjem srednje frakcije destilata u temperaturnom rasponu 175-370°C. Sastoji se od parafina, naftena, olefina i aromata koji sadrže 15-20 ugljikovih atoma u molekuli. Cetanski broj mu je oko 50, energetska vrijednost 38-40 MJ kg^{-1}, plamiše 64-80°C, gustoća oko 0,850 kg $dm-^{3}$, viskoznost 1,9-4,1 mm^2s^{-1}. Svako gorivo koje se koristi u dizel motorima umjesto naftnog dizela mora imati karakteristike slične ovima [2]. Sirovina za proizvodnju dizel goriva može biti i biomasa, iz koje se različitim procesima mogu proizvesti različiti tipovi dizel goriva.

2. BIOMASA I BIOGORIVA

Biomasa je biološki materijal od živućih, do skoro živućih organizma ili njihovih metaboličkih proizvoda. 75 % biomase u svijetu čine ugljikohidrati ponajviše celuloza i hemiceluloza 20 % čini lignin, a 5 % sva ostala biomasa [3]. 70-90 % trenutno tehnički dostupne biomase otpada na drvnu biomasu i biomasu žitarica [4]. Biogoriva jesu goriva proizvedena iz biomase [5], koja mogu biti kruta tekuća ili plinovita. Različitim procesima konverzije se biomasa iz voluminoznog, teško manipulativnog materijala male gustoće energije pretvara u goriva fizikalno-kemijskih karakteristika koje omogućuju njihovo ekonomčno skladištenje, transport i uporabu.

Glavni procesi konverzije biomase u goriva i energiju mogu se podijeliti na [6] :

- Izravno izgaranje gdje biomasa izgara dajući energiju kao npr. drvo za grijanje i kuhanje.
- Fizikalnu ekstrakciju gdje se npr. ulja i masti ili ugljikovodici iz nekih vrsta algi izdvajaju za korištenje kao goriva. Primjer su riblje i maslinovo ulje za uljne lampe, ili loj za stearinske svijeće.
- Biokemijsku konverziju gdje se biomasa pretvara u goriva raznim kemijskim i biokemijskim procesima poput hidrolize, saharaifikacije, fermentacije, esterifikacije. Tipična goriva dobivena biokemijskom konverzijom su biodizel, bioetanol, biometanol, biobutanol, bioplin.
- Termokemijsku konverziju gdje se goriva dobivaju kombinacijom djelovanja temperature i kemijskih procesa. Termokemijska konverzija se može podjeliti na subkategorije a to su : *uplinjavanje, piroliza, izravno ukapljivanje i neizravno ukapljivanje*. *Uplinjavanjem* biomase tj. nepotupnom oksidacijom dobiva se generatorski plin koji se može koristiti izravno kao gorivo u motorima sa unutarnjim izgaranjem kao što se to činilo npr. u vrijeme nestašice goriva za vrijeme II. svj. rata. *Piroliza* je zagrijavanje biomase na bez prisustva kisika. Pirolizom npr. drveta na 400-500°C dobiju se gorivi produkti kao što su drveni ugljen i rasvjetni plin te niz ostalih produkata. Brzom pirolizom na temperaturama iznad 550°C dobije se bioulje. *Neizravno ukapljivanje* uključuje najprije uplinjavanje nepotpunom oksidacijom ili parnim reformiranjem pri čemu se dobije sintezni plin koji se zatim, Fisher-Tropschovom sintezom prevodi u kapljevite ugljikovodike.
  Izravno ukapljivanje uključuje HTU (Hydro Thermal Upagrading) proces, Bergiusov proces i Karrickov proces

Prema izvoru sirovina iz kojih se proizvode biogoriva se mogu podijeliti na četiri generacije [7] :

- Prva generacija su biogoriva proizvedena nizom konvencionalnih tehnologija od šećera, škroba, biljnog ulja i životinjskih masti. Osnovne sirovine za proizvodnju s najčešće kukuruz, pšenica, palma, šećerna repa, uljana repica i ostale biljne vrste sličnih osobina. Tipična goriva ove genaracije su biodizel i bioetanol.
- Druga generacija biogoriva se temelji na sirovinama koje se ne koriste u proizvodnji hrane. To uključuje razne nejestive sirovine i usjeve kao i otpadnu biomasu porijeklom iz poljodjelstva, stočarstva, šumarstva, industrije i kućanstava te postrojenja za obradu komunalnog otpada i otpadnih voda. U ovu katergoriju spada bioplin i biodizel proizveden iz otpadnog jestivog ulja i kafilerijske masti, bioetanol iz lignocelulozne biomase, zatim biometanol, biodimetileter, biobutanol, FT (Fischer-Tropsch) dizel, HTU (Hydro Thermal Upgrading) dizel i dr.
- Treću generaciju biogoriva temeljena su na biomasi iz specijalnih kultura koje se nisu uzgajale ranije poput mikroalgi. Odlikuje ih nekonvencionalan način uzgoja, relativno mala potrebna površina, niski proizvodni troškovi i visok prinos. Biomasa mikroalgi može se zavisno od vrste satojati od ugljikohidrata, triglicerida ili dugolančanih (C30) ugljikovodika sa 30 ugljikovih atoma u lancu. Iz biomase mikroalgi može se proizvoditi bietanol, biodizel, ugljikovodična goriva dobivena krekiranjem dugolančanih ugljikovodika iz algi, ili FT dizel.

- Četvrta generacija biogoriva se bazira na genetski optimiziranim sirovinama koji su dizajnirani tako da pored velikog prinosa biomase imaju povećanu apsorpciju ugljik-dioksida iz atmosfere te tako koriste i u ekološkom smislu.

3. KATEGORIZACIJA DIZEL GORIVA IZ BIOMASE TE NJIHOVA SVOJSTVA I MOGUĆNOSTI PROIZVODNJE

Prema kakvoći, vrstama sirovina i procesima proizvodnje dizel goriva iz biomase se mogu klasificirati u više skupina.

3.1. Biljna ulja kao dizel gorivo

Biljna ulja mogu se kratkoročno rabiti kao gorivo u dizel motorima, ali se pri duljoj uporabi javljaju znatni problemi. Visoka viskoznost otežava ubrizgavanje goriva i njegovo raspršivanje, a to za posljedicu ima loše izmješavanje sa zrakom, odnosno nepotpuno sagorijevanje. Relativno visoko vrelište pridonosi također stvaranju taloga na injektorima te razgradnji i razrijeđivanju ulja za podmazivanje. Kombinacija visokog vrelišta i viskoznosti uzrok su problemima pri startu i vremenskoj zadršci pri paljenju [8].

3.2. Mikroemulzije biljnih ulja s alkoholima

Problem viskoznosti biljnih ulja može se donekle riješiti emulzifikacijom biljnih ulja s alkoholima uz pomoć tenzida (emulgatora). Tako se u većoj mjeri mogu riješiti kratkoročni (viskoznost), ali ne i dugoročni problemi karakteristični za biljna ulja kao što su napotpuno sagorijevanje i nastajanje naslaga koksa [9]. Relativno visok udio alkohola (>30% vol.) u takvim smjesama znatno snizuje cetanski broj dobivenog goriva koje uz to pokazuje i loša hladna svojstva.

3.3. Produkti pirolize biljnih ulja

Piroliza ili krekiranje je postupak razlaganja većih organskih molekula pri povišenoj temperaturi (300-500°C) u svrhu dobivanja produkata niže molekulske mase i drukčijih svojstava. Svojstva produkta nastalog pirolizom biljnog ulja nisu zadovoljavajuća, a to se odnosi prije svega na viskoznost i hladna svojstva [8].

3.4 Biodizel

Biodizel je monoalkilester masnih kiselina. Osnovni proces dobivanja biodizela je katalitička ili nekatalitička transesterifikacija triglicerida i/ili esterifikacija masnih kiselina. Kao monovalentni alkohol koji se veže na masne kiseline prilikom transesterifikacije ili esterifikacije najčešće se koristi metanol pa se biodizel često naziva i metilesterom. Sumarne jednadžbe tipične transesterifikacije triglicerida i esterifikacije masnih kiselina prikazane su slikama 3.1. i 3.2.

$$\begin{array}{lcccccl}
CH_2 - OCOR_1 & & & & CH_3 - O - COR_1 & & CH_2 - OH \\
| & & & & & & | \\
CH - OCOR_2 & + & 3\,CH_3OH & \rightarrow & CH_3 - O - COR_2 & + & CH - OH \\
| & & & & & & | \\
CH_2 - OCOR_3 & & & & CH_3 - O - COR_3 & & CH_2 - OH \\
\\
\text{triglicerid} & & \text{metanol} & & \text{metilester} & & \text{glicerol}
\end{array}$$

Slika 3.1. Transesterifikacija triglicerida

$$\begin{array}{lcccccc}
RCOOH & + & CH_3OH & \rightarrow & RCO\text{-}OCH_3 & + & H_2O \\
\\
\text{masna kiselina} & & \text{metanol} & & \text{metilester} & & \text{voda}
\end{array}$$

Slika 3.2. Esterifikacija masnih kiselina

Sirovine za proizvodnju biodizela mogu biti biljna ulja, prehrambenih i neprehrambenih uljarica, životinjskih masti i ulja, ulja mikroalgi, otpadna jestiva ulja i masti te kafilerijske i nejestive životinjske masti. Ulja i masti za proizvodnju biodizela se iz ishodišnog materijala (uljarice, otpaci, ribe..,) dobivaju različitim procesima ekstrakcije i/ili rafinacije. Prema tome biodizel se može svrstati u biogoriva prve, druge i treće generacije. U proizvodnji biodizela transesterifikacijom se kao sporedni proizvod dobiva glicerol, kemijski spoj svekolike primjene. Glicerol se može APR (Aqous Phase Reforming) procesom pretvoriti u vodik i ugljik-dioksid od kojih se dalje može proizvesti metanol koji se koristi za proizvodnju biodizela. Najčešeće korišteni katalizatori su hidroksidi i metoksidi natrija i kalija kod transesterikfikacije triacilglicerola, te sumporna i p-toluensulfonska kiselina kod esterifikacije masnih kiselina.

Osnove inudustrijske proizvodnje biodizela razvijene su tijekom 1940-ih godina [10]. Biodizel se danas proizvodi u mnogim krajevima svijete alkalno kataliziranom transesterifikacijom iz sirovina prve (uljana repica, uljana palma, suncokret, soja, loj), i druge generacije (otpadna jestiva ulja i masti), a u skorijoj budućnosti planira se i proizvodnja iz sirovina druge (jatropa, karanja, mahua...) i treće generacije (mikroalge).

Omjer neto energije za biodizel je pozitivan i ovisno o vrsti sirovine iznosi 2,9-9 [11]. Stanovit broj postrojenja za proizvodnju biodizela izgrađen je i korišten u Srbiji tijekm naftnog embarga početkom 1990-ih.

Fizikalno kemijske i uporabne karakteristike biodizela koje su bliske onom naftnog dizela čine bidizel gorivom koje se može koristiti u motorima i vozilima s minimalnim ili nikakvim modifikacijama. Za transport i skladištenje biodizela može se koristiti postojeća infrastruktura.

Nedostaci proizvodnje biodizela prve generacije su viši proizvodni troškovi, niži omjer neto energije, velike potrebne površine za uzgoj uljarica te štetan učinak uzgoja na okoliš.

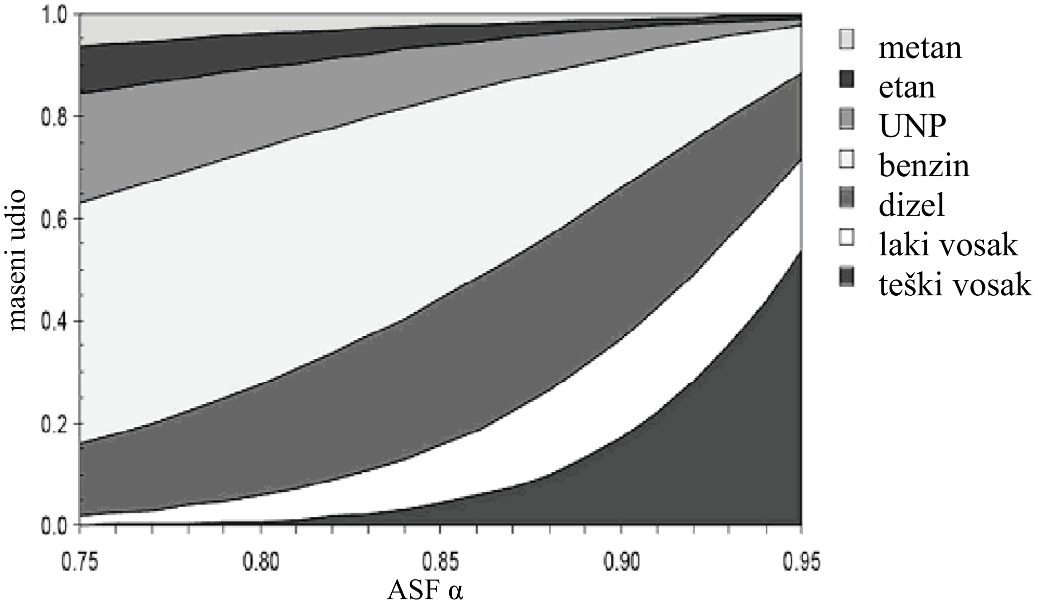
3.5. NExBTL dizel (Neste Oil x Biomass to Liquid)

Proizvod naftne tvrtke Neste Oil. Polazna sirovina su jednako kao i za biodizel tracilgliceroli biljnog ili životinjskog porijekla. Međutim umjesto transesterifikacije se radi hidrogenizacija uz katalizator. Produkt je bezbojan ugljikovodik koji ne sadrži kisik niti aromatske spojeve. Sporedni proizvodi su propan i benzin. Količina vodika koja se dodaje u procesu je 2-3 % na masu ulja ili masti. Karakterizira ga viši cetanski broj (84-89), niža temperatura zamućenja (-

30°C), snižena emisije dušikovih oksida, ugljik-monoksida i čvrstih čestica, ne sadrži aromatske spojeve niti sumpor.
Nedostaci vezani za proizvodnju NE-BTL dizela jednaki su kao i za biodizel.

3.6. FT dizel (Fischer-Tropsch dizel)

Fischer-Tropschovu sintezu su 1923.g. iznašli Franz Fischer i Hans Tropsch. Radi se sintezi ugljikovodika iz sinteznog plina tj. mješavine plinova ugljik-monoksdia (CO) i vodika (H_2),.
Posredstvom katalizatora, najčešće na bazi kobalta ili željeza pri temperaurama 250-300°C i tlakovima 25-60 bara odvija sljedeća reakcija [4] :
$CO + 2H_2 \rightarrow -(CH_2)- + H_2O$ (1)
Rezultat reakcije su laki ugljikovodici (C_1-C_2), UNP(C_3-C_4), benzini (C_2-C_{11}), dizel(C_{12}-C_{20}), i voskovi (>C_{20}). Nastali ugljikovodici su uglavnom ravnolančani parafini, dok olefini i razgranati parafini i olefini nastaju u vrlo malim količinama [11]. Teoretsku distribuciju produkata različite duljine lanca opisuje Anderson-Shulz-Flory (ASF) jednadžba :
$\log(W_n/n) = n\log\alpha + \log[(1-\alpha)^2/\alpha]$ (2)
gdje je W_n maseni udio produkta koji se sastoji od n ugljikovih atoma, a α faktor vjerojatnosti rasta lanca. α ovisi o vrsti katalizatora i uvjetima procesa. Distribucija produkata FT sineze u zavisnosti od faktora α prikazana je slikom 3.3.. Laki i teški voskovi mogu se dalje podvrći hidrokrekiranju kako bi se dobile nižemolekulske frakcije.



Slika 3.3. Distribucija produkata FT sinteze u zavisnosti od faktora α

U vrlo egzotermnoj FT reakciji 20 % kemijske energije se oslobađa kao toplina.
Sintezni plin za FT sinetzu dobiva se na dva načina ; uplinjavanjam i reformiranjem. Uplinjavanje je pojam koji se koristi za proizvodnju sinteznog plina iz čvrste ili teške tekuće mase, dok se pojam reformiranje koristi za proizvodnju sinteznog plina iz plinovite ili lake tekuće mase [1]. Prilikom proizvodnje sineznog plina, kruta, tekuća ili plinovita organska tvar se podvrgava oksidaciji uz ograničen dotok kisika pri čemu nastaje ugljik monoksid i vodik. Isparena voda sadržana u samom materijalu ili voda nastala pirolizom pod utjecajem topline oslobođene oksidacijom reagira sa organskom tvari biomase dajući također vodik i ugljik monoksid.

Tipične reakcije pri npr. autotermalnom reformiranju (ATR) metana gdje nastaje sintezni plin prikazane su sljedećim formulama :

$$CH_4 + 3/2O_2 \rightarrow CO + 2H_2O \quad \Delta h<0 \qquad (3)$$
$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad \Delta h>0 \qquad (4)$$
$$CO + H_2O \rightarrow CO_2 + H_2 \quad \Delta h<0 \qquad (5)$$

Sirovina za proizvodnju sinteznog može biti biomasa u svim oblicima i to prve , druge ili treće generacije. Kako bi se olakšala manipulacija i snizili troškovi transporta do postrojenja za FT sintezu krutu biomasu je potrebno najprije podvrgnuti sušenju ili torefakciji čime se povećava energetska gustoća biomase, ili brzoj pirolizi čime se biomasa pretvara u bioulje koje je tekuće što olakšava manipulaciju.
FT procesi su se naveliko koristili za proizvodnju sintetskih goriva u vrijeme kada fosilna goriva nisu bila dostupna kao npr. u Njemačkoj i Japanu tijekom 1930-ih i 1940-ih, i u Južnoafričkoj republici za vrijeme naftnog embarga. Danas se FT proces koristi za proizvodnju tekućih goriva iz ugljena u Južnoafričkoj republici (Sasol 1,2 i 3), te nešto u SAD-u, a za proizvodnju tekućih goriva iz prirodnog plina FT proces se koristi u Maleziji i Nigeriji (Shell) [1]. FT sintezom iz biomase se dizel gorivo proizvodi u Njemačkoj tzv. Carbo-V procesom tvrtke Choren. Osnova Carbo-V procesa je FT sinteza kojoj prethodi spora piroliza i gasifikacija nastalih produkata [12].
FT dizel je po fizikalno kemijskim karakteristikama vrlo sličan naftnom dizelu i može se koristiti u postojećim vozilima bez modifikacija. Goriva proizvedena FT procesom su ″ultra čista″ jer ne sadrže sumpor niti aromatske spojeve, a mješavine klasičnih naftnih goriva i goriva proizvedenih FT sintezom imaju smanjene emisije čađe i SO_2.
Za proizvodnju dizela FT procesom troše se velike količine energije, efikasnost termalne konverzije je oko 50 % tj. za svaki MJ goriva proizvedenog FT procesom utroši se još jedan MJ iz biomase. Nedostaci proizvodnje FT dizela iz biomase prve i druge generacije su visoki proizvodni troškovi, velike potrebne površine za proizvodnju biomase, te štetan učinak te proizvodnje biomase na okoliš.

3.7. Dimetileter

Dimetileter je plin formule CH_3OCH_3, svojstava sličnih ukapljenom naftnom plinu (UNP). Iz biomase se proizvodi procesom koji se sastoji od tri osnovna koraka. Biomasa (najčešće lignocelulozni materijal) se najprije uplinjava, a iz dobivenog sintezinog plina se uz posredstvo katalizatora proizvede metanol koji se zatim dehidratira u dimetiler. Dimetileter se može koristiti kao zamjena za UNP i to za pokretanje benzinskih i dizel motora. Za razliku od klasičnog naftnog dizel goriva ima nešto viši cetanski broj (55), ne sadrži sumpor niti krute čestice. Nedostaci su mu niža energetska vrijednost, kompliciranije skladištenje i manipulacija jer je u plinovitom stanju, izrazito niska viskoznost što može izazvati istjecanje na pumpama i injektorima, te otežano podmazivanje [2].

3.8. Dizel gorivo iz biljnih ugljikovodika i ugljikovodika mikroorganizama

Određene vrste kopnenih biljaka i mikroalgi akumuliraju dugolančane ugljikovodike (C30) koji se sastoje od triterpenoida čijim se krekiranjem (pirolizom) može dobiti 62 % benzina, 15 % dizela, 15 % mlaznog goriva i 3 % teškog ulja. Također stanovite vrste gljiva i bakterija mogu fermentacijom gotove biomase proizvesti ugljikovodike čijom se daljnjom obradom (krekiranjem) mogu proizvesti tekuća goriva [2].

3.9. HTU (Hydro Thermal Upgrading) dizel

HTU je postupak u kojem se vlažna biomasa kuha u vodi pri povišenom tlaku (120-180 bara) i povišenim temperaturama (300-350°C) u vremenu od 5-20 min. Kao produkt dobije se 25 % plina koji se sastoji uglavnom od ugljik dioksida, voda, 10 % u vodi topivih organskih tvari i 45 % teške organske u vodi netopive tekuće faze. Teška organska faza koja sadrži 10-18 % kisika i skrućuje se na 80°C se dalje katalitičkom hidrodeoksigenacijom prevede u dizel koji je po karakteristikam skoro identičan naftnom. U vodi topiva organska faza se koristi za proizvodnju bioplina uobičajenim postupkom. Efikasnost termalne konverzije procesa je 70-90 % [13].

4. ZAKLJUČAK

Dizel goriva iz biomase koja su po fizikalno kemijskim i uporabnim karakteristikama idenitična naftnom dizelu i mogu biti njegov nadomjestak jesu biodizel, NE-BTL dizel, FT dizel i HTU dizel. Navedena tekuća dizel goriva se mogu koristiti u dizel motorima bez ikakvih modifikacija. Praktična su za uporabu i mogu se brzo i lako implementirati koristeći postojeću infrastrukturu za skladištenje, transport i distribuciju što im daje prednost posebno pred plinovitim gorivima poput biovodika. U usporedbi s naftnim dizelom, dizel iz biomase je zdravstveno i ekološki prihvatljiviji jer ne sadrži nikakve toksične tvari, a emisije štetnih tvari iz ispuha su daleko niže. Bolja mazivost i viši cetanski broj biodizela i FT dizela također su prednost jer mogu utjecati na produljenje radnog vijeka motora.
Nedostaci proizvodnje dizel goriva iz biomase se ponajviše odnose na tip biomase iz koje se proizvode. Pri proizvodnji iz biomase prve i druge generacije problem su nerealno velike površine potrebne za uzgoj i proizvodnju biomase i katastrofalan učinak te proizvodnje na okoliš[14][15]. Omjer neto energije dizel goriva iz biomase prve i druge generacije niži je nego kod naftnog dizela.
Kroz povijest su dizel goriva proizvedena alternativnim postupcima iz biomase i ugljena (biodizel i FT dizel) u uvjetima nestašice nafte u određenoj mjeri nadomještala naftni dizel, a razvoj, proizvodnja i korištenje dizel goriva iz biomase nastaviti će se i dalje.

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DIESEL FUELS FROM BIOMASS

Summary: *Biomass can be used as raw material for production of full range of different types of diesel fuel. According the type of biomass used in production, diesel fuels from biomass can be classified into first, second, third, and fourth generation, while varieties of technological processes can be calssified into direct extraction, biochemical conversion, and thermochemical conversion. Diesel fuels derived from biomass are straight vegetable oils, microemulsions of vegetable oils with alcohols, products of pyrolysis of vegetable oils, biodiesel, NExBTL diesel, FT diesel, dimethyl ether, diesel fuel from vegetable and microbial hydrocarbons, and HTU diesel. All of these fuels can be produced from raw materials of first, second, third, and fourth generation. Substitute for petrodiesel can be biodiesel, NExBTL diesel, FT diesel, HTU diesel. In view of health and ecological issues those fuels are more acceptible than petrodiesel, however their production from first and second generation biomass is not sustainable.*

Key words : diesel fuels, biomass, biofuels, conversion

ELECTRIC VEHICLE MODELLING FOR REAL APPLICATION

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Abstract: *Electric vehicles are often mentioned as part of the solution to the problems of contemporary society such as air pollution, climatic changes, smog and noise in the urban environment, limited fossil fuel resources and their rising price. However there are several shortcomings which limit their wide application. The main of those are the high price and mass of the battery, or its limited capacity. In the present article a calculation and an analysis of the possibility of a limited capacity battery application for the urban usage is given. Such a battery would have a lower price and its capacity would fulfill the needs of the majority of the average users which use the car for everyday short urban transfers. For such purpose, the energy requirement has to be calculated carefully. In the first part of the article a comparison between the standard driving cycles with a real route on the streets of the city of Rijeka (Croatia) was done. The real data have been collected with a GPS device. The driving speed and the road slope were calculated. An electric vehicle energy requirement model is presented. With the data obtained, the required energy was calculated for different vehicle specifications: lower or higher mass, with or without the regenerative braking system. The influence of the hills in the route on the driving range was evaluated.*

Key words: electric vehicle, driving cycle, energy consumption simulation

1. INTRODUCTION

In the last few decades the crude oil prices are constantly rising. The reasons for that are the political circumstances but also the depletion of the resources. A direct consequence is a growth of the prices for the fuels used to provide power for vehicles: diesel and gasoline. This is a major concern for countries without natural crude oil reserves because all their national economy is dependent on the global market fuel prices. Another problem related to the usage of fossil fuels is the occurrence of smog, the emission of toxic gases and the increase of the frequency of respiratory system diseases in urban environment [15]. This problem was noticed for the first time in the Los Angeles area in 1940 [10].

By the end of the 1980's in some cities emission regulations were introduced, and even limitations to vehicle circulation were set. On global scale the use of fossil fuels and the emission of the so called greenhouse gases are sometimes related to the climatic changes and global warming as well as extreme weather phenomena.

In order to mitigate climate changes and global warming effects, our intention is to reduce greenhouse gasses emissions, to integrate renewable energy sources and to increase overall energy efficiency [12]. Energy utilities all over the world are collaborating with many R&D teams to develop technologies, concepts and solutions which will gradually evaluate the electric energy power system into a vision usually known as a Smart Grid. Part of the solution and an important area of interest is automotive sector, as a significant. There are different replacement options for internal combustion engine vehicles. Some authors see a hybrid electric vehicle as the best temporary solution [1], [2], [8], [9]. Most of the authors see some kind of electric drive as the best long term solution [1], [5], [11], [14], [15]. In spite of the complex internal combustion engine and its systems, an efficient electric motor, a power controller and a battery system would be installed in the vehicle. It has to be highlighted that electric vehicles are not the definitive solution to the problems because electric energy still has to be produced which is often done in thermal power plants in which fossil fuel is burnt. But electrical networks are powered also from emerging, renewable, clean energy sources such as hydro power plants, wind power plants as well as photovoltaic systems. Certain amount of energy is obtained from nuclear power plants which do not contribute to air pollution but which present some other shortcomings and dangers. Furthermore, in thermal power plants natural gas can be used. The reserves of natural gas are grater then those of crude oil and the natural gas combustion products present a smaller environmental impact. Some countries have abundant coal reserves while do not have oil. From the economic point of view, for such countries it is more convenient to produce the electricity from coal, and by partial electrification of the transport sector, reduce the dependence on expansive oil products. Coal burning is usually considered dirty from the ecological point of view, but some advanced, cleaner coal burning technologies were developed too. Finally, an important fact is that it is simpler to control one centralized pollution source such as the power plant than thousands of vehicles.

Electric vehicles are not a new invention. They appeared in the first half of the 19th century, hence before the internal combustion engines. At the end of the 19th century there were different solutions to drive vehicles, starting with horses and carriages, over steam power vehicles, to internal combustion engine vehicles. All of these solutions had their good and bad characteristics. At the beginning of the 20th century, as the consequence of the mass production, the invention of the electric starter and the development of the petroleum industry the internal combustion engine driven vehicles became the leading technology and all the other technologies gradually lost their importance. Although they were silent, comfortable and clean in comparison to the internal combustion engine vehicles, the big mass and price as well as small range stopped the electric vehicle development. By the end of the 20th century there were some individual attempts of the automotive companies to bring the electric vehicles to life (GM EV1, Toyota Rav 4). Despite the high technological level and initial success on the market, they did not achieve world wide popularity.

Today electric vehicles are again an important issue for societies considering sustainable development. Most of the big automotive companies have in their production or have announced an electric or a hybrid car. The battery electric car Nissan Leaf has been elected car of the year. Also many amateurs convert their conventional cars into electric ones. New battery technologies are being developed with higher specific capacity but their mass and price still represent the main limiting factor to a wider use of electric vehicles.

In this article an algorithm for the electric energy consumption calculation is introduced. It takes into account the main vehicle's parameters as well as the traffic conditions and it can be used to optimize the battery capacity for a determined application. It was analyzed the consumption in standardized driving cycles and it was compared to a real driving cycle with or without taking into account the slopes, with different mass vehicles, with or without the regenerative braking system.

2. THE REAL DRIVING CONDITIONS

For the calculation of the consumption and the emissions from internal combustion engine vehicles, standard driving cycles are usually used. There are different kinds, some more appropriate for highway regimes, some for suburban regimes and some for urban regimes with many stops and accelerations but with limited top speed. It is considered that battery electric vehicles are most appropriate for the use in cities since there they do not need a high maximal speed and a great driving range, and there is the possibility of recuperation of part of the energy during decelerations with the regenerative breaking system. For the urban driving conditions the ECE-15 or ECE-47 driving cycles are used in Europe, Fig. 1 and 2.

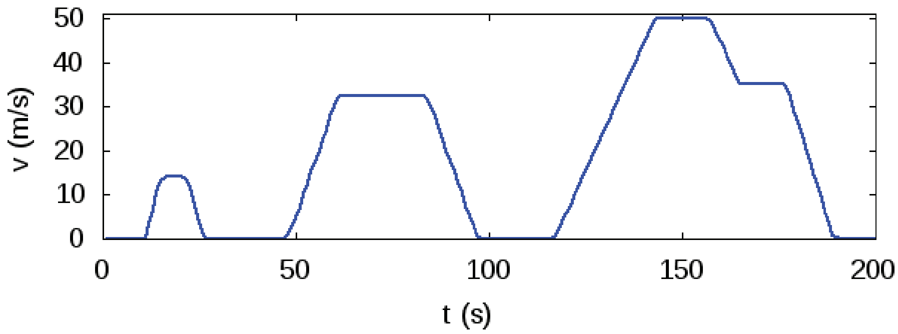

Figure 1. The speed profile for the ECE-15 driving cycle

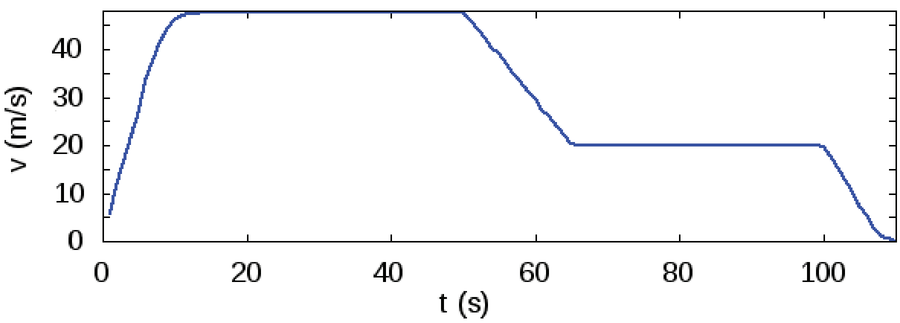

Figure 2. The speed profile for the ECE-47 driving cycle

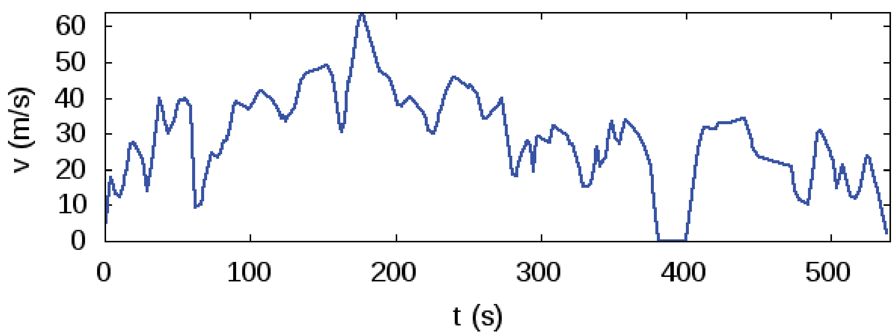

Figure 3. Velocity profile obtained with the GPS device in the urban driving conditions

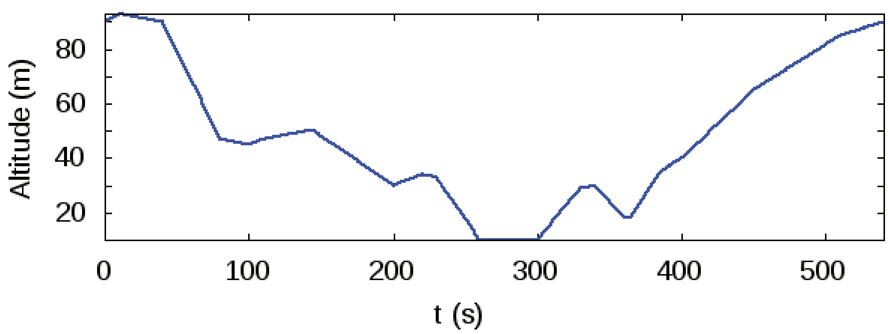

Figure 4. Terrain configuration

It is questionable if this is an appropriate system for electric vehicle simulation since it supposes quite strong accelerations which could be lighter in real driving. On the other hand, it ignores the road configuration for what concerns slopes. It is very important to highly optimize the electric vehicle according to the real conditions of use like the daily range, traffic velocity and terrain configuration [8], [9]. For the vehicles powered by the still relatively cheap gasoline such an optimization is less important. The need for additional range or power is easily solved with a greater fuel tank, which has a negligible influence of the whole vehicle mass or price. For an electric vehicle, the increase of the range requires the increase of the battery capacity, which has significant impact on the vehicle mass and price. It follows that is very important to optimize the components, especially the battery pack, according to the real usage conditions.

In order to obtain these real usage conditions, GPS devices can be used [8], [9]. In this work a real urban driving route has been analyzed, taking into account the terrain configuration, and it was compared to the before mentioned standardized driving cycles. The driving speed was obtained with a GPS device located in the car that was driving along a characteristic route. The GPS device stores data into a **.plt* file in which it writes down the latitude and the longitude (in decimal °), the altitude (in feet) and the time.

The calculation of the coordinates from the longitude and the latitude is done according to:

$$x = R_E \cdot \sin(\theta) \cdot \sin(\varphi) \tag{1}$$

$$y = R_E \cdot \sin(\theta) \cdot \cos(\theta) \tag{2}$$

where R_E=6371000 m is the average Earth radius.

The time interval between two recorded points is:

$$dt = t_n - t_{(n-1)} \tag{3}$$

The distance covered in the interval dt, between two successive points, is:

$$ds = \sqrt{\left(\left(x_n - x_{(n-1)}\right)^2 - \left(y_n - y_{(n-1)}\right)^2\right)} \tag{4}$$

The velocity is

$$v = \frac{ds}{dt} \; . \tag{5}$$

From the described analysis of the real driving cycle it follows the velocity diagram, Figure 3.

In the second part of the analysis it was supposed that the driving route passes over hills. For this purpose the route obtained with the GPS device was loaded into the Google Earth software and the exact altitude of the route was obtained, Figure 4. The route starts at the altitude of 90 m over the sea level and descends to 10 m after which rises again to 90m. In the final part of the route, between 400s and 540s the average slope is 6.5%.

3. MATEMATICAL MODEL OF THE ELECTRIC VEHICLE

The evaluation of the battery capacity starts with the calculation of the force needed to overcome the resistance to motion, the traction force [3], [13]. The traction force consists of the force of inertia, aerodynamic drag, rolling resistance and slope climbing force.

$$F_{tr} = m \cdot a + F_{aer} + F_{rol} + F_{sl} \tag{6}$$

where *m* is the vehicle mass. The aerodynamic drag is

$$F_{aer} = \frac{\rho}{2} \cdot A \cdot C_d \cdot v^2 \tag{7}$$

where ρ is the rolling resistance, *A* is the vehicle cross section, C_d is the coefficient of aerodynamic drag and *v* is the velocity. The force needed to overcome the rolling resistance is:

$$F_{rol} = m \cdot 0 \cdot \left(1 + \frac{v}{44}\right) \tag{8}$$

The force necessary for climbing hills is:

$$F_{sl} = m \cdot g \cdot \sin(\alpha) \tag{9}$$

where g is the gravitation acceleration and α is the angle of the slope.
The described forces are presented in Figure 5.
The driving torque necessary to overcome the traction force is

$$M = \frac{F_{tr} \cdot r_w}{i} \tag{10}$$

where r_w is the wheel radius and *i* is the transmission ratio of the gearbox.
The electrical power necessary to obtain this torque at a defined rotation speed *n* is:

$$P_{mot} = \frac{M \cdot \omega}{\eta_{mot}} \tag{11}$$

where the angular velocity is

$$\omega = 2 \cdot \pi \cdot n \,. \tag{12}$$

The rotation speed is obtained from the vehicle speed from the expression:

$$n = \frac{v \cdot i}{2 \cdot \pi \cdot r_w} \tag{13}$$

The efficiency of the electric motor is calculated according to the formula

$$\eta_{mot} = \frac{M \cdot \omega}{\left(M \cdot \omega + M^2 \cdot k_c + \omega \cdot k_i + \omega^3 \cdot k_w + C\right)} \tag{14}$$

where k_c is a coefficient of losses due to electric resistance in the coils and eventually brushes (copper losses), k_i is the coefficient of losses due to magnetization and eddy currents in iron parts of the motor (iron losses), k_w is the coefficient of losses due to friction in bearings of the motor and on the brushes and due to aerodynamic drag (windage losses) and C are the remaining losses.

In case of regenerative braking, when the motor is working as generator, the power of the generated current is:

$$P_{mot} = M \cdot \omega \cdot \eta_{mot} \,. \tag{15}$$

A good approximation of the open circuit voltage for a lead-acid battery is:

$$U = \left(2.15 - \left(\left(2.15 - 2\right) \cdot DoD\right)\right) \cdot N \tag{16}$$

where DoD is the depth of discharge and N is the number of cells in the battery. When the electric motor produces the power P_{mot}, the electric current is:

$$I = \frac{U - \sqrt{\left(U^2 - 4R \cdot P_{mot}\right)}}{\left(2 \cdot R\right)} \tag{17}$$

where R is the internal resistance.

When the regenerative breaking is performed, the battery recharging current is:

$$I = \frac{-U + \sqrt{\left(U^2 + 4R \cdot P_m\right)_c}}{\left(2 \cdot R\right)} \tag{18}$$

The effective energy that leaves the battery is dependent on the electric current and on the type of the battery:

$$E_{(b\ aotu)\ t} = I^k \cdot d \tag{19}$$

where k represents the Peukert coefficient, which for a lead-acid battery equals 1.2. More details on electric vehicle modelling can be found in [3], [4], [7] and [11].

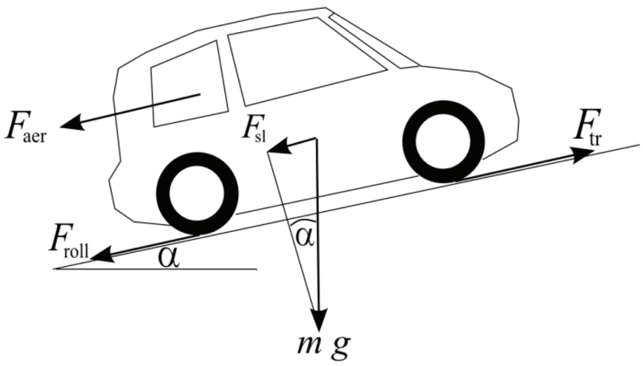

Figure 5. Forces acting on the vehicle in motion

4. RESULTS ANALISYS

Two computer programs were written in the Octave language. The first program calculates the velocity and the height in relation to time from the data extracted from the **.plt* file obtained with the GPS device. The second program calculates the electric energy consumption for given speed and height profile. The programs are written according to the mathematical model exposed in the previous section.

It was supposed the utilization of an average city car. The basic characteristics used in the calculation are presented in Table 1. The analysis was performed for two different car masses in order to evaluate the mass influence on the consumption. Further, it was performed the simulation for the vehicle without and with the regenerative breaking system. It allows the conversion of part of the kinetic energy into electric energy and its storing into the battery instead of its dissipation to the environment in the form of heat as it is done during the conventional breaking. It was supposed the regenerative breaking ratio of 0.7. This means that 70% of the breaking is done with the electric motor/generator, while 30% is done by classical breaks, which can not be completely replaced by regenerative breaking.

Table 1. Vehicle data

Vehicle parameter	
mass	m = 1000 kg / 700 kg
frontal section surface	$A = 1.7\ m^2$
coefficient of air resistance	$C_d = 0.32$
wheel radius	$r_w = 0.3$ m
transmission ratio	i = 6
transmission efficiency	$\eta = 0.97$
regenerative breaking ratio	RBR = 0.7

There were simulated 6 cases: the standard driving cycles ECE-15 and ECE-47, the real driving cycle obtained with the GPS device, Figure 3, with the assumption of flat terrain (GPS flat), the same data with the application of the real terrain configuration with slopes, Figure 4, (GPS hills), the same real driving cycle but with the presumption of the car mass of 700 kg instead of the 1000 kg of the other cases (GPS hills 700 kg), and finally the same real driving cycle with the use of the regenerative breaking system (GPS 70% regen).

For every case it was calculated the necessary electric motor power, rotation speed, motor efficiency, battery voltage, battery current and cumulative energy consumption according to the given equations, (6) - (19). It was calculated for the given velocity and height profiles.

In Figures 6 to 11 an example of time dependent simulation results is presented. It is the case of the 1000 kg vehicle with the 70% regeneration breaking system on the real road profile. The velocity and terrain profiles, as input parameters, are presented in Figures 3 and 4. In Figure 6 the electric energy power required by the electric motor is presented. It is somewhat greater then the power of the drag forces acting on the car body because the motor works with some losses. In the periods when the power is negative, the regenerative breaking is active and the motor operates as generator producing electric energy which is stored into batteries. In Figure 7 the motor rotation speed is showed. It is supposed a fixed gear ratio. Hence it can be noticed that the motor rotation velocity is proportional to the vehicle speed, Figure 3. In Figure 8 the motor efficiency is presented. It depends on the rotation velocity and on the torque according to expression (14). It can be observed that it is higher then 0.9 most of the time, and it drops considerably only for very low rotation speeds. Its lower value was limited in the calculation to 0.3, because lower values would result in high currents. In Figure 9 the battery voltage is presented, according to the expression (16). In the simulations it was used a lead-acid battery with 30 cells. In Figure 10 it is presented the electric current that leaves the battery. It is proportional to the motor power. When it is negative, it is the current generated due to regenerative breaking and it flows to the battery. In Figure 11 it is presented the cumulative energy that leaves the battery. The regenerative breaking has a relatively weak positive influence and it is barely noticed the decrease in charge removed level during the initial descent, which translates to the refilling of the battery. The reason for that is that it is a dynamic driving cycle with lot of accelerations. Even if there are also decelerations and descents, the efficiency of regenerative breaking is limited by various factors. The first is that the breaking can not be performed only with the electric motor due to safety reasons and reaction time. In the calculations it was taken that 70% of the breaking was done with the motor/generator. The motor/generator efficiency limits the regenerative breaking efficiency, equation (14). The current needed to recharge the battery is also greater than that released afterwards from the battery, equations (17) and (18).

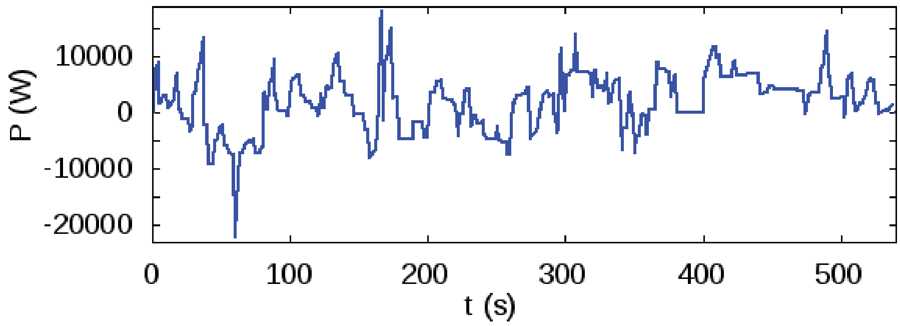

Figure 6. Electric motor power

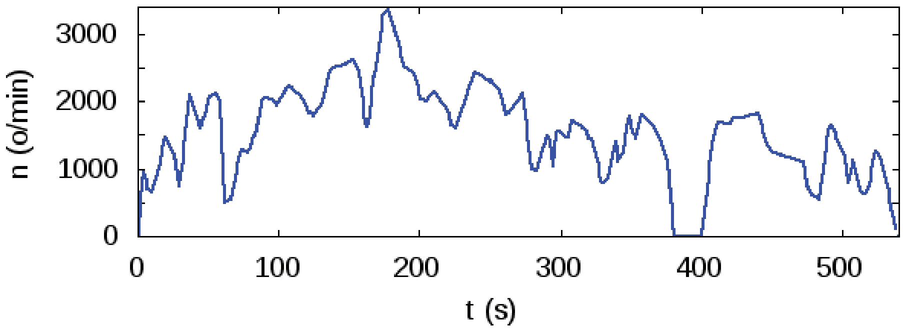

Figure 7. Electric motor rotation speed

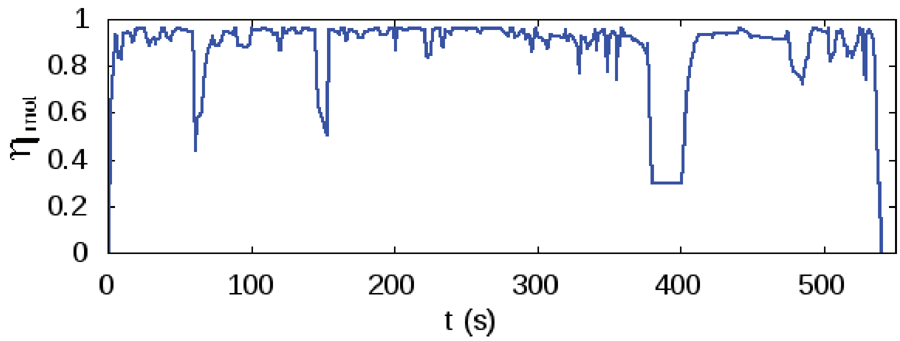

Figure 8. Electric motor efficiency

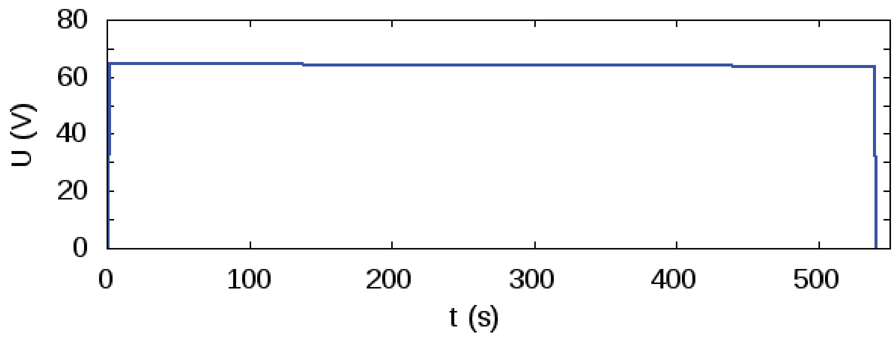

Figure 9. Battery voltage

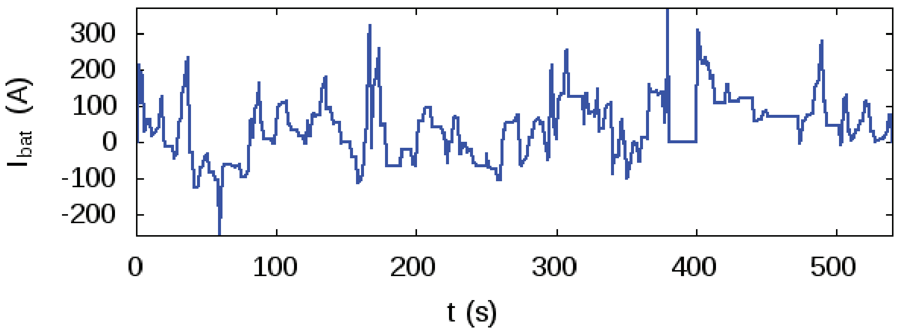

Figure 10. Current leaving battery

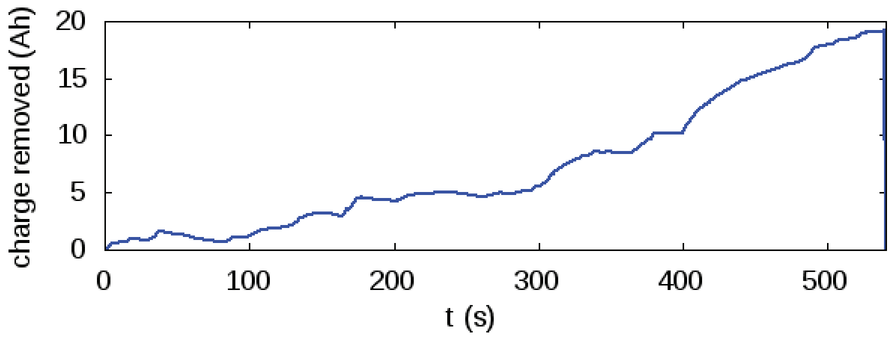

Figure 11. Cumulative charge removed from battery

Table 2. Simulation cases results summary

Denomination	**Distance (m)**	**Energy (Ah)**	**Specific consumption (Ah/km)**
ECE-15	1012.1	3.3107	3.27
ECE-47	961.46	2.9205	3.04
GPS flat	4372.8	13.529	3.09
GPS hills	4372.8	21.651	4.95
GPS hills 700kg	4372.8	13.785	3.15
GPS 70% regen	4372.8	19.155	4.38

In Table 2 the summary of all the simulated cases is reported. For every of these cases it was calculated the distance, energy consumed and the specific energy consumption. It can be noticed that the driving cycles ECE-15 and ECE-47 result with very similar distances and energy consumption, which results in similar specific energy consumption. The ECE-15 cycle is a slightly more dynamic and energy consuming case. The real driving cycle obtained with the GPS device (GPS flat) gave similar results, and it is placed between the two standard cycles according to specific consumption. This confirms that the standard driving cycles are correctly selected in order to simulate average urban driving conditions. However, the specific consumption can vary considerably due to different driving style and traffic conditions. Often a lower consumption is possible with careful driving if the traffic allows it.

The mentioned standard driving cycles are used for flat terrain and they neglect the influence of slopes. Its influence is highlighted with the case GPS hills. On the same distance and with same velocity profile as for the GPS flat case, 60% more energy is consumed in order to climb the hills. In the next case, GPS hills 700kg, it was estimated the influence of the vehicle mass on the specific energy consumption. For the vehicle mass reduction from 1000 to 700 kg (30%) the reduction in energy consumption on the same course was 21.651 Ah to 13.785 Ah (36%).

In the last case it was analyzed the influence of the regenerative breaking system on energy saving. This system is expected to be especially effective in terrains with hills. However, from Table 2 it can be seen that the efficiency of such a system is limited. In comparison to an equivalent case without the regenerative breaking system (GPS flat), 2.496 Ah less energy is consumed, which equals to a 12% reduction. The efficiency of such a system depends on the terrain configuration as well.

5. CONCLUSION

It was made a model and a computer program of an electric car that allows the evaluation of the electric energy consumption in real driving conditions. Two standard and 4 real driving cases were simulated. The input parameters for velocity and altitude for the real driving cycle were obtained with a GPS device.

The first conclusion that outcomes from the results is that the standard driving cycles are well chosen to simulate the average urban traffic conditions because the specific consumption obtained for the real, measured driving case is very similar. However, different driving style or traffic conditions would strongly influence the consumption.

The results of the simulation of the urban cycle on a hilly terrain confirm that slopes have a great influence which can not be neglected. Energy consumption increases by 60% on the same route compared to the cycle without slopes. On such a terrain the vehicle mass is essential. With a decrease of the vehicle mass by 30% it was achieved a reduction in energy consumption by 36% on the same route. It highlights the importance of weight saving. The use of light, high tech, expensive materials can translate to cost savings not only by reducing energy consumption, but also allowing a lower capacity and cheaper battery pack. Beside the vehicle body materials, a more expensive, but high specific capacity battery can be convenient on such a terrain due to its lower mass. Particularly Li-ion and Li-polymer batteries showed good performances regarding energy density and power density [1], [5].

On the other hand, regenerative breaking showed relatively smaller benefits for the decreasing of the energy consumption. The reason for that is that it is impossible to store all the breaking energy into batteries because all the elements of the chain (engine, controller, recharging battery) work with a limited efficiency. However, the modern controllers allow this function without a substantial price increase so it is obvious to take advantage of this feature. Beside energy saving, the regenerative braking function removes part of the load from the standard breaking system, which has benefits for its maintenance costs. The regenerative breaking benefits are highly dependent on the terrain configuration. For instance, if the route starts with a descent, the energy obtained from breaking can not be saved since the batteries are full at the start.

Careful modelling and optimisation is very important in order to obtain also financial benefits from electric vehicles usage. One of the main optimisation parameters is the driving route and dynamics, which has to be studied in advance.

For further work it would be necessary to gain experience with a real electric vehicles on which experimental measurements would be performed. This way a greater precision and credibility of the numerical simulations could be achieved.

Electric vehicles have their specificities. They have various advantages such as silent operation, no gas emissions in cities and low maintenance costs. They have also some disadvantages which are mostly related to the battery system. In first order it is a limited range and big recharging duration. However, with a good optimization of the vehicle, its propulsion system, sometimes of the user's habits too, it is possible to achieve financial benefits in certain circumstances in comparison to internal combustion engine.

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MODELIRANJE ELEKTRIČNIH VOZILA ZA KONKRETNE PRIMJENE

Sažetak: Električna vozila se spominju kao dio rješenja problema suvremenog društva kao što su zagađenje zraka, klimatske promjene, smog i buka u urbanim središtima, ograničene rezerve fosilnih goriva i njihova cijena u porastu. Ipak postoji niz nedostataka koji donekle sprečava njihovu široku primjenu. U prvom redu to su visoka cijena i masa, odnosno mali kapacitet baterija.U članku je iznesen proračun i analiza koji omogućuju procjenu mogućnosti korištenja baterija manjeg kapaciteta, a samim time i manje mase i cijene, a koje bi zadovoljile potrebe velike većine korisnika koji koriste vozilo na kraćim gradskim relacijama. U prvom dijelu je izvršena usporedba standardnih ciklusa vožnje sa realnim dionicama odvoženim po Rijeci. Realni podaci su prikupljeni GPS prijemnikom, te je proračunata brzina i uspon u vožnji. S tim podacima je izračunat potreban utrošak energije za pogon vozila različitih karakteristika: veće ili manje mase, sa ili bez sustava regenerativnog kočenja te je procjenjen utjecaj uspona i nizbrdica na radius vozila.

Ključne riječi: elekrična vozila, simulacija potrošnje energije

THE EVALUATION OF BENEFITS AND LIMITATIONS OF USING ELECTRIC VEHICLES IN URBAN AND SUBURBAN AREA OF THE CITY OF RIJEKA

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Abstract: *In this paper we present the results of two conversions of petrol driven cars into electrical vehicle (EV). The conversion was recently performed by the members of the Green Technologies Association, Rijeka. We present the analysis of performances, installed components, work required, related costs as well as technical characteristics of converted vehicles. Financial aspects of the conversions are also discussed together with the return on investment. At the same time, a brief history and present trends of EVs' is given together with the EU governments incentives and perspectives of the further development. The advantages and drawbacks of the electric propulsion are emphasized and compared with market ready competitive technologies. Furthermore, the authors are discussing various aspects of use of electric vehicles in the wider area of the city of Rijeka which is a very specific micro region in terms of terrain configuration. Current sociological, climatological and economical indicators and trends are presented. The air pollution caused by the use of the internal combustion engines in the city of Rijeka is discussed as well.*

Key words: Electric vehicles; Prototype analysis; Alternative fuels history

1 INTRODUCTION

The electric vehicle (EV) is electricity driven vehicle that uses one or more electric motors for propulsion. Typically, three main types of EVs are distinguished: those directly powered from an external power station, those that are powered by stored electricity generated at an external power source, and those that are powered by an on-board electrical generator (hybrid electric vehicle, HEV) or a hydrogen fuel cell. [1, p. 227]
Electric vehicles had their days of glory at the turn from 19th to 20th century. At that time internal combustion engines (ICE) were in their early stages of development. The relatively shy return of EVs occurring during the last twenty years can be directly correlated with fuel shortages and rise of oil prices, but also with the rise of environmental awareness. Modern electric cars are quite competitive regarding the range, driving performances and costs.
The aim of this article is to briefly summarize the history of electric vehicles, to present the current situation and perspectives, to discuss suitability of using EVs in the wider region of the city of Rijeka (Croatia) and to present the performances of two battery electric vehicles (BEV) conversions performed by the Green Technologies Association in Rijeka (GTA).

2 ELECTRIC VEHICLES – HISTORICAL TRENDS AND PERSPECTIVES

2.1 History of electric vehicles

The history of electric vehicles is full of ups and downs. It is closely related to the history of batteries, and in general to the development of efficiency of electric motors. Upon the findings of Italians Alessandro Volta and Luigi Galvani, in 1821 the Briton Michael Faraday demonstrated the principles of electric motor (generator). [2, p. 63] In 1827 Hungarian Ányos Jedlik started experimenting with DC motors and created the first model of electric car. [3]
In the mid-1830s appeared first experimental light-weight EVs in USA, UK and the Netherlands. Those were the years when British Empire abolished the slavery, Texas split from Mexico in perturbations (Alamo) leading to American Civil War, Egypt and Turkey fought in war, and Charles Darwin was cruising around the world developing his evolution theory.
In 1859 the Belgian Gaston Planté demonstrated the first lead-acid battery cell. This was a long waited break-through that furthered the progress of electric cars. In 1881 French Gustave Trouvé presented the first usable EV. It was a tricycle applying the Planté's lead battery as a power source. During early 1880s other similar electric tricycles with lead batteries were also demonstrated in the USA and UK. It is worth remembering that in 1885 the German Benz demonstrated the first ICE vehicle.
Next few decades become the most intensive period in electric car deployment. That was the golden age of electric mobility that lasted on to around early 1920s. Most major technological inventions were achieved in this period and electric cars have never again experienced any similar prosperous age of technological development and deployment. Few of those inventions deserve to be mentioned here:

- the principle of regenerative braking which became standard feature in every modern EV (presented for the first time in Paris in 1887),
- the New Yorker coin-operated mechanism system of recharging with both voltmeter and wattmeter (around 1900),
- electric cars with easily interchangeable battery systems developed to overcome the range limits,
- followed by fast battery swapping system with batteries on rollers and
- hybrid engines (around 1900), to mention just a few.

One of the main preoccupations at that time, as it is today, was the fast charging of the batteries. [2, p. 64] All these innovations presented a challege for individuals and teams that were trying to break different records. The most notable example are the speed races where Belgian Camille Jenatzy was the most successful. He broke the competitors' records three times in one year and was the first man speeding at over 100 km/h. Actually his record equaled 105,9 km/h. Jenatzy achieved this record in 1899 with the electric car named "Jamais Contente" (Engl. "The Never Satisfied").
Commercial fleets looking to achieve new applications readily accepted electric cars. By the end of 19th century thriving taxi companies with electric cars were set up in London (15 cars), New York (13 cars) and Paris. [2, p. 64]
At the turn of the century three types of cars were contesting for market control. Those were: the electric, the steam engine and the gasoline ICE car. In 1903 there were around 4.000 registered motor vehicles in New York: 53% were steam-powered, 27% gasoline ICEs, and 20% electricity driven. In the USA the peak volume of electric cars was reached in 1912, counting around 30.000 vehicles altogether. But since 1909 the Ford-T was on its way to achieve market dominance. Despite the noisiness and unpleasant exhaust fumes, the ICE cars had desirable advantage – the range was greater, the cost was lower and refueling time was

almost equal to zero, compared to the time necessary to refill electric car batteries. The crucial moment to foster the wider acceptance of ICE cars was the invention of electric starter built into most ICE cars after 1913.
During the First World War EVs still constituted a thriving industry. There were two crucial conditions to war peak in production and use: the gasoline shortage and the requisitioning of ICE vehicles to take part in the war operations, and an extensive development of new electric power plants. By the end of the First World War, the USA alone had an estimated 50,000 EVs on the road.
After the war expectations were high. However, expectations faded soon and EVs lost ground to the fossil fuel ICE vehicles. Some companies continued the production of electric cars throughout 1920s, but decreasing sales, the stock market crash in 1929 and the international economic depression left most of the companies bankrupt.
It was not until the Second World War that electric car production resumed again. Again there was a wartime peak, caused by oil shortage so the priority was given to warfront use of fossil fuels.
The public debates in the 1960s were focused on environmental pollution problems and the ICE private cars were identified as one of the largest contributors to air pollution in cities. The electric car was presented as an acceptable solution. [2, p. 66] During the 1960s and 1970s most major car producers were involved in research and development activities (R&D) regarding drive systems and battery types for electric cars. But those prototypes never got commercialized.
In 1990 California introduced their first zero-emission regulations, what enforced new initiatives in development of EVs. Hybrid drive regained attention and all major car producers restarted investing in development of this sector. Historically, the 1990s was the most intensive period in relation to both electric and hybrid car R&D. [2, p. 70] Up to date HEVs have been sold in more than 1,5 million examples worldwide. [4, p. 165]

2.2 Current situation and perspectives of electric vehicles

It is estimated that today there are around 1 billion cars rolling worldwide. The automotive industry is one of the largest economic forces, employing nearly 10 million people and generating a value chain exceeding $3 trillion per year [5]. Continuous more-than-hundred-years development of ICEs improved their efficiency, reduced emissions and prices. Reducing CO_2 emissions in transport happens to be one of today's major challenges for the entire automotive industry. However, the increasing demand for personal mobility and total dependence on oil make this goal particularly difficult for carrying it out. [6] Yang reports that the Chinese government announced the aim of becoming the world's largest producer of electric cars [7, p. 834], but the road of fulfilling this goal is a bit bumpy.
During the last 20 years there have been around 450 EV prototypes developed by car manufacturers. Until 2004 the R&D activities were mostly initiated by large vehicle manufacturers. Since 2004 a number of startups are looking for their fortune in EV industry. This substantially pushed the growth of R&D activities. In 2003 there was only one company working on EVs, and in 2011 there were 76, only quarter of which could be categorized as large vehicles producers. Apparently, the automobile industry currently finds itself in the so-called era of ferment, in which the more or less stable and fixed regime of ICE vehicles producers becomes threatened by new technologies and new manufacturers. [8]
What is holding the EV technology of becoming the buyer's first choice? Electrical drive has its pros and cons. Discussing them brings to better understanding of successfulness of

application in transport, and of effectiveness of reducing transportation sector impact on climate change.

Advantages:

- EVs have no exhaust fumes from tailpipe and bearing in mind that the largest application is expected in urban areas, EVs do not contribute to local air pollution.
- The electricity for EVs is produced in large-scale power plants, where needed power is produced with much higher energy efficiency (EE) and much lower pollution rate compared to ICE vehicles. That way environmental pollution is significantly lower per energy unit produced, and if electricity is produced from renewable energy sources (RES), environmental pollution equals practically to zero.
- EVs are way more energy efficient than ICE vehicles; i.e. 60% vs. 20%, respectively (conventional values).
- The regenerative braking partly converts accumulated kinetic energy back to recharge the batteries. This lengthens the driving range (included in the previously mentioned average of 60% of overall efficiency).
- Noise pollution is lowered to greater extent since the EVs are much quieter in comparison to conventional vehicles.
- Maintenance costs are significantly reduced since there is no regular servicing required (oil change, fuel filter, spark plug etc.).
- Energy costs per km are around 90% lower because electricity has currently much lower price per energy unit than fossil fuels.
- In most of the highly industrialized countries it is possible to receive abundant incentives for choosing electric or hybrid cars instead of the fossil fuel drive.

Disadvantages:

- The current initial costs of EVs are notably higher than of similar sized ICE vehicles, and this is mainly due to high battery prices.
- Driving range is limited by battery capacity and can hardly be compared to ICE vehicles range what causes the range anxiety by the potential buyers. [9] Other influences affecting the driving range include driving style and the use of inbuilt electrical components and equipment.
- Recharging infrastructure is still scarce, which doesn't foster longer journeys.
- Although recharging period can last more than 8 hours, fast rechargers can refill the battery in around half an hour. However, ICE vehicles get their tanks refueled in several minutes.
- The absence of noise is considered to be an advantage, but bikers and pedestrians are partly used to rely on car noise when interacting with traffic.

The mentioned incentives are the result of policies striving to reduce greenhouse gases and to increase energy efficiency. Developed countries governments are passing laws that require car makers to produce vehicles with lower emissions levels. The EU calls for a gradual lowering of manufacturers' fleet average CO_2 emissions towards 130 g/km in 2015, and for 2020 the target is set at 95 g/km. [10, p. 51] Forms of incentives vary substantially, from new car invoice subsidy (in Spain up to 6.000 Eur), over various tax and registration exemptions, all the way to free recharging, free parking and no congestion fees when entering the city with EV (e.g. 8 Ł exemption per day in London, UK). [11]
It is interesting to note that during the Second World War German authorities very actively promoted the use of EVs by making them tax-exempt. At the same time British authorities also wanted to enhance the use of EVs and made strong marketing campaigns in which the

advantages of electric driving were strongly emphasized, very similar to the advertising campaigns shown some thirty years earlier. [2, p. 65]
Roughly looking at countries with incentives for EVs and dispersion of all types of EVs, brings to conclusion that people still need to be subsided to give preference to EV when buying a car. [7, p. 832]. However, the experience from China and Taiwan regarding the advocacy of using electric bikes and electric scooters instead of ICE motorcycles suggests that subsidies alone may not be a sufficient launching strategy and that much better results in commercialization of EVs would be achieved by combining incentives with posing limitations to fossil-fueled alternatives. [7, p. 831]
Hidrue and colleagues researched the willingness to pay for EVs in the USA and found out that the most important individual EV attributes are (in order): range, charging time, performance, and pollution reduction. They also discovered that potential buyers are willing to pay \$35 – \$75 per mile (20,5 – 46,6 Eur per km) of added driving range and \$425 – \$3.250 (264,1 – 2.019,5 Eur) per hour reduction in charging time (for a 50 mile or 80,5 km charge). [12, p. 701] The Lieven's team study results from Germany show that the cruising range is important for the first car in the family, while for the second car that is of considerably lower importance. Price is important for almost all uses and types of EV cars, except for sports cars where performance is most important. [13, p. 238] Considering demographical characteristics, the most ready to purchase an EV are young males living a green life style, who have a place for an EV outlet at home, expect gas prices to rise, tend toward smaller petrol cars and have frequent long drives. Frequent long drives was a surprise but may be explained by respondents' motivation for fuel cost savings. [12, p. 701]
Discussing technology of energy storage system in BEV, it should be emphasized the wideness of technology array being currently researched. The two main battery types used in BEVs are nickel metal hydride (NiMH) and lithium-ion (Li-ion) batteries, with lead-acid batteries constantly used in modest share. During the 1990s, the majority of the models used either lead-acid or nickel-based batteries. Lithium-cobalt batteries appeared in 1995 with lithium-manganese batteries following in 1999, but these were unreliable because of being unstable. [6]
NiMH batteries were the flagship technology during the 1990s. Currently they are used as secondary energy source in over 95% of all HEVs, where they are used in conjunction with the ICEs. Major car manufacturers have so far invested substantially in this technology during the last 10 years. The major advantage from a manufacturing point of view is their safety compared to Li-ion batteries (so far no incidents have been reported in the press). [6]
Lithium-ion batteries are mostly used as primary energy sources. They are light, compact, store more energy than NiMH and operate with cell voltage of ~4 V. Drawbacks are that their cost is notably higher and that they can be considered unsafe (although kinetically stable in practice, thermodynamically they are unstable). EV manufacturers have determined that lithium batteries represent the best option for EVs to be competitive in the automobile industry. [6]
For the past few years the new generation of lithium batteries is emerging: so called iron phosphate batteries ($LiFePO_4$). The $LiFePO_4$ battery technology is closely related to other lithium chemistry batteries so they share many characteristics. However, lithium iron phosphate technology has longer life cycle and is much safer (thermal and chemical stability).
It was mentioned that BEVs and HEVs don't use same batteries. The reason for this is the fact that the BEV battery pack has high specific energy, while the HEV battery pack has the high specific power intended for the short periods of time usage (e.g. during maximum acceleration).
Fuel cell electric vehicles (FCEVs) are closely related to BEVs. The drive train is practically the same, having the major difference in main energy source – hydrogen. Fuel cells are

superior to batteries, especially in weight and volume, they can produce electricity as long as the hydrogen is supplied, and have the potential for high reliability and low manufacturing costs. The main drawbacks are in the fuel – hydrogen production, its availability and price. Current fuel cell systems are estimated to be about five times more expensive then ICEs. Generally, BEVs are more suitable for short range and small vehicles, while the FCEVs are more suitable for long ranges and medium and large vehicles. Both technologies could be expected to coexist in the future. [6]
There are numerous researches of other technologies for energy storing (e.g. capacitors, lithium-air) what should lead to better energy density, safety and price reductions.
Høyer is not very optimistic regarding the bright future of pure electric cars. In his conclusions he refers to "The biofuel directive" (EU COM, 2001) and envisions the hybrid electric vehicles as main technology in next transport technology era. [2, p. 70] Sierzchula and colleagues conclude that EVs commercialization is to happen first in niche markets, especially in specialty vehicles such as low speed vehicles and in expensive sport cars. [8, p. 62] Currently commercialized EVs are still offered in small production series, and these are not likely to be profitable in the short term.

3 CHARACTERISTICS OF RIJEKA REGION, CROATIA

3.1 Social, geographical and climatological characteristics

Located in north-west part of Croatian coast, Rijeka used to be a thriving industry city and port, where at the beginning of 20th century was located around half of total Croatian economy. Today Rijeka is regional administrative, health, university, cultural, financial and transport hub with manufacturing industry in modest share. It is the main sea-port in Croatia and 3rd largest city in Croatia. The GDP p/c in Primorsko-goranska County (the region surrounding Rijeka) in 2008 was 12.680 Eur. This was 18,7% above the national level. [14] According to 2011 census, in closer urban area of Rijeka city lived 128.735 people, what is about 10% less then it was registered in 2001 (144.043 people). [15] Recent data show that in May 2012 there were 12.435 registered unemployed persons. [16] In 2010 more than 10% of inhabitants participated in various forms of City of Rijeka social assistance program (13.249 persons). [15] University of Rijeka with over 19.000 students is considered as large university in Croatian terms. [17]
The terrain configuration of populated wider urban and suburban region is characterized by steep hills rising from sea level up to the altitude of around 200 meters above the sea level. Further on, the city itself is from three sides surrounded by mountains and from the southern side by the sea. This combination gives to this region a very specific climatic and landscape characteristics.
The climate of the Rijeka city region, according to Köppen's classification, has characteristics of mildly warm humid sub-Mediterranean climate with hot summers (Cfa class). [18, p. 32] There are approximately 1.920 hours of sunshine per year. Temperatures below zero are rare, and so is the snow, which doesn't occur more than 3 days per winter and almost always remains just in traces. Due to the terrain configuration Rijeka has frequent rainfalls during the winter. Strong and cold wind *bura* (bora) occurs mostly in wintertime. Table 1 presents selected indicative climatological data for Rijeka.

Table 1. Indicative climatological data for Rijeka

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average high, °C	8,7	9,5	12,4	16,1	20,9	24,6	27,7	27,6	23,6	18,6	13,4	10,0	**17,76**
Average low, °C	2,7	3,2	5,5	8,8	12,0	16,2	18,6	18,5	15,3	11,1	7,1	4,1	**10,26**
Avg. precipitation, mm	134,9	114,3	104	110,7	102,4	110,8	82	100,2	165,3	175,7	183,4	154,2	**Σ= 1.537,9**
Avg. No of rainy days	11,0	9,4	10,2	11,6	12,3	11,9	9,1	9,2	9,8	10,9	12,4	11,6	**Σ= 129,4**

Source: World Meteorological Organization [19]

Occasionally, air pollution in the city of Rijeka reaches the 3rd (the worst) grade of air quality. [20, p. 25] In the city centre air pollution from traffic is dominant and it is most notable at the Mlaka locality. In wintertime situation gets aggravated because of the use of oil in many central heating boilers. Almost every major road in Rijeka feels the consequences of traffic generated air pollution. Other significant pollutants are oil refinery, thermoelectric power plant (both in Urinj locality in eastern suburb), and the port.

3.2 Appropriateness of using electric vehicles in Rijeka urban and suburban areas

Described mild weather conditions do not pose important threat to EVs battery capacity during the wintertime. But the hilly geographical characteristic of the terrain is not the win-win solution for electric car owners because of compromised driving range. Hybrid cars seem to be better, although more costly solution. However, if aiming at the reduction of air pollution from fossil fuels combustion in ICE vehicles in populated areas, regional and local public administration should provide incentives for EV and hybrid purchases. In 2010 there were 4.695 marked parking places in the city and up to date there are no parking spots with charging possibilities for EVs. [15]

When it comes to commercial vehicles, it is important to remember that trams and trolleybuses used to operate in the city of Rijeka. While trams belong to distant first decades of 20th century, trolleybuses are still remembered by many citizens. In time interval 1952 – 1969 Rijeka exploited trolleybuses on two diametric lines connecting eastern and western city suburbs. Although citizens objected the withdrawal of trolleybuses for the reasons of ecology, in the time of cheap oil diesel buses were more cost-effective. During almost 18 years of service trolleybuses run over 22,5 millions of km and commuted more than 260 millions of passengers. [21] For comparison, in 2010 all urban and suburban buses run 9,7 million km commuting 40,9 million passengers. [15] In 2006 the remaining supporting pillars for electrical installations for trolleybuses were cut down, what can be understood also as sign of not willingness to reintroduce trolleybus lines.

Trolleybuses have many advantages over the diesel buses. For example, on hilly routes their electric motors are more effective in providing torque at start-up. There is no noise and no exhaustion fumes throughout the city centre, plus the fact that the power comes from central plant and that the electro-motor can be overloaded for short periods without damages. Given their acceleration and braking performance, trolleybuses can outperform diesel buses also on flat routes.

Recently Siemens engineers announced to have developed and starting to conduct pilot project – the eHighway concept. Basically, the project consists of electrification of trucks and selected highway lanes via overhead electrified wires similar to trolleybus or tram lines. The trucks are hybrids, designed to automatically switch either to electric mode (when being attached to the overhead lines) or to diesel (once having left the electric lines). [22] It can be expected to see similar projects for urban application quite soon.

4 CASE STUY – THE RESULTS OF PERFORMED EV CONVERSIONS

The Green Technologies Association (GTA) is a cluster established by the initiative of one of the authors of this paper (I.O.). GTA is established during the summer of 2011 in Rijeka with the aim of research, development, promotion and application of green technologies. Prof. Orlić is currently the president of the GTA, and members of the cluster are scientists from the University of Rijeka and the entrepreneurs from Primorsko-goranska and Istarska counties. Currently there are several projects running in different stages of progress and electric car conversion is the first completed project, followed by the EV charging station at one shopping mall in Zagreb. Members of association are actively advocating green technologies, mostly through presentations and consultancies.

At the late spring this year it was agreed with two car owners to convert their ICE cars to EVs, i.e. Renault Clio and Daewo Matiz. The owners aspire towards living the green life style and have the possibility to invest in EVs. In Table 2 are presented general data before and after the conversion.

Generally, the BEV drive train consists of three major subsystems [6]:

- electric motor propulsion system: electric motor and transmission, controller and power converter;
- battery system – batteries, battery management system (BMS) and charging unit,
- auxiliary system – heating/cooling, electronic pumps and other electronic auxiliaries.

The motor can also act as a generator, converting the braking energy to the useful electricity for charging the batteries.

The conversion of cars from ICE to electric drive included the removal of ICE, exhaust system and fuel reservoir and installation of new electric components. The required new components are typically: electric motor, batteries and batteries management system, battery charger, electric motor controller, DC/DC converter for auxiliary systems, electric gas pedal and other smaller electronic components (contactor, fuses, wires, gauges, electric heater).

In our case the selected electric motor (Agni 95R DC PM motor) that replaced the ICE has lower available peak power totaling 36 kW (72 V x 500 A). The original ICE in Daewoo Matiz had 38 kW of peak power, while the Renault Clio ICE had the peak of 55 kW. Installed electric motor has more torque in whole revolution range, so acceleration and uphill performance won't be affected. In fact, e-Matiz can run better than the ICE version, while Clio remained almost at the same level or slightly slower, with lower maximum speed.

Although alternating current (AC) motors have more advantages than DC motors, in our specific case the selected Agni DC permanent magnet motor had more benefits. First benefit is the system cost – motor and dedicated controller are far more affordable than the similar AC motor and controller. Also Agni motor is very light, having only 11 kg, and has only 18 cm diameter, which leaves more space under the hood for batteries.

To simplify homologation formalities the gearbox was not removed and no structural changes were introduced. The gearbox is fully functional and it's best application is in driving uphills , thus avoiding overheating of the motor and controller. However, the main drawback of using the gearbox is energy loss. It is estimated that gearbox will introduce 10% to 30% of energy loss, depending on driving conditions.

All auxiliary systems, such as ventilation, electric windows, and all equipment running on 12V, was left untouched, but other systems which use ICE to run, such as servo brakes and servo steering, required adding vacuum pumps.

Table 2. Comparative data of converted cars

	Renault Clio	Daewo Matiz
Year of production	2003	1999
Total chilometers driven	173.550 km	100.025 km
Body style	3 door	5 door
Drive	front	front
Electronics	air-condition, front windows openers, ABS, servo steering	air-condition, front windows openers, ABS, servo steering
DATA BEFORE CONVERSION		
Engine type and volume	petrol, 1.2 litres	petrol, 0.8 litres
Engine weight	170 kg	150 kg
Engine power	55 kW	38 kW
Torque	105 / 4250 N*m	69 / 4600 N*m
Weight of empty car	985 kg	835 kg
Nominal consumption, combined	6,0 l/100 km	6,1 l/100 km
Experienced average consumption	5,9 l/100 km	6,2 l/100 km
Nominal acceleration, 0-100 km/h	13 s	18,5 s
Nominal highest speed	170 km/h	144 km/h
DATA AFTER CONVERSION		
Electrical engine types and characteristics	Agni 95r; DC, 78V, 16 kW	Agni 95r; DC, 78V, 16 kW
Electric engine torque (manufacturer data)	70 / 0-5.000 N*m	70 / 0-5.000 N*m
Electrical engine weight	11 kg	11 kg
Batteries types	Sinopoly; SP-LFP100AHA, LiFePo4	Winston; WB-LYP160AHA, LiFePo4
No. of batteries	24	24
Total weight of batteries	81,6 kg	139,2 kg
Expected batteries lifecycle (recharging at DOD 80%)	2.000 cycles, cca. 10 years	2.000 cycles, cca. 10 years
Batteries charger	ATIB; HFK 72V/35A	ATIB; HFK 72V/35A
Controller	Kelly; KDZ72551, 24V-72V, 550A, PM with Regeneration	Kelly; KDZ72551, 24V-72V, 550A, PM with Regeneration
Converter	Kelly; KDCC Series DC/DC, 72V to 13.5V, 300W, 25A	Kelly; KDCC Series DC/DC, 72V to 13.5V, 300W, 25A
Average driving range	60 km	100 km

It is useful to notice that the Daewo Matiz owner has autonomous photo-voltaic (PV) system with peak power of 2.000 W which will be used for recharging the car batteries as well as for electricity production for home use. In this way the owner will be fully independent from the grid and electricity rising prices.

The average final price of our conversion is 9.300 Eur. The profit is barely achieved, but it was neither intended to. Table 3 presents the total costs average brake-down.

Table 3. The brake-down of the average conversion costs (VAT included).

DESCRIPTION	COST, Eur	SHARE
Electric engine	1.000	10,8%
Batteries	3.460	37,2%
Batteries charger	595	6,4%
Controller	370	4,0%
Converter	120	1,3%
Contactor	60	0,6%
Various smaller parts and nonspecified costs	505	5,4%
Work of mechanic	600	6,5%
Total banking	40	0,4%
Total shipping & forwarding	240	2,6%
Total customs	160	1,7%
Total Value Added Tax (V.A.T.)	2.150	23,1%
TOTAL	9.300	100%

The presented cost split (Table 3) reflects the true market situation of late spring 2012, but it cannot be completely relied on because of exchange rates, regular changes in prices, volume order discounts and the fact that some components were bought in Croatia (chargers and smaller parts such as pumps and cables), while others were imported. The presented final cost does not include hundreds of hours spent by the members of GTA.

As expected, batteries are the most expensive components of EV. It is interesting, but also indicative to note that in total costs components count in 65,7%, work of mechanic which also includes the study required for homologation purposes counts in 6,5%, banking, shipping and forwarding services count in 3,0%, while state impostures total in quite high 24,8%. The Croatian government is obviously slow in introducing EV incentives as compared to other EU countries.

Table 4. Calculation of conversion profitability

	Petrol BMB EURO BS 98+ CLASS (INA)		Electricity, 2-tariff home model (HEP) vs. private photovoltaic system		
	Renault Clio	Daewo Matiz	Renault Clio	Daewo Matiz	
Average energy consumpt., litres vs. kWh	5,9	6,2	13,0	12,0	per 100 km
Energy price, per litre vs. per kWh	1,38		0,09	0,01	Eur
Date of energy price	28.6.2012				
Electric energy, higher tariff			0,15		Eur
Electric energy, lower tariff			0,07		Eur
Share of lower tariff in total recharging time from public network			75%	67%	
Share of own electricity production in total recharging time				90%	
Average cost of energy per 100 km	8,12	8,53	1,22	0,12	Eur
Average driven path in one year	12.000	18.000	12.000	18.000	km
Total energy cost per year	**974**	**1.536**	**146**	**22**	**Eur**
Maintenance and various costs	100	100	30	30	Eur
Motor lubricant	75	75			Eur
Regular service and control					Eur
Technical examination	50	50	50	50	Eur
Regular liability insurance	293	293	243	243	Eur
Environment fee (Ministry)	10	10	2	2	Eur
Usage of public roads (County)	50	50	50	50	Eur
Impostures (County)	27	27	27	27	Eur
Total nonenergy costs per year	**604**	**604**	**401**	**401**	**Eur**
Total cost per year	**1.579**	**2.140**	**548**	**423**	**Eur**

In the Table 4 compared are various components of costs before and after conversion. The costs are split to direct energy costs (related to mileage), and costs of owning a car (not related to mileage).

Apparently, total costs of owning and driving an electric car are 2,9 (Clio) to 5,1 (Matiz) times lower than in pre-conversion condition. This implies the reduction of cost by 65% and 80%, respectively. Such a high ratio achieved by Matiz is the result of using solar PV system.

Closer look at the energy costs shows that before conversion Renault Clio owner used to spend approximately 8,1 Eur per 100 km. After the conversion energy cost is only 1,2 Eur/100 km – this represents significant cost cut of 85%.

On the other hand, the fuel cost for Daewo Matiz was 8,5 Eur/100 km. The energy cost for the converted car is now only 0,1 Eur/100 km! This is due to the use of the above-mentioned owner's private PV system which reduces the energy costs by impressive 99%.

The total yearly savings achieved with Clio account to approximately 1.031 Eur, while the Matiz offers similar but more lucrative 1.717 Eur (driving and owning combined). Confronting these data with total conversion prices, the return of investment period for Renault Clio equals 8,2 years, while Daewo Matiz will recover the investment in 5,9 years. Although these periods are to certain extent acceptable, lifecycle savings should be notable within 2,5 years to be attractive to buyers. [25] Of course, with the rising oil prices and incentives for EVs and HEVs the return on investment periods are expected to be shorter.

5 CONCLUSION

Two ICE to EV conversions were successfully performed by the Green Technologies Association in Rijeka during the summer 2012. Small private cars (Renault Clio and Daewo Matiz) were aimed to the range of 60 and 100 km, respectively. The return of investment is expected in approximately 5-8 years, but it will probably be much shorter due to the rising oil prices. In the mean time, the owners will enjoy the benefits of the very low energy cost of only 2-15% comparing to the former gasoline costs.

Currently, our estimate is that the total number of BEVs in Croatia is below ten. However, the Ministry of Environmental and Nature Protection is working on incentives to foster the conversions and purchase of new EVs and HEVs. Their activities are in accordance with EU directives and „20-20-20 goals". New initiatives for recharging stations are announced as well, so we hope that these incentives will soon encourage more car owners to convert their ICE to EVs.

Huge R&D efforts are invested into the improvement of battery technologies so the significant price reductions could be expected within next few years. This should lead to better market acceptance of EVs and in strengthening entrepreneurial initiatives in the field of converting ICE cars, but also in developing and producing new types and brands. Almost every major car manufacturer is developing EVs, and some of them are already on the market. Soon there could be expected a surge of EVs (BEVs and HEVs) on the road, what will gradually regain the characteristics of mainstream propulsion technology. The time of electric vehicles and hybrid electric vehicles is coming.

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EVALUACIJA PREDNOSTI I NEDOSTATAKA KORIŠTENJA ELEKTRIČNIH VOZILA U URBANOM I SUBURBANOM PODRUČJU GRADA RIJEKE

Sažetak: *Članovi Udruge zelenih tehnologija konvertirali su dva automobila s klasičnog pogona na fosilna goriva, u automobil na električni pogon. U ovom radu predstavljene su karakteristike novih e-vozila i dat kompletan pregled ugrađenih kompomponenti, radova i povezanih troškova uz izračun isplativosti investicije.*
Također, u ovom radu pregledno je prikazana povijest razvoja električnih vozila, tehnološki dosezi i trendovi prisutni u industriji e-vozila te adekvatnost poticanja i perspektive daljnjeg razvoja. Istaknute su prednosti i mane električnog pogona.
U nastavku rada teorijski se analiziraju aspekti korištenja električnih vozila na širem području grada Rijeke kao modela mikroregije specifičnog reljefa. Dan je prikaz trenutnog stanja odabranih socioloških, klimatoloških i ekonomskih pokazatelja i trendova. Posebno su istaknute vrijednosti onečišćenja zraka u gradu Rijeci uzrokovane korištenjem motora s unutrašnjim sagorijevanjem.

Ključne riječi: Električna vozila; Analiza prototipa; Povijest alternativnih goriva

OBNOVLJIVI IZVORI ENERGIJE

RENEWABLE ENERGY SOURCES

INFLUENCE OF SMALL SOLAR POWER PLANTS ON POWER QUALITY

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Abstract. *The solar power plants are usually connected to the distribution network in node with transformer. Small, mini and micro solar power plants are connected as real dispersed production in the middle or at the end of line as consumers. This paper describes measurements, according to standard SIST EN 50160, at 274 m long line, fed at one side from 20/0,4 kV transformer and at the other side from small solar power plant and in between are 15 users (houses).*

Key words: Dispersed production, small solar power plants, SIST EN 50160, measurements

1. INTRODUCTION

Slovenia has at least 10 times less classic energy resources as other countries in the World. Situated in front of Alps Slovenia has quite a lot of precipitation which offers a lot of possibilities to use existing hydro potential, solar energy and biomass.

Nowadays we have to assure independency at least with electric energy supply similar as we had a goal to be self-sufficient in providing food some years ago. Projection of consumption and production shows quite opposite [1].

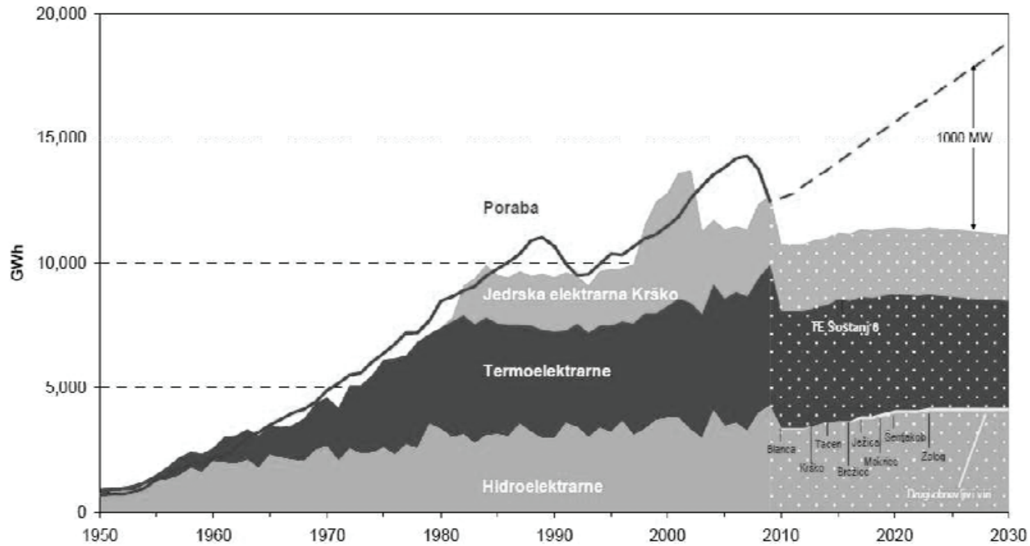


Figure 1. Covering electric energy consumption in Slovenia.

Increased use of renewable sources and efficient energy use are most important options to cover consumption with production together with building new large power plants.

Solar energy can be exploited in two ways: with thermal systems and by using photon effect [2].

Photon effect is used in photosynthesis (generally called bioconversion) and to produce biomass, for photo-chemical synthesis and for photovoltaic effect in which solar radiation is directly converted in electric energy in semiconductor "solar cells".
In spite of medium high geographic latitude (radiation angle of incidence) is in Slovenia large number of sunny days and therefore a lot of options to use all three possibilities of exploiting solar radiation [3]. Hydro power plants are not easy to install into space while there is no problems with building solar power plants on roofs of new or already built objects.

Table 1. - Number and power of grid connected solar power plants

Year	Number of PV systems	Total power [kW]	Part in energy consumption [‰]
2003	1	4,5	0,000375
2004	1	7,5	0,000625
2005	6	73,9	0,006158
2006	8	117	0,009750
2007	14	397	0,033083
2008	57	1060	0,088333
2009	202	7240	0,603333
2010	330	18440	1,536667
2011	459	34150	2,845833
sum	1078	61490	5,124167

Government of Republic of Slovenia has decided, similar as in some other countries, to encourage electric energy production in solar power plants with subventions or by buying electric energy from qualified producers at higher price [4] and [5]. Prices and bonuses for buying electric energy from solar power plants differ according to power plants nominal power. In accordance to that the number of power plants is rising [6].

2. DISTRIBUTION LINE

Power plant is connected to low voltage electric network via low voltage cable NAYY-O 4x70+2,5 0,6/1 kV lead to the pillar of low voltage network and fed from the 20/0,4 kV transformer station.

Measurements [7] were performed according to standard SIST EN 50160 [8] for a week at three phase distribution line shown in figure 2. All together seven instruments were used measuring frequency, voltage level, voltage deviation, fast changes in voltage, voltage sags, overvoltages, voltage unbalances and harmonic voltages. Measuring points were at power plants, low voltage side of transformer and five larger consumers (figure 2).

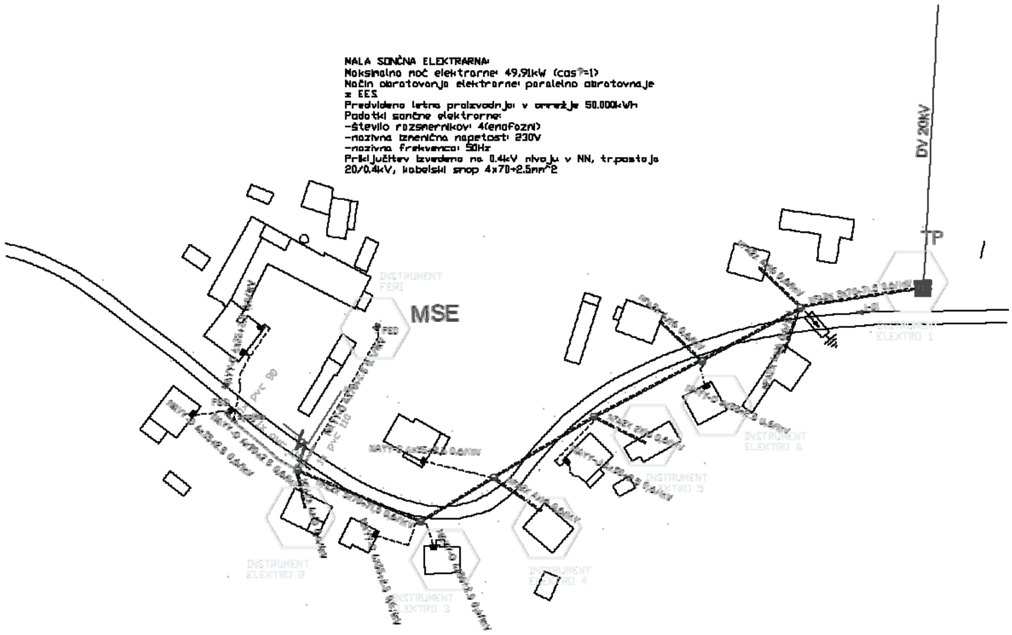
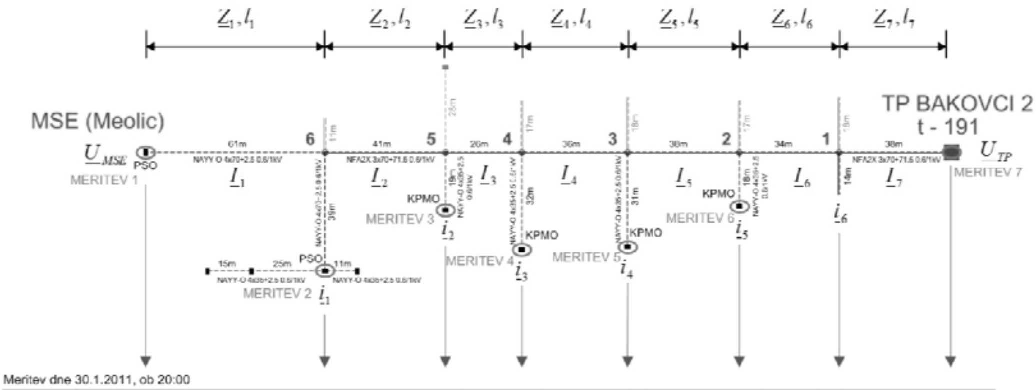


Figure 2. Three phase distribution line fed from two sides.

3. MEASUREMENTS

We payed most attention to voltage level [9] due to fear that power plant at the end of distribution line would damage voltage profile. Figure 3 shows values of measured voltages for January 30TH 2011 at 8:00 PM when small solar power plants was not feeding energy into the grid. Individual voltages of average 10-minute effective values for phases L_1, L_2 and L_3 are shown. Values are obtained from measurement data, exported from programme CODAM Plus and imported to MS Excel.

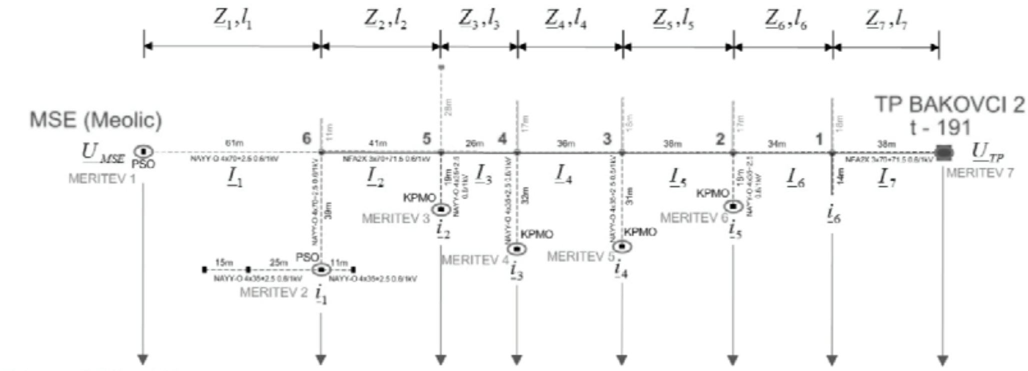


Meritev dne 30.1.2011, ob 20:00

	$\underline{U}_{MSE}$ (V)	$\underline{U}_1$ (V)	$\underline{U}_2$ (V)	$\underline{U}_3$ (V)	$\underline{U}_4$ (V)	$\underline{U}_5$ (V)	$\underline{U}_6$ (V)	$\underline{U}_{TP}$ (V)
faza L_1	235.91	232.14	235.75	235.84	235.02	235.45	/	235.54
faza L_2	234.98	235.44	233.71	233.36	236.34	235.95	/	236.66
faza L_3	232.75	234.64	235.57	235.03	233.74	234.19	/	235.84

Figure 3. Measured voltages for January 30TH 2011 at 8:00 PM.

Measured voltages for February 1[ST] 2011 at 2:20 PM when small solar power plant was feeding the grid with energy are shown in figure 4. Individual voltages of average 10-minute effective values for phases L_1, L_2 and L_3 are shown. Values are obtained from measurement data, exported from programme CODAM Plus and imported to MS Excell.



Meritev dne 1.2.2011, ob 14:20

	$\underline{U}_{MSE}$(V)	$\underline{U}_1$(V)	$\underline{U}_2$(V)	$\underline{U}_3$(V)	$\underline{U}_4$(V)	$\underline{U}_5$(V)	$\underline{U}_6$(V)	$\underline{U}_{TP}$(V)
faza L_1	240.95	236.8	238.52	239.04	239.2	238.77	/	237.09
faza L_2	241.02	239.55	236.87	237.15	238.94	238.47	/	238.03
faza L_3	238.35	239.77	239.47	239.55	237.17	237.15	/	237.86

Figure 4. Measured voltages for February 1[ST] 2011 at 2:20 PM.

Voltage deviations from nominal (agreed) voltage U_c are smaller from class of used instruments at individual measurement points and phases and do not exceed allowed deviation values at no point (figure 5). Largest deviations were (negative) at evening peeks.

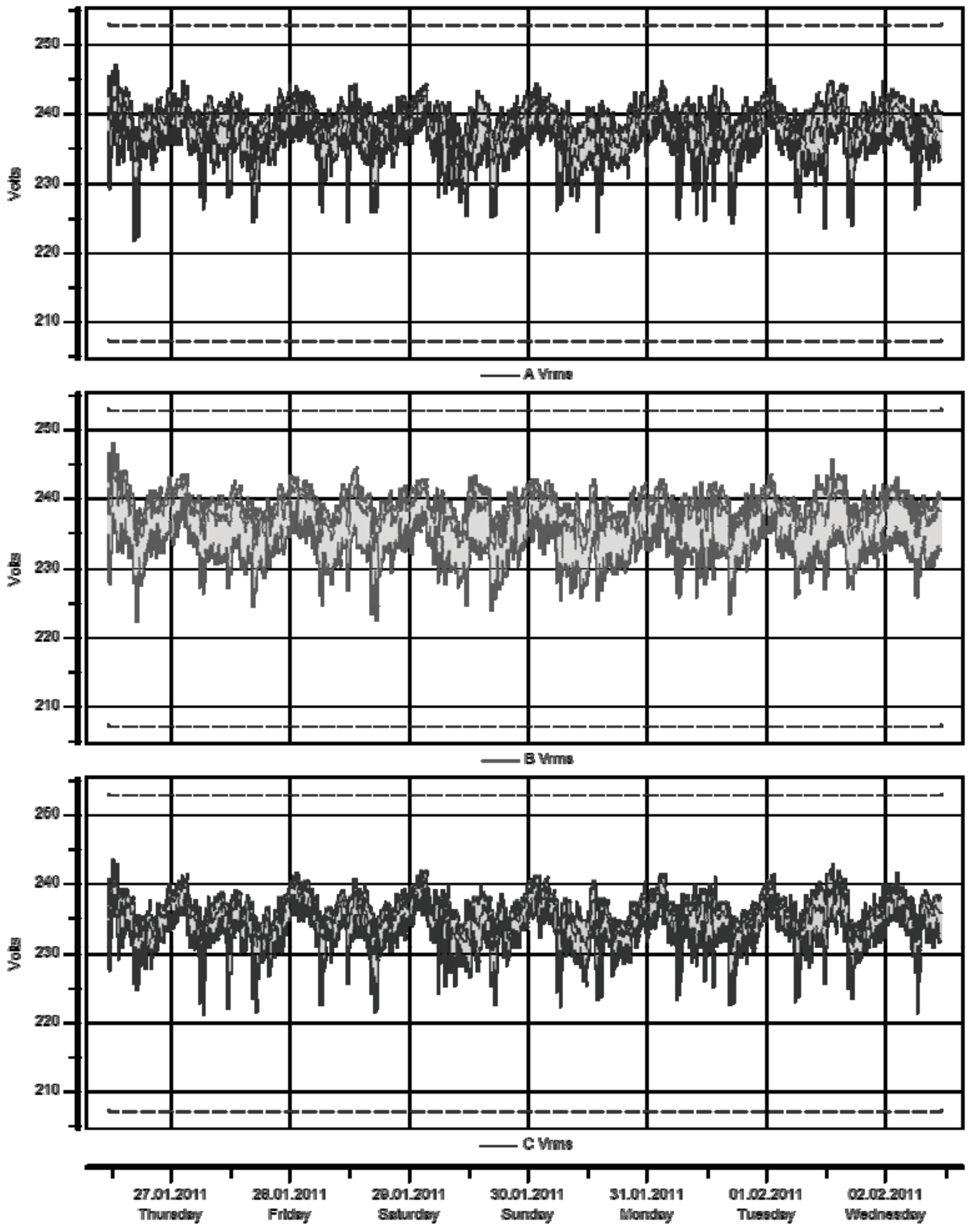


Figure 5. Voltages at solar power plant.

Voltage deviations from nominal (agreed) voltage U_c are even smaller at the transformer station (figure 6) and never exceed allowed deviation values.

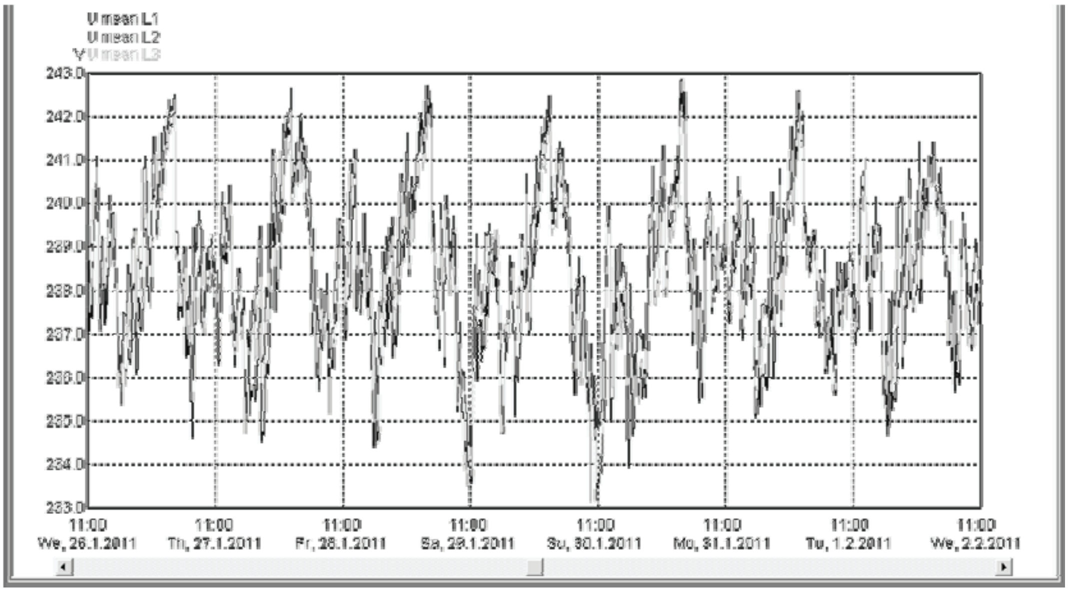


Figure 6. Effective values for phases L1, L2 and L3 at the transformer station.

Largest voltage Total Harmonic Distortion (THD) was measured at solar power plant (2,39 %, figure 7) together with long term flicker P_{lt} (1,30 %, figure 8). Both values were decreasing towards transformer station (THD = 1,9 %; Plt = 0,26 %).

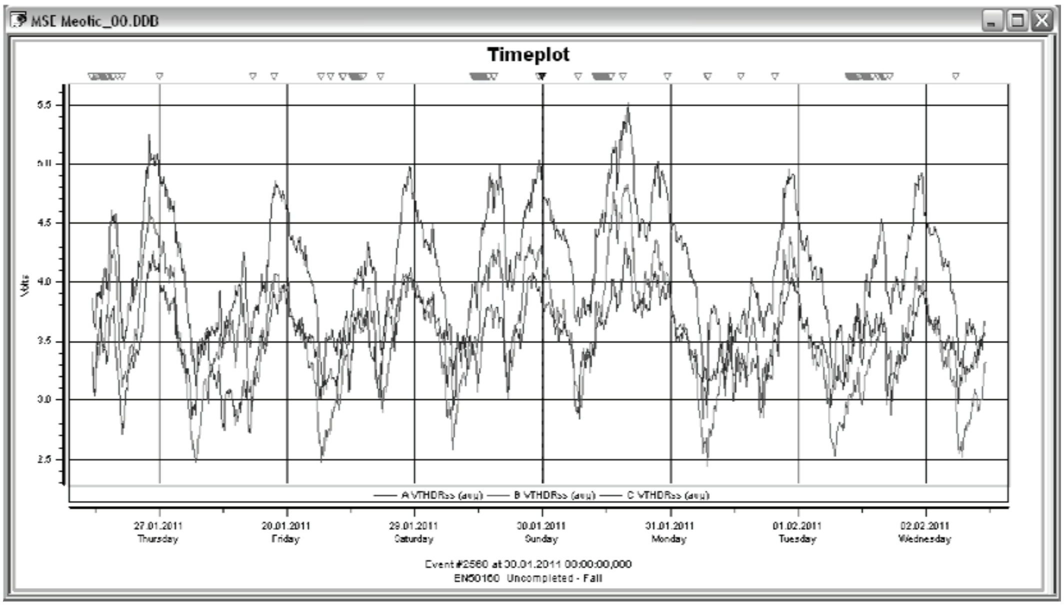


Figure 7. 10 minutes effective values of voltage THD_u.

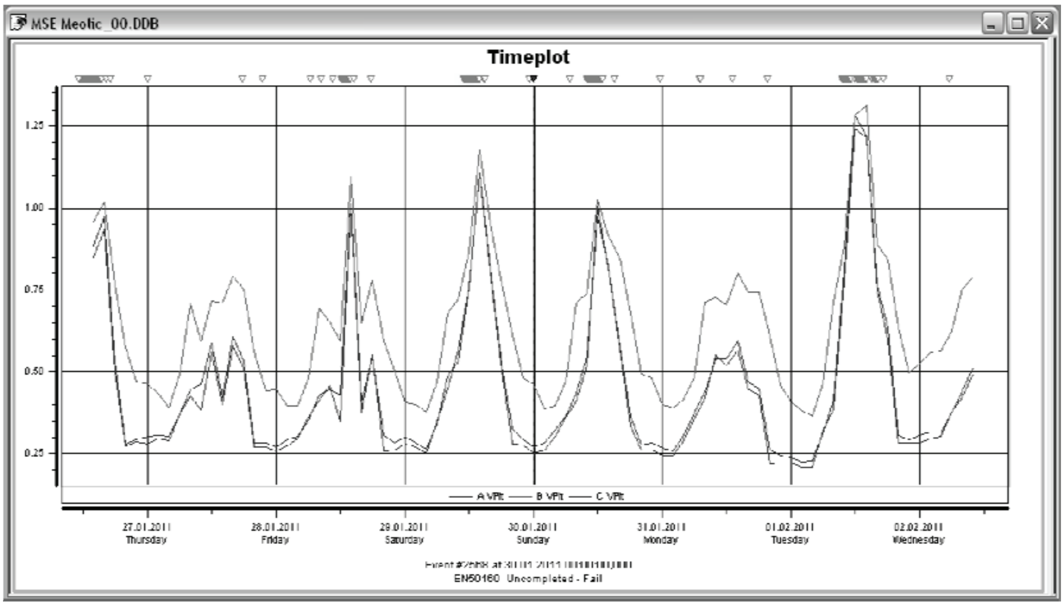


Figure 8. Long term flicker P_{lt}.

4. CONCLUSION

We have decided to perform measurements at distribution line due to fear that dispersed production (power plant at the end of distribution line) would damage voltage profile of such line. We had quite some difficulties finding such distribution line. Energy Law [10] enables every consumer and producer of electric energy access to the grid and distribution companies define with their regulations the way and place of connection [11]. For producers (power plants) as connection point is usually defined node with the transformer where power plant has less influence.

Measurements were performed according to standard SIST EN 50160 for a week at three phase distribution line.

Voltage deviations from nominal (agreed) voltage U_{c} are smaller from class of used instruments at individual measurement points and phases and do not exceed allowed deviation values at no point (figure 5). Largest deviations were (negative) at evening peeks.

Largest voltage Total Harmonic Distortion (THD) was measured at solar power plant (2,39 %) as random value independent from production or consumption. Just the opposite the long term flicker P_{lt} occurred always when power plant was producing energy but was not largest at maximum power ($P_{\text{lt}}(P = 8{,}7\text{ kW}) = 1{,}02\ \%$; $P_{\text{lt}}(P = 7{,}4\text{ kW}) = 1{,}30\ \%$). Both voltage Total Harmonic Distortion (THD_u) and long term flicker P_{lt} values were decreasing towards transformer station (stronger supply point).

Research will be continued in two directions: we will locate more distribution lines with dispersed production and perform measurements at medium voltage due to connection of larger power plants.

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UTJECAJ MALIH SOLARNIH ELEKTRANA NA KVALITETU ENERGIJE

Sažetak: *Solarne elektrane su obično priključene na distribucijsku mrežu u čvoru s transformatorom. Male, mini i mikro solarne elektrane su povezane, kao pravi raspršeni proizvođači, u sredini ili na kraju linije kao i potrošači. Ovaj članak opisuje mjerenja, prema standardu SIST EN 50160, na 274 m dugoj liniji, napajanoj na jednoj strani od 20/0,4 kV transformatora i na drugoj strani iz male solarne elektrane. Između se nalazi 15 korisnika (kuća).*

Ključne riječi: disperzirana proizvodnja, male solarne elektrane, SIST EN 50160, mjerenja

NOWCASTING GLOBAL SOLAR IRRADIANCE BY FUZZY LOGIC

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Abstract: *As the installed power of photovoltaic plants and other solar energy conversion systems increases worldwide, accurate and high-resolution solar irradiance predictions are of vital importance for a balanced operation of the electric grid. This paper is focused on short-time (minute to hours) forecasting of global solar irradiance. Basically, a new model for nowcasting clearness index, based on fuzzy sets theory, is reported. There are two arguments for this choice: (i) The stochastic component of solar irradiance is isolated by means of clearness index and (ii) Fuzzy logic, as an alternative to the binary logic, exhibits the flexibility to capture patterns from chaotic systems, like weather. The general structure of the model, its performance on measured data and results of comparison with other approach are discussed.*

Key words: PV plant, Short-time forecasting, Fuzzy logic, Solar irradiance

1. INTRODUCTION

Due to intermittent weather patterns, the solar power plants output may be strongly variable in time. This is different from the rather stable output of the traditional power plants and may create difficulties for the electrical grid operators in their attempt to cover the end user demands. Therefore, it is important to have tools for modeling and forecasting the electric energy generated through solar technologies. The experience with wind energy shows that accurate wind speed forecasts can substantially reduce grid integration costs [1]. This suggests that accurate solar irradiance forecasting can be used for proper power grid operating and for scheduling conventional power plants.

The performance of PV plants significantly depends on the fact that direct solar radiation is incident or not on the PV arrays. Fast variation of solar radiation may generate the so called “solar ramp” problem, which is one of the greatest obstacles in operating the power grid [2]. The term refers to grid management when solar irradiance changes rapidly causing a massive shift in power. Solar thermal systems react to solar irradiance changes in minutes while the PV systems react in milliseconds. Since there are situations when the fluctuation on solar radiative regime is on a time scale of minute or less [2, 3], nowcasting of solar irradiance on very short time periods becomes an opportune research area.

Changes in solar irradiance at a point due to a passing cloud can exceed 60% of the peak of solar irradiance in seconds [2]. The time it takes for a passing cloud to shade an entire PV system depends on various factors, namely the PV system size and cloud speed. In Ref. [2] it is showed that a 75% ramp in 10-seconds measured by a pyranometer was associated with 20% in the same 10-second ramp in a 13.2-MW PV plant in Nevada. On the other hand, PV systems monitoring at less than 1 minute sampling (e.g. 10 seconds [4] and 15 seconds [5], [6]) shows that hourly averaging of solar irradiance and PV modules temperature underestimates the delivered PV power in high irradiance conditions. Since the output of PV modules reacts rapidly to changes of solar irradiance and their temperature changes slowly,

PV modules will give higher power than calculated from hourly averages. These show that nowcasting the solar irradiance on shorter periods (1 minute) is very important for proper grid management.
Depending on the time horizon, different forecast methods may be considered. In the shortest time domain ("Nowcasting", 0-3 hours), the forecast is based on extrapolations of real-time measurements [7]. The methods currently in use for nowcasting solar radiation at ground level are the following: statistical methods such as Autoregressive Integrated Moving Average (ARIMA) models [8], Markov processes [9] and artificial intelligence techniques [10].
This paper is focused on the practice of clearness index nowcasting on very short time intervals by using fuzzy logic modeling.

2. NOWCASTING SOLAR IRRADIANCE

2.1. Clearness index

The solar irradiance can be defined as the sum of two terms: deterministic and stochastic. The seasonal and diurnal variations of solar irradiance are described by well-established astronomical relations. The stochastic component of solar irradiance can be isolated by means of the clearness index accounting for all random meteorological influences, being a measure of the atmospheric transparency [11]. For a review of statistical behavior of solar radiation components based on clearness index see Ref. [12]. In this paper we are using the instantaneous clearness index k_t defined as:

$$k_t \equiv \frac{G}{G_{ext}} \tag{1}$$

where G and G_{ext} denote the horizontal global solar irradiance on the ground and at the top of the atmosphere, respectively.

2.2. Fuzzy logic

Fuzzy set theory have been introduced in 1965 by Lotfy A. Zadeh [13] and basically fill with real numbers the interval between 0 and 1, allowing intermediate values between these two extremes. Since Aristotle, the theory of logic stated that every proposition must either be TRUE or FALSE, excluding the middle. In contrast, fuzzy logic is designed to allow computers to make use of the distinctions among data with shades of gray. It proposes making the membership function operate over the range of real numbers [0, 1]. This should not lead to confusion between the degree of truth used in fuzzy theory and probabilities, which are conceptually distinct.

In fuzzy set theory, physical properties are described by user-supplied *linguistic variables* that are no numbers but linguistic values, called *attributes* and expressed by words or sentences. A fuzzy set is defined as $A = \{(x, m_A(x)) : x \in X\}$. The *membership function* $m_A(x)$ is associated to every attribute, indicating the degree to which the attribute is characteristic of a linguistic variable. In classical set theory a membership function $m_A(x)$ takes only the values 1, if $x \in A$, or 0, otherwise. Such sets are also called *crisp sets*. A generalization of this characteristic function $0 \le m_A(x) \le 1$ is used to indicate the degree of belonging of an element x to a fuzzy set A.

The operations with different sets in terms of membership functions are:
- *Fuzzy intersection* (**AND**): $m_{A \cap B} = \min\left(m_A(x), m_B(x)\right), \quad \forall\, x \in X$
- *Fuzzy reunion* (**OR**): $m_{A \cup B} = \max\left(m_A(x), m_B(x)\right), \quad \forall\, x \in X$

Generally, a fuzzy logic model is a functional relation between two multidimensional spaces. The relation between the input and output fuzzy spaces is known as Fuzzy Associative Memories (FAM). Inside FAM, the linguistic variables and the attributes are specified and the associative rules between different fuzzy sets are elaborated in order to set up the following construction:

IF (*premises*) **THEN** (*conclusions*)

Every premise or conclusion consists on expression as:

(*variable*) **IS** (*attribute*)

connected through fuzzy operator **AND**.

There are the following steps to follow:
- *Fuzzification* is a coding process in which each numerical input of a linguistic variable is transformed in the membership functions values of attributes.
- *Inference* is a process in two steps: (i) The computation of a rule by intersecting individual premises, applying the fuzzy operator **AND**: (ii) Often, more rules drive to a same conclusion. To obtain the confidence level of this conclusion (i.e., the membership function value of a certain attribute of output linguistic variable) the individual confidence levels are joined by applying the fuzzy operator **OR**.
- *Defuzzification* is a decoding operation of the information contained in the output fuzzy sets resulted from the inference process, in order to provide the most suitable output crisp value. There are more methods used for defuzzification (for details see [14]); in this paper, we apply the Center of Gravity (COG) method, one of the most popular. According to COG, the desired output crisp value is computed with the equation:

$$y_{crisp} = \frac{\sum_i c_i \int m_{y_i}(x)dx}{\sum_i \int m_{y_i}(x)dx} \tag{2}$$

In Eq. (2) c_i is the center of the membership function, the integral $\int m_{y_i}(x)dx$ represents the area under the membership function $m_{y,i}(x)$ corresponding to the attribute i of the output linguistic variable y.

2.3 Database

Data measured continuously in Timisoara (Romania) for ten days between 12 June and 20 June 2010 are used to develop the fuzzy model. The data consists of global and diffuse solar irradiance values, measured with a 15 second lag during day-light [15]. From these data, the time series of clearness index values was calculated with Eq. (1). In order to diminish the heteroscedasticity of the database we adopt the usual procedure, i.e. keeping only those measurements associated to sun elevation angles larger than a given threshold (in this case, 5 degrees). First, a sub-database has been obtained for each day by removing solar irradiance values associated to sun elevation angle less than 5 degrees (this also includes the night-time interval). Next, the database for the series of ten consecutive days is obtained by concatenation of the sub-databases prepared for each day in part.

The model has been tested against data measured in 9 days of the year 2010 also measured at the station of Timisoara. These days are characterized by different radiative regimes, as shown in Fig. 1. In this figure, sunshine number ξ (a Boolean quantity stating if the sun shining ($\xi = 1$) or not ($\xi = 0$) [16]) measured at 15 seconds interval is plotted with respect to time (counted by the index of measurement) for every day. It can be seen that the day 28/08 is characterized by a fully unstable radiative regime, while the days 14/11 and 20/11 are characterized by a fully stable radiative regime. However, the days 14/11 and 20/11 are essentially different: 14/11 is a complete sunny day ($\xi = 1$) while 20/11 is an overcast day ($\xi = 0$).

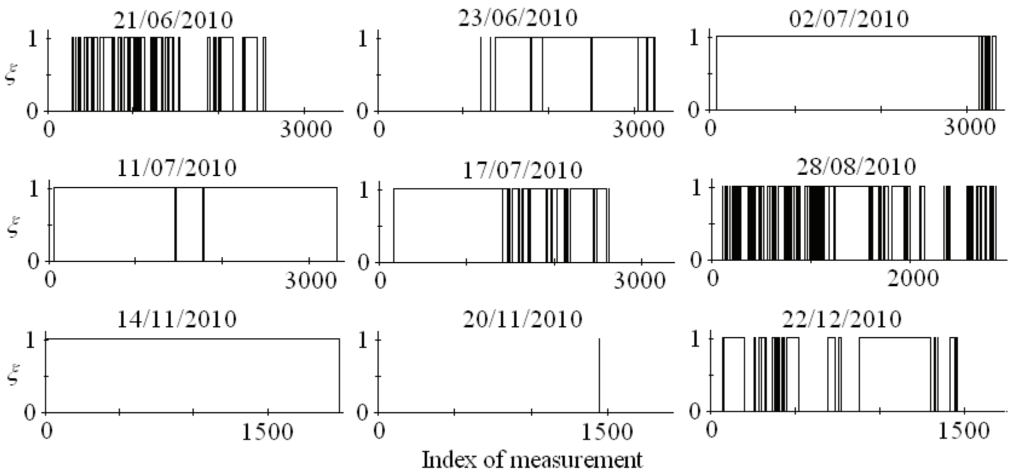

Figure 1. Sunshine number ξ in nine days used to test the fuzzy model.

2.4 Model description

The presentation is focused on the model structure and functioning. The algorithm forecasts the instantaneous clearness index k_t (Eq. 1). According to the fuzzy logic procedures, first the input variables have been chosen. The first input variable is k_t^{t-1}, the clearness index measured at time t - 1 (the prediction will be made for the time t). Since clearness index is a measure of the atmospheric transparency it encapsulates information on the state of the sky. Tests regarding sunshine number forecasting demonstrate that it may be correlated with the sun elevation angle [17]. Since sunshine number is also a measure for the state of the sky, a relation may exist also between k_t and sun elevation angle. Ref. [18] demonstrated that the accuracy of forecasting the sunshine number decreases with the increasing of radiative regime stability. Thus, in addition to k_{t-1}, two other variables have been considered at input: relative sunshine $\bar{\sigma}$ and sun elevation angle h. Here $\bar{\sigma}$ represents the relative sunshine over 5 minutes prior to the moment $t - 1$ at which the prediction is made. Both h and $\bar{\sigma}$ are included in the list of input variables, for a complementary quantification of the state of the sky and thus for enhancing prediction in case of variable sky.

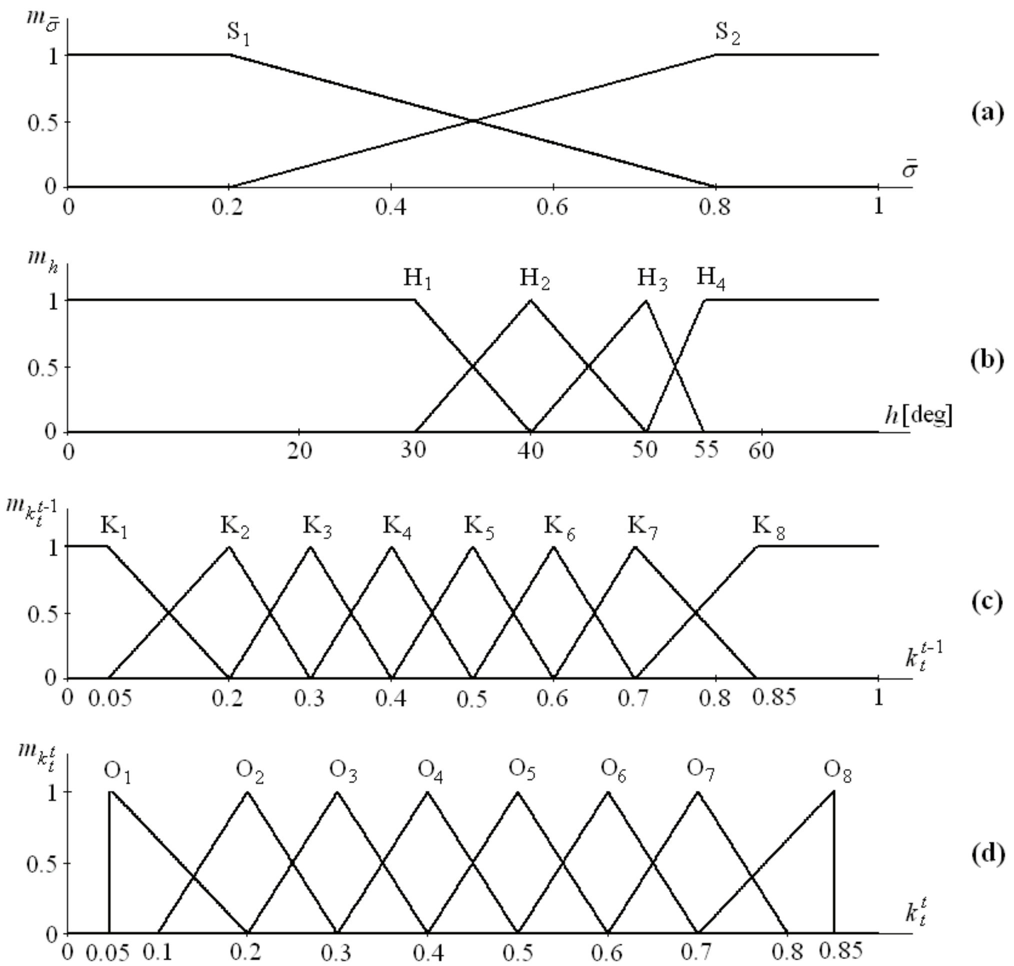

Figure 2. The membership functions of the attributes characterizing the variables: (a) relative sunshine; (b) sun elevation angle; (c) input clearness index at the moment $t-1$; output clearness index at the moment t.

The attributes of each input variable and the attributes of the output variable are schematic represented in Fig. 2, where the notations are indicated. The membership functions are triangular, described by typical linear equations with the coefficients specified in Fig. 2. The mapping of the inputs to the output of the fuzzy system, materialized in the rules-base, is listed in Table 1 as a matrix. There are 64 rules, the each rule (i = 1,2; k = 1,2,3,4; j = 1…8; m = 1…8) reads:

$$\text{IF } \bar{\sigma} \text{ IS } \mathbf{S}_i \text{ AND } h \text{ IS } \mathbf{H}_j \text{ AND } k_t^{t-1} \text{ IS } \mathbf{K}_k \text{ THEN } k_t^t \text{ IS } \mathbf{O}_m \tag{3}$$

Table 1. Matrix of the system rules-base. Each rule is a fuzzy implication in sense of Eq. (3)

$\bar{\sigma}$		S$_1$				S$_2$			
h		H$_1$	H$_2$	H$_3$	H$_4$	H$_1$	H$_2$	H$_3$	H$_4$
	K$_1$	O$_1$	O$_1$	O$_1$	O$_1$	O$_1$	O$_1$	O$_1$	O$_1$
	K$_2$	O$_2$	O$_2$	O$_2$	O$_2$	O$_2$	O$_2$	O$_2$	O$_2$
	K$_3$	O$_3$	O$_3$	O$_3$	O$_3$	O$_3$	O$_4$	O$_4$	O$_4$
k_t^{t-1}	K$_4$	O$_4$	O$_4$	O$_4$	O$_4$	O$_4$	O$_4$	O$_5$	O$_5$
	K$_5$	O$_5$	O$_5$	O$_5$	O$_5$	O$_5$	O$_5$	O$_6$	O$_5$
	K$_6$	O$_6$	O$_6$	O$_6$	O$_6$	O$_6$	O$_6$	O$_6$	O$_6$
	K$_7$	O$_6$	O$_7$	O$_7$	O$_5$	O$_7$	O$_7$	O$_7$	O$_5$
	K$_8$	O$_6$	O$_7$	O$_6$	O$_4$	O$_8$	O$_8$	O$_6$	O$_4$

With this information the model can be run. The inputs are the relative sunshine averaged over 5 minutes prior to the moment $t - 1$ when the prediction is made, the instantaneous clearness index at the moment $t - 1$ and the sun elevation angle at moment t (sun elevation angle is exactly calculated from astronomical consideration). The output of the algorithm is the instantaneous clearness index k_t^t at the moment t.

2.5. Model accuracy

For each day a scatter plot of the estimated and measured instantaneous clearness index is displayed in Fig. 3. By comparison with Fig. 1, this sequence reveals an intimate relation between estimation accuracy of k_t and the stability of the radiative regime. In the sunny day 14/11 the points are clustered close to the first diagonal showing that the model forecasts the clearness index with very high accuracy. This observation is also valid for the days 02/07 and 20/11 demonstrating that the forecasting accuracy does not depend on the season. Conversely, a large scatter of model outputs relative to the measured data occur in the days 21/06 and 28/08 characterized by a highly fluctuating solar radiative regime.

Statistical indicators of forecasting accuracy of the clearness index for each among the nine days are collected in Table 2. In addition to the statistical indicators, for each day, the relative sunshine σ_d (an indirect measure for the cloud cover amount) and the daily mean sunshine stability number $\bar{\zeta}_d$ (an indirect measure of the cloud cover variability [19]), are included.

The models performance has been measured using two statistical indicators, relative root mean square error (*rRMSE*), relative mean bias error (*rMBE*) and absolute percentage error (*MPE*) defined as follows:

$$rRMSE = 100 \cdot \left[n \cdot \sum_{i=1}^{n} (F_i - y_i)^2 \right]^{1/2} \Big/ \sum_{i=1}^{n} y_i \tag{4a}$$

$$rMBE = 100 \cdot \sum_{i=1}^{n} (F_i - y_i) \Big/ \sum_{i=1}^{n} y_i \tag{4b}$$

$$MPE = 100 \cdot \frac{1}{N} \sum_{i=1}^{n} |F_i - y_i| / y_i \tag{4c}$$

where y_i and F_i are i-th measured and computed quantities, respectively, while n is the number of measurements taken into account.

A first conclusion from Table 2 is the high performance of the model, *rRMSE* ranging from 0.9% in perfect steady clear sky day ($\sigma_d = 0.993$ and $\bar{\zeta}_d = 0.0005$) to 27.4% in the day with highest variability of the sky ($\sigma_d = 0.525$ and $\bar{\zeta}_d = 0.0369$). Second, numerical results from Table 2 not only confirms the above remark that there is a relation between the prediction accuracy and solar regime stability (here measured by $\bar{\zeta}_d$), but also complete it. *rRMSE* clearly decrease with increasing $\bar{\zeta}_d$ and is influenced by σ_d.

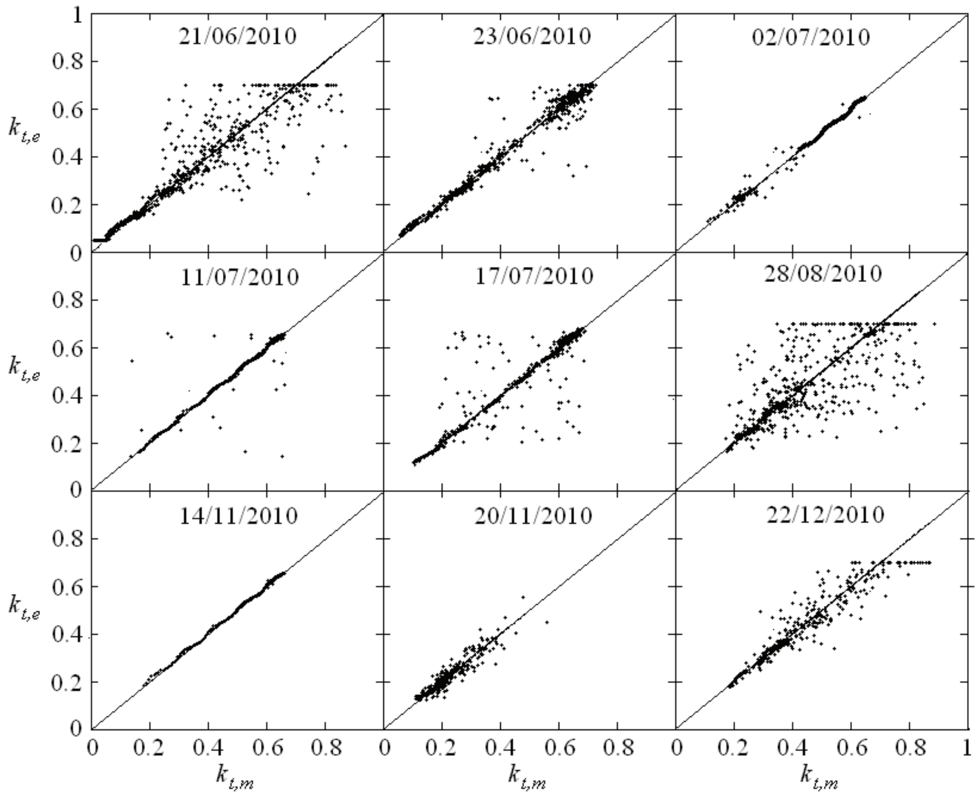

Figure 3. Scatter plots of measured $k_{t,m}$ and estimated $k_{t,e}$ clearness index for different nine days of 2010.

Table 2. Statistical indicators of accuracy for forecasting instantaneous clearness index at 1 minute lag in nine days of the year 2010. σ_d is the daily relative sunshine, $\bar{\zeta}_d$ is the daily mean of sunshine stability number and *N* is the number of forecasted values. The days are sorted by ascending $\bar{\zeta}_d$.

Date	$\bar{\sigma}_d$	$\bar{\zeta}_d$	*N*	*rRMSE* [%]	*rMBE* [%]	*MPE* [%]
14/11	0.9930	0.0005	396	0.9	0.4	0.9
20/11	0.0020	0.0005	383	10.2	0.8	6.7
11/07	0.9481	0.0011	679	7.4	0.2	2.5
02/07	0.9250	0.0020	686	2.1	0.4	1.7
23/06	0.5301	0.0040	689	9.1	0.4	5.9
17/07	0.6531	0.0068	673	15.1	0.2	6.9
22/12	0.4644	0.0114	347	12	-1.4	7.1
21/06	0.3035	0.0173	689	27.4	0.4	36.0
28/08	0.5205	0.0369	594	25.7	-1.4	16.4

Table 3. Statistical indicators of accuracy for forecasting instantaneous clearness index at 10 minutes lag in nine days of the year 2010. *N* is the number of forecasted values.

Date	*N*	*rRMSE* [%]	*rMBE* [%]	*MPE* [%]
14/11	46	2.7	1.5	2.3
20/11	45	28.1	0.5	19.1
11/07	81	11.8	0.3	5.5
02/07	82	6.1	0.6	4.6
23/06	82	15	0.3	15.2
17/07	80	26.9	0.4	17.2
22/12	40	32.3	0.2	22.8
21/06	82	52.3	1.3	57.2
28/08	70	37.4	-1.3	28.6

Table 4. Statistical indicators of accuracy for forecasting instantaneous clearness index at 30 minutes lag in nine days of the year 2010. *N* is the number of forecasted values.

Date	*N*	*rRMSE* [%]	*rMBE* [%]	*MPE* [%]
14/11	14	5.8	3.2	4.7
20/11	13	48.4	-0.5	35.2
11/07	26	27.7	2.1	22.5
02/07	26	6.6	1.9	6.6
23/06	26	22.3	-0.1	22.7
17/07	25	15.3	2.3	14.4
22/12	12	55	5.5	52.7
21/06	26	61.4	1.8	77.7
28/08	22	29.5	0.2	25.2

To conclude, the accuracy increase of the forecasting procedure determined by a more stable solar radiative regime found in ARIMA modeling of sunshine number [18] is exhibited by the fuzzy model too. In order to increase the fuzzy model accuracy, further developments should include in the list of the linguistic variables a measure for the fluctuation of the radiative regime.

A question arising is whether the above model can be used for forecasting solar irradiance at different time intervals. Results from testing the model for 10 and 30 minutes ahead forecasting solar irradiance follows. The same dataset as in the previous case has been used. For each day the database was constructed by staking lines of data measured 10 or 30 minutes. This time the relative sunshine has been calculated over the period between two prediction moments.

Results of testing the model against measured data are inserted in Table 3 and Table 4, respectively. Statistical indicators show a decreasing of the forecasting accuracy compared to the previous case, with r*RMSE* ranging between 2.7% and 52.3% in case of 10 minutes lag and between 5.8% and 61.4% in case of 30 minutes lag. Generally, the model accuracy is correlated with the daily solar radiative regime, but this relation may be affected by the larger interval between the two moments of forecasting (see results in 20/11). In a time interval of 10 minutes it is possible to have a serious instability while the samples at the beginning and at the end of this time interval indicate stability. This risk increases with a longer forecasting interval, thus moving average should be adopted to maintain the prediction accuracy at a reasonable level. To conclude, a well working fuzzy model at a certain time scale needs recalibration to perform at a different time scale (e.g., a fuzzy model for forecasting one day ahead solar irradiation is reported in [20]).

The performance of the fuzzy model is comparable to the one of other models. For example, in Ref. [21] are reported results of testing several forecasting models (Regression in logs, UCM, ARIMA, Transfer function, ANN and Hybrid) at a resolution of 5, 15, 30 and 60 minutes. The forecasting quantity is the average value of solar irradiance over each time interval. For 5 minutes forecast horizon *MPE* has been found between 12.6% and 16.7%, for 15 minutes between 18.97% and 42.8% and for 30 minutes between 18.6% and 65.9%. The ARIMA model, one of the most performing, reached *MPE* 13.2%, 1.9% and 18.6% for forecast horizons of 5, 10 and 15 minutes, respectively. The comparison of these results with the ones reported in Tables 2, 3 and 4 shows that *MPE* are of the same order. This gives a relative advantage to the fuzzy model reported here, which has the harder job to predict the *actual* value at a given horizon of time.

3. CONCLUSIONS

This paper reports a fuzzy model for short-time forecasting instantaneous clearness index, from which global solar irradiance can be easily computed. In order to predict the clearness index value at moment *t*, the model needs at input the measured value of the clearness index at *t* - 1, relative sunshine during the period (*t* - 1, *t*) and the sun elevation angle at moment *t*. Overall results demonstrate that the fuzzy model performs comparable with other models-based on different approach. In conclusion, the model reported here forecasts global solar irradiance on short-time period with acceptable accuracy for practice and can be easily adapted to user's needs.

ACKNOWLEDGEMENTS

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TRENUTNA GLOBALNA SOLARNA DOZRAČENA ENERGIJA ODREĐENA FUZZY LOGIKOM

Sažetak: *Kako se instalirana snaga fotonaponskih elektrana i drugih solarnih energetskih sustava povećava u svijetu, točna i visoko razlučiva predviđanja sunčevog zračenja od vitalne su važnosti za uravnoteženi rad električne mreže. Ovaj rad je usmjeren na kratkoročno (od minute do sata) prognoziranje globalnog sunčevog zračenja. Uglavnom, razvijen je novi model za trenutni indeks prozirnosti koji se temelji na teoriji „fuzzy" skupova. Postoje dva argumenta za ovaj izbor: (i) stohastička komponenta sunčevog zračenja je izolirana pomoću indeksa prozračnosti i (ii) „fuzzy" logika, kao alternativa binarnoj logici, pokazuje fleksibilnost za hvatanje uzoraka iz kaotičnih sustava, kao što su vremenske prilike. Prikazana je opća struktura modela, njegova izvedba na izmjerenim podacima i rezultati usporedbi s drugim metodama.*

Ključne riječi: fotonaponski sustavi, kratkoročno predviđanje, fuzzy logika, solarna dozračena energija

THE USE OF THE SOLAR PROCESS HEAT – IMPLEMENTATION IN SLOVENIA

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Abstract: *In principle, there is enormous potential for using solar thermal systems in industry: about 30% of the total industrial heat demand is at temperature levels below 100°C which can be provided with commercially available solar thermal collectors. However, the market in Europe and globally is very much in its infancy - a few hundred installations exist. Eu cofinanced the project Solar process heat where the marked was examined, professional discussion about the potential applications were performed, technical guidelines for planning the solar installations in different industrial processes were developed and some good practice collected. In involved countries Spain, Austria, Germany and Slovenia some new installations were build. One of the examples is also the solar installation in wool production industry at company SOVEN in Slovenia. SOVEN is a sheep wool processing company, producing wool as well as semi and final wool products. Environmental considerations are important to the company and are an element in the marketing of their products. The hot water demand is mostly for washing, sanitizing and colouring processes in wool processing which require 40 - 45 °C. A solar thermal system was installed which is the first solar process heat installation in the region. The annual solar fraction is calculated to be 70 %. As the results of 3 years project activities managed to create a very positive interest on European level and implement 6 new installations.*

Keywords: renewable energy sources, solar heat, industrial procesess

1. INTRODUCTION

The use of solar energy in commercial and industrial applications is currently insignificant compared to the use in swimming pools and the household sector [1]. Most solar applications for industrial processes have been on a relatively small scale and are mostly experimental in nature. Only a few large systems are in use world-wide. On the other hand, if one compares the energy consumption of the industrial, transportation, household and service sectors, then one can see that the industrial sector has the biggest energy consumption in the OECD countries at approximately 30%, followed closely by the transportation and household sectors. The major share of the energy which is needed in commercial and industrial companies for production processes and for heating production halls, is below 250°C. The low temperature level (< 80°C) complies with the temperature level which can easily be reached with solar thermal collectors already on the market. For the medium temperature level, a number of new collector designs are currently being developed.

To be able to make use of the huge potential for solar heat in industry and to open a new market sector for the solar thermal industry, it is necessary to integrate solar thermal systems

into the industrial processes in a suitable way. This may include further development of the solar thermal components so that they fulfill the requirements stipulated.
In 2009 Solar process heat (SO – PRO) project has started. It was cofinnaced by European Commission Intelligen Energy Eurpe program. Within the project 7 partners have cooperated. The coordinatormof the project was O.Ö. Energiesparverband, Upper Austria (Austria). Other partern were: ESCAN (Region of Castillas y Madrid,Spain), Energy Centre České Budějovice (South Bohemia Czech Republic), GERTEC (North-Rhine Westphalia Germany), Sächsische Energieagentur (Saxony (Germany), Energy agency of Podravje (Slovenia) and Fraunhofer-Institut für Solare Energiesysteme (Germany) The project follows these recommendations and takes a strategic approach by:

- implementing comprehensive regional campaigns in 6 European regions
- by carrying out a broad European dissemination, including an international training seminar, to ensure the impact of the project on European level.
- by bringing together know-how in industrial processes (scientific partner Gertec), in solar thermal (scientific partner ISE) and in regional market development (regional partners), and by involving the main target groups industrial and solar companies (supporting partners in the regional networks).

The project takes a trans-sectoral approach as many of the application possibilities for solar process heat identified by the IEA Task 33, such cleaning and drying, occur in a large number of companies across industrial sectors [2].

2. CHECKLISTS FOR DECISION MAKERS IN INDUSTRY

Self-assessment checklists were prepared which allow decision makers in industry to make a first, preliminary analysis whether solar thermal would be suitable for their processes [2]. Based on a draft "European" version in English, the project partners translated and adapted the checklist to their regional conditions, involving main stakeholders in their regions (planners of industrial technologies and of solar systems, solar companies, regional energy agencies and consultants, industrial companies). The checklists are split into two steps:

- **first step: "K.O. criteria":**

- does the company need process heat below 100°?
- is space available to install solar thermal collectors at company site?
- is this space oriented towards south/south-east/south-west or on a flat roof?
- does the company use fossil fuels for process heat during summer months?

if answered with "no", rather unlikely that solar process heat will be economically feasible.

- **second step: "O.K. criteria":**

- is process heat required from March to September? at least during 5 days/week?
- plans for reconstruction/expansion at the site for the next years?
- is heat recovery from other processes technically or economically not possible?
- is a pay back period of > 5 years for energy investments acceptable?
- is there a general interest in the use of renewable energy sources?

In total, 9,500 copies of the regional checklists and 2,000 copies of the European version were printed and disseminated.

3. PLANNING GUIDELINES

The development of the planning guideline was a rather challenging task as only a limited amount of respective literature existed [3]. A task force was formed which – based on proposals by ISE - discussed and decided which solar and industrial system concepts to include and which representative temperatures and daily, weekly and annual load profiles to use. One main objective of the guidelines is to link industrial process engineering and solar thermal engineering by providing the basic information necessary for both of these fields. The approach to include the guideline in one publication allowed the project partners to include a fourth process "Heating of make-up water for steam networks" which was found to be highly relevant by the regional stakeholders. Each of the partners selected a location within their region, for which ISE carried out solar system design simulations (on which the nomograms in the regional versions are based). Partners strongly involved regional stakeholders in the development process of the planning guidelines, for example by detailed discussions with the engineering departments of solar companies and industrial companies, universities and other experts, by organising specific meetings and by proof-reading of the document by solar companies, energy consultants and planners. One European and 6 regional planning guidelines were developed, printed and disseminated including among others: load profiles / nomograms /system concepts for the four priority applications:

- heating of hot water for washing or cleaning
- heating of make-up water for steam networks
- heating of baths or vessels
- convective drying with hot air

An example of the system concept is presented in Picture 1.

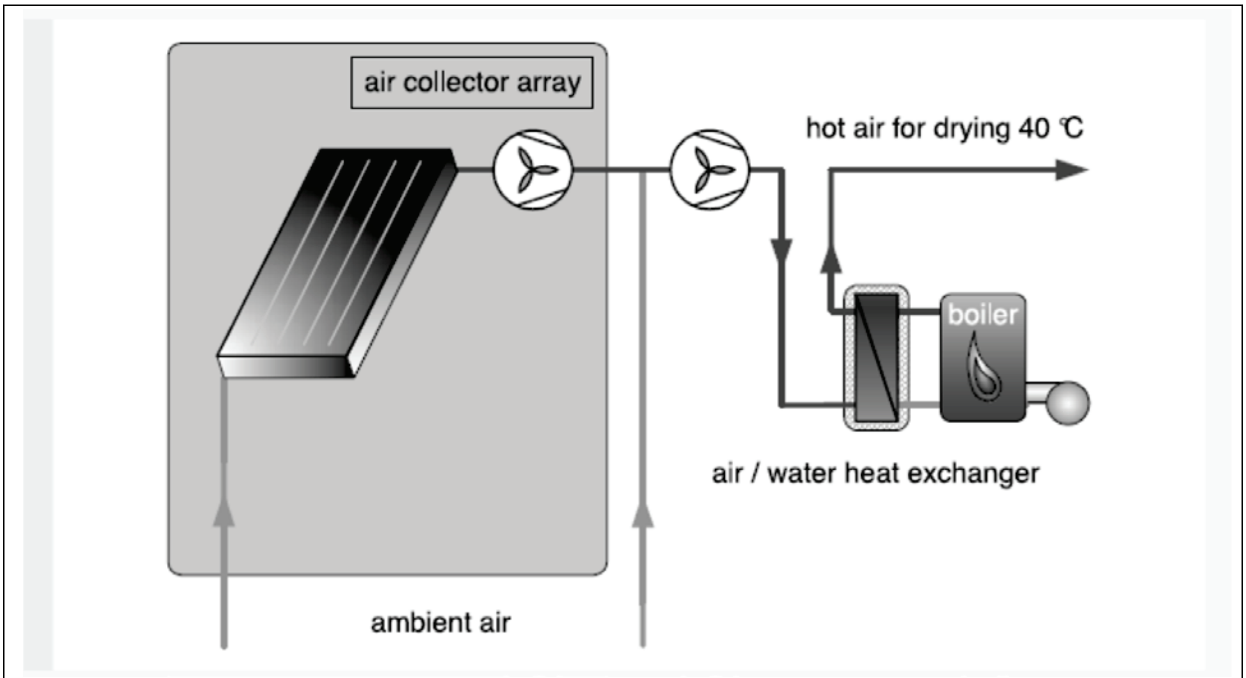

Figure 1. Planning guidelines - Exemplary system concept of an open drying process. The open air collector system is serially supported by a boiler (solar fan left, conventional fan right) [3].

4. IMPLEMENATION IN SLOVENIA

4.1. SOVEN: Sheep wool processing, Slovenia

SOVEN is a sheep wool processing company in Selnica ob Dravi, producing wool as well as semi and final wool products. Environmental considerations are important to the company and are an element in the marketing of their products. The hot water demand is mostly for washing, sanitizing and colouring processes in wool processing which require 40 - 45 °C. A solar thermal system with 7 m ² was installed which is the first solar process heat installation in the region. Investment costs were about 5,500 Euro, the annual solar fraction is calculated to be 70 %. Solar process heat is used mainly for washing, sanitizing and colouring processes in wool production. The main washing processes are the final stage washings. This means that the most of the process heat is used for washing of the final products. The main processes use relatively low washing temperatures with the exception of sanitation measures on the equipment.

Technical description

- 3 Vitosol solar flat plate collectors with 2,3 m² of absorption surface each
- together there is a 6,9 m² absorption surface of the array
- inclination: 45°, deviation from South-orientatio n: 5°
- mounted on pillars on the roof
- 1 hot water storage tank of 500 l

The main washing process utilizes an average water temperature of 40 - 45°C. For equipment washing and sanitation an average water temperature of 60°C is sufficient. Installation of small size solar process heat installations is not difficult at first glance but if no proper planning is made details can be overlooked. The possible financing can be difficult to find when a large investment like this is carried out especially when there are no government subsidies available. Initial project idea and the following actions proved to be quite decisive on making the company decide to use solar process heat. The cooperation with the expert from Energy agency was also very important. They have also seen the marketing potential of being the first one in the region

4.2. PP AGRO: animal feed production company, Slovenia

The company Agrokombinat now under the name PP Agro is an animal feed production company from Maribor with approx. 30 employees. It also has a lot of farming land on which it produces the resources for their animal feed products. The initial activities were prepared to install the solar panels at the animal feed production but the company management decided to use the solar process heat in their dislocated milking house. They were thinking of making a renewed milking facility that uses hot water for washing and sanitation purposes in the process. And a lot of the production is carried out during the summer days. This is why solar energy is an interesting alternative to fossil fuel use for this company. There are also the long term financial benefits for using solar process heat that are important to every company. Solar process heat is used mainly for washing and sanitizing processes of the milking equipment and the storage tanks. The main washing processes are the daily periodic processes. This means that the most of the process heat is used for washing of the equipment. The main processes use relatively low washing temperatures with the exception of sanitation measures on the equipment.

Technical description

- 14 Solimpeks Tinox Wunder solar flat plate collectors with 2,2 m² of absorption
- surface each

- together there is a 30,8 m² absorption surface of the array
- inclination: 60°, deviation from South-orientati on: 30°
- mounted on pillars on the roof
- 2 hot water storage tanks 2,2 m³ each

It is worth to spread the information very often and wide as much as possible because some companies already have their own development strategies in the field of sustainable energy and they just need an idea and not a lot of discussions, calculations and documentation. Initial project idea and the following actions proved to be quite decisive on making the company decide to use solar process heat. The cooperation with the expert from Energy agency was also very important. Also making the right connections between the solar equipment sellers and the company is also important for the establishing of a partner relationship.

5. CONCLUSIONS

The main conclusions [2] drawn from the project are:
· **Market outlook:** in principle, project partners are very positive market outlook for solar process heat: in highly developed markets where also dedicated funding programmes are available, already in the coming years, a noticeable market development could take place. In less developed solar thermal markets, this development is expected to take place in the mid-term.
· **Policy support:** substantial policy support is needed to allow solar process heat to deliver its full potential in economic and environmental terms, most important instruments are:
- including solar process heat in national and regional renewable action plans and policies
- R & D support
- support to dissemination on European/national/regional levels
- dedicated financial support on national and regional levels (e.g. subsidies, tax incentives) through well-designed programmes, possibly also programmes that support energy efficiency measures in industry (where solar process heat fits in very well technically)

· **Dissemination:** further efforts are needed to overcome the significant information gaps on solar process heat among stakeholders. On European level, such a policy measure could include the support to a project ("So-Pro+") which extends So-Pro activities to other European countries as well as possibly to other application areas (e.g. midtemperature heat applications). On national and regional levels, similar actions need to be carried out for the local and regional stakeholders. Here training and the promotion of best practice examples have a key role to play.

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Keywords: renewable energy sources, solar heat, industrial procesess,

APPLICATIONS OF CARNOT FOR DEVELOPMENT IN SOLAR THERMAL ENERGY

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Abstract: *CARNOT is a toolbox extension for Matlab®/Simulink®. Three examples of use of this toolbox for simulation of heat producer systems are presented. The study of the influence of the hydraulic balance in „umbrella" individualized-collective solar installations shows that for a decrease of maximum 20% of the nominal mass flow, there is no significant incidence on the solar fraction. The influence of weather data time step and thermal capacity on two models of solar collectors is studied. The choice of the schema for an industrial high temperature installation is aided by simulation.*

Key word: Matlab solar simulation, Conventional And Renewable eNergy system Optimization Toolbox

1. INTRODUCTION

Systems for heat production are more and more complex. They are more and more often multi-sources and multi-uses and these different functions should be integrated in order to optimise the efficiency of the whole product. A flexible, easy-to-use and easy-to-modify simulation software is then important.

2. PRESENTATION OF CARNOT

The CARNOT (Conventional And Renewable eNergy systems Optimization Toolbox) is an extension for the softwares Matlab®/Simulink® created in 1998 by Hafner at the Solar-Institut Juelich, Germany. It is a tool for the calculation and simulation of the thermal components of heating systems with regards to conventional and renewable elements. The CARNOT Toolbox is a library of typical components of these systems. It is organized in block sets like the Simulink® Library itself. The handling of the blocks is exactly the same as in Simulink®, so that users familiar with Simulink® can directly use the new block set in the same way.

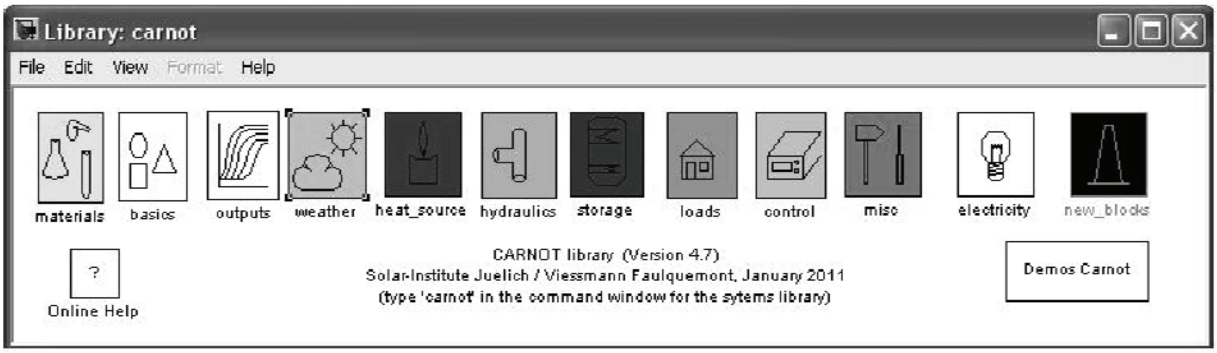

Figure 1. Screenshot of the library

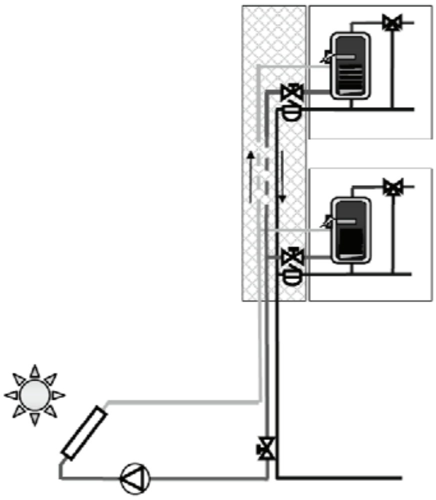

Fig 2. Principle of individualized-collective solar installtion

The library allows simulating hydraulics and heat transfers at the same time. For this purpose, the connection between the components are special vectors called THV (Thermal Hydraulic Vector) which contain all the necessary information about the flow and the energy transfer (type of fluid, mass flow, temperature, pressure...). Each THV corresponds to a physical pipe connection between components. The information is only transported by the vector, whereas the calculation is performed inside the blocks.

The CARNOT Library also contains a wide range of elements which can be user-defined and some basic functions to facilitate the modelling.

The components of the library are regularly validated with experimental data and compared with other simulation software. The results of these studies are available in the toolbox.

The library is today used in some laboratories, universities and companies in Germany (Viessmann, Vaillant, Solar-Institut Jülich (SIJ), University of Bayreuth...), maintained by a group of its users, and will be soon licensed under the GNU LGPL License[1].

3. CASE STUDY 1: STUDY OF THE INFLUENCE OF THE HYDRAULIC BALANCE IN „UMBRELLA" INDIVIDUALIZED-COLLECTIVE SOLAR INSTALLATIONS

3.1 Object of the study

Individualized-collective solar installations are large solar installations in which both solar energy storage and additional back-up heating are individualized. The individual domestic hot water (dhw) cylinders are connected in parallel to the solar loop. A way to simplify the installation of the solar pipes is to work with an "umbrella" configuration: each tank has its own loop which directly comes from the roof by the ventilation shafts. Thus, the balancing valves are on the roof and with an easy access for their adjustments. One main disadvantage of this technique is that the global hydraulic balance is hard to achieve with a high accuracy. So a study is made with CARNOT to estimate the impact in the solar fraction of a non perfect balance.

3.2 Numerical model

The weather data was generated with Meteonorm 6.1.0.13 for the city Perpignan (France). The installation has 6 identical apartments equipped with dhw cylinders of 300 litres using an electric backup-heater in upper part. The solar field has 9 flat plate solar collectors (2.5 m²) oriented south at an inclination of 60°.

A main hydraulic valve separates the mass flow in two parts which deserve 3 apartments. In each branch, a second valve distributes the fluid in each apartment. The fraction for the distribution is given by a constant factor. The model for the simulation is shown in Fig. 3.

3.3 Results

In this first study, only the adjustment of the main valve is changed in order to simulate a bad hydraulic balance. As it can be can seen in Table 1., for a decrease up to 20% of the nominal mass flow, there is no significant change of the solar fraction. And even at only 25% of the nominal mass flow (reduction -75%), the solar fraction remains rather stable. This can be explained by the fact that the solar heat exchanger inside the tank is oversized. A standard solar heat exchanger dimensioned for up to 7.5 m² of solar collector is used, whereas in this case the solar collector field has only 3.75 m² per cylinder.

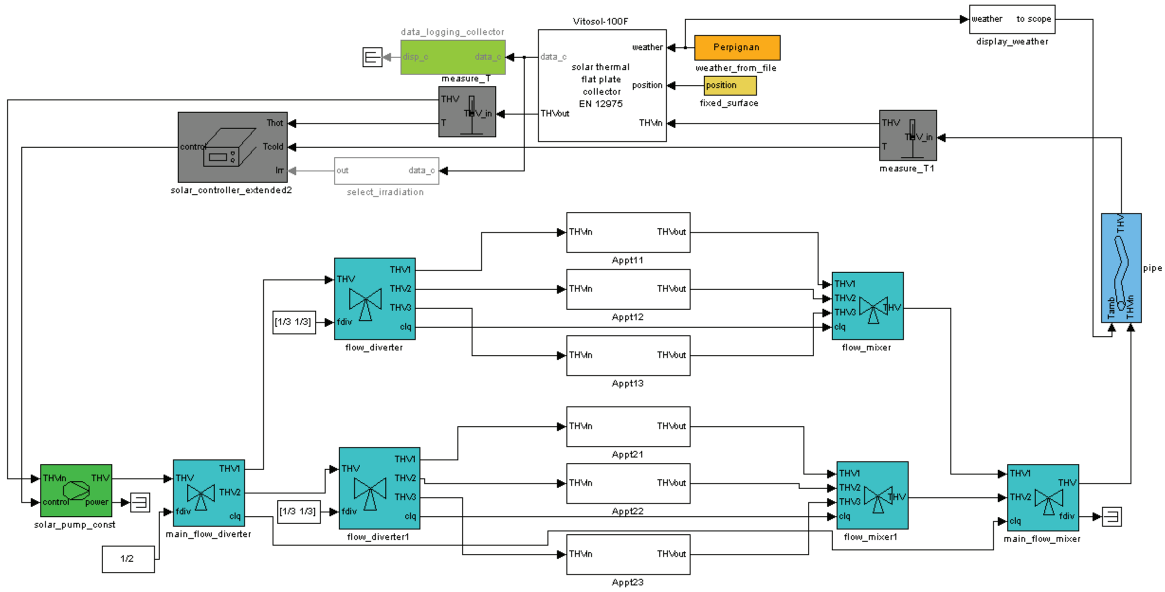

Figure 3. Matlab/Simulink model of an installation with 6 apartments

A study must be made with smaller heat exchanger, lower solar fraction to understand the main phenomenon. This study will also be completed with the case when the apartments have not the same consumption (in time, volume...).

Table 1. Results of the simulation for different adjustments of the main valve.

	Apt 11/12/13			Apt 21/22/23		
Global solar fraction	Mass flow	Solar fraction	Ratio fraction/global fraction	Mass flow	Solar fraction	Ratio fraction/global fraction
68,8%	1	68,8%	100,0%	1	68,8%	100,0%
68,8%	+10%	68,9%	100,2%	-10%	68,7%	99,8%
68,8%	+20%	69,0%	100,3%	-20%	68,6%	99,7%
68,6%	+50%	69,3%	101,1%	-50%	67,8%	98,9%
67,8%	+75%	69,9%	103,1%	-75%	65,7%	96,9%

4. CASE STUDY 2: INFLUENCE OF WEATHER DATA TIME STEP AND THERMAL CAPACITY ON TWO MODELS OF SOLAR COLLECTORS

4.1 Object of the study

The influence of the collector thermal capacity, the time step of the weather data and the collector model on the energy gain of thermal solar collectors is investigated.

4.2 Numerical models

4.2.1 Collector model from EN 12975

This collector model is the one proposed and used in EN 12975[2]. The equation for the energy balance is the following:

$$\frac{\dot{m}\, cp\, (T_{out} - T_{in})}{A} = F'(\tau\alpha)K_{dir}I_{dir} + F'(\tau\alpha)K_{dfu}I_{dfu} - c_1(T_m - T_{amb}) - c_2(T_m - T_{amb})^2 - c_3 v_{wind}(T_m - T_{amb}) - c_6 v_{wind} I_{glb} + c_4\left(E_{longwave} - \sigma_{SB}(T_{amb} + 273.15)^4\right) - c_5\frac{dT_m}{dt} \quad (1)$$

Often in test reports the optical efficiency or conversion factor η_0 is given. The correlation for $F'(\tau\alpha)$ is:

$$\eta_0 = F'(\tau\alpha)(K_{dir}(15^\circ) * 0.85 + K_{dfu} * 0.15) \quad (2)$$

The incidence angle modifier K_{dir} is dependent on the angle θ(L) and θ (T)

$$K_{dir} = Kb(L) * Kb(T) \quad (3)$$

where Kb(L) and Kb(T) are given in lookup-tables in dependancy of θ (L) and θ (T).

4.2.2 Collector model 2x1

The 2x1 model of a flat plate collector is a two-node model that includes thermal capacity of the collector and heat transfer between the absorber and the fluid. Optical collector properties are modelled as in the EN 12975 model. The collector is divided in two parts: the absorber and the fluid. The energy balance of the absorber is a differential equation to calculate the absorber temperature (T_a):

$$c_{col}\frac{dT_a}{dt} = ULIN(T_{amb} - T_a) + UQUA(T_{amb} - T_a)^2 + USKY(T_a - T_{sky}) + U_{wind}w_{wind}(T_{amb} - T_a) - hi(T_a - T_f) + \dot{q}_{solar} \quad (4)$$

The energy balance for the fluid is a differential equation to calculate the fluid temperature (Tf):

$$c_{fl}\frac{dT_f}{dt} = \frac{\dot{m}\,cp}{A_{coll}}(T_{in} - T_f) + hi(T_a - T_f) \quad (5)$$

where the heat capacity of fluid per surface (cfl) is:

$$c_{fl} = \frac{M\,cp}{A_{coll}} \quad (6)$$

4.2.3 Global conditions of the simulation

The weather data come from Meteonorm 6.1.0.13 for the city Nantes (France) with two time step: 1 hour and 1 minute. The azimuth of the collector is 0° (south) and its incidence angle is 45°. The inlet temperature is constant and the algorithm for controlling the pump is:

- turns ON when the difference between the collector mean temperature and the inlet temperature of the fluid is above than 3 K;
- turns OFF when the outlet temperature is equal or below the inlet temperature.

4.2 Results

The results for a typical flat plate collector (see Fig 4) show that there is a major difference between the EN model and the 2x1 model for low thermal capacity up to 15%. For large thermal capacity there is no difference between hourly and minutely weather data. In general the energy gain is higher at low thermal capacity.

For the hourly data both models show a trend towards a constant value at lower thermal capacity. For the minutely data the collector yield rises almost constantly. The important difference between the models is that the 2x1 model shows the expected linear relationship between thermal capacity and yield whereas the EN model tends to increase more at low capacity. It should be examined further if the models and hourly weather data is still suitable for collectors with very low thermal capacity like evacuated tube collectors.

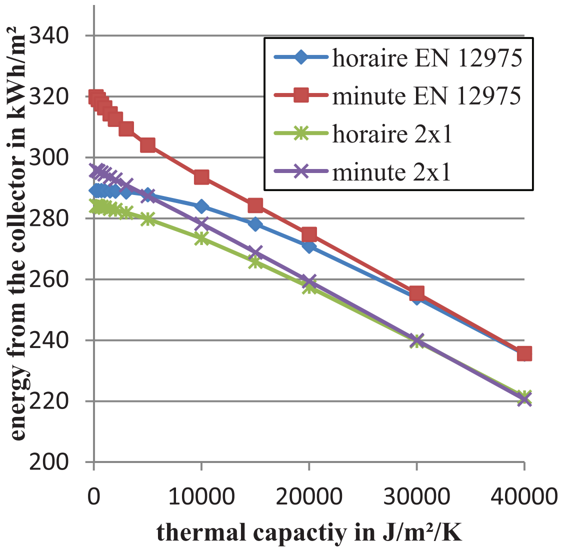

Fig 4. Results of the simulation with a constant inlet temperature of 80°C.

5. CASE STUDY 3: OPTIMIZATION OF THE SCHEMA OF AN INDUSTRIAL HIGH TEMPERATURE INSTALLATION

5.1 Object of the study

The project is to use solar energy to preheat the water of the pickling bath for the produced dhw cylinders. In a preliminary design an engineering bureau proposed a schema with a buffer tank between the collectors and the heating loop.

The current study is made to economically compare this solution (called Solution withB) to a hydraulic schema without buffer tank (called Solution withoutB). Furthermore, the type of solar collector (flat plates or vacuum tubes) is tested.

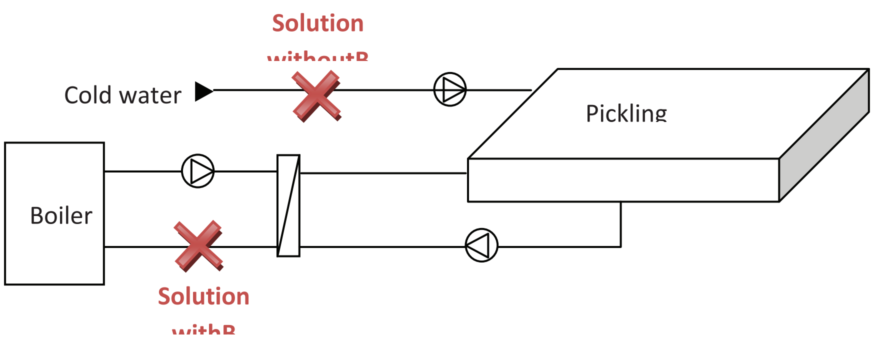

Figure 5. Schema of the initial installation. The position to feed in the solar energy of the two solutions are marked by the red crosses.

5.2 Solution with buffer tank (Solution with B)

The pickling bath needs to be regularly refilled (see Fig. 5). The idea was to pre-heat this new fresh water with solar energy. The buffer tank has a volume of 5m^3, which corresponds to the daily needs of fresh water, a loss coefficient of 1.2 W/(m^{2}K) and an axial conductivity of 1 W/(m K). The mass flow of fresh water is fixed and equal to 200l/h. The temperature of the cold water is 20°C.

5.3 Solution without buffer tank (Solution without B)

The solar installation can also be integrated in the heating loop of the bath (see Fig. 5). In this case, the most important thing is to achieve as often as possible a set temperature. To model this constraint, a PID controller is used to keep a temperature of 95°C. The inlet temperature is assumed to be constant and equal to 85°C.

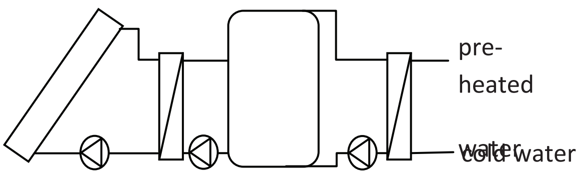

Figure 6a. Schema of the Solution with B.

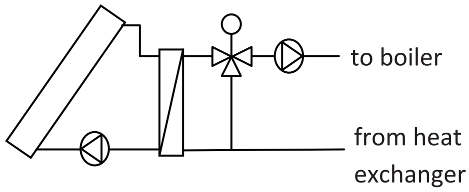

Figure 6b. Schema of the Solution without B

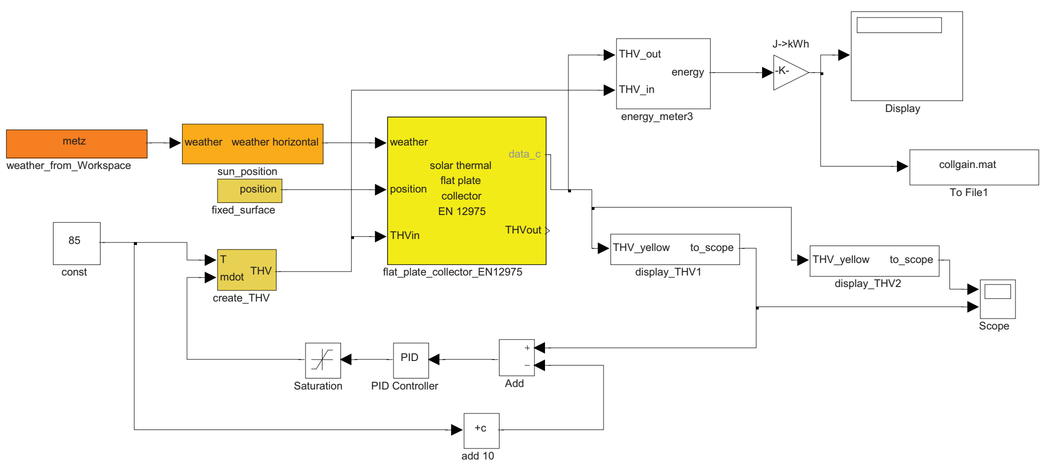

Figure 7. Model Matlab/Simulink with CARNOT blocs for the simulation.

5.2 General parameterisation

- The weather data are those for Metz (France) and come from Meteonorm 5.1.
- The two types of collectors have the properties defined in Table 2.
- The collector field is assumed to have a maximal area of 100 m^2, which correspond to 43 flat plate collectors (exactly 98.9 m^2) or 33 vacuum tubes collectors (exactly 99 m^2). The azimuth of the collector field is 0° (south), with an incidence angle of 30°.

Table 2. Main parameters of the solar collectors according to EN 12975. c3, c4 and c6 are supposed nuls.

Property	Vacuum tubes	Flat plate
A (m^2)	3	2.3
η_0	0.789	0.791
c1 (W/(m^{2}K))	1.36	3.757
c2 (W/(m^{2}K^2))	0.0075	0.0147
c5 (J/m^{2}K))	7800	5350

5.3 Installation prices

The Table 3. shows the prices of the different components for all the configurations. In the studied case, the cheapest solutions are the "Solution withoutB". As the solar field global area is set, using vacuum tubes collectors is more expensive than using flat plates.

Table 3. Rough estimation of the installation prices in Euros.

		Solution withB – Flat plates		Solution withB – Vacuum tubes		Solution withoutB – Flat plates		Solution withoutB – Vacuum tubes	
Product	Unit Price	Number	Total price	Number	Total price	Number	Total price	Number	Total price
Flat plate	550	43	23650			43	23650		
Vacuum tubes	900			33	29700			33	29700
Mounting set	60	43	2580	33	1980	43	2580	33	1980
Buffer tank (1 m^3)	1000	5	5000	5	5000				
Pump and heat exch.	5000	2	10000	2	10000	1	5000	1	5000
Installation per collector	100	43	4300	33	3300	43	4300	33	3300
TOTAL price			**45530**		**49980**		**35530**		**39980**

5.4 Results

The simulation allowed comparing the different useful solar gains of the schemas. As expected, the system with the best efficiency is the solution with buffer tank and vacuum tubes (see Table 4.). Vacuum tubes collectors have a better efficiency than flat plate collectors and store the energy enables to minimise the effect of the delay which can occur between the solar gains and the need of heat. The price of one kWh per square meter of installed collectors after 10 years is a good indicator to choose the optimal cost/efficiency solution. Because of their bad efficiency, the flat plate collectors have to be avoided without storage tank in this project. The global installation costs almost twice the price of the other solutions. The best solution seems to be the "Solution withoutB" using vacuum tubes collectors, but the difference is slight and other parameters needs to be taken into account such as available space for the tank, ease of installation, etc.[1]

Table 4. Performances and costs comparison.

		Useful solar gains ($kWh/(m^2year)$)	**Installation price (€) (see Table 3.)**	**Energy price (10 years of operation) $1kWh/m^2$ (€)**
Solution withB	**Vacuum tubes**	516.6	**49980**	0.10
	Flat plate	429.4	**45530**	0.11
Solution withoutB	**Vacuum tubes**	450.2	**39980**	0.09
	Flat plate	148.5	**35530**	0.24

6. CONCLUSION

These three study cases are examples of use of CARNOT in real situation. They show that it can be a good tool for development of new products for the market of solar energy.

REFERENCES

[1] Free Software Foundation (2007), GNU Lesser General Public License, Version 3.

[2] EN 12975-2:2006-06, Thermal solar systems and components – Solar collectors – Part 2: Test Methods

[1] Finally the Solution withoutB was installed using a 180 m² vacuum collector field. In difference to the initial study the collectors were mounted directly on the roof with an inclination of only 10°. The simulation study predicted an energy yield of 398 kWh/m² for this situation. The measurement of the first year of operation showed an energy yield of 388 kWh/m².

PRIMJENE CARNOT-A U RAZVOJU SUNČEVE TOPLINSKE ENERGIJE

Sažetak: *CARNOT je dodatak alatima za Matlab®/Simulinku®. Prikazana su tri primjera korištenja ovog alata za simulaciju sustava generatora topline. Studija utjecaja na hidrauličku ravnotežu sveobuhvatnih individualizirano-kolektivnih solarnih postrojenja pokazuje da smanjenje od maksimalno 20% u odnosu na nominalni maseni protok nema značajniji utjecaj na udio solarne uštede. Proučavan je utjecaj meteoroloških podataka, vremenskog koraka simulacije i toplinskih kapaciteta dva modela solarnih kolektora. Izbor sheme za industrijsku visokotemperaturnu instalaciju je potpomognut simulacijom.*

Key words: Matlab solarna simulacija, Conventional And Renewable eNergy system Optimization Toolbox

UČINKOVITO KORIŠTENJE ENERGIJE U STAMBENIM OBJEKTIMA

EFFICIENT USE OF ENERGY IN BUILDINGS

PARAMETRI ZA OPTIMIRANJE ENERGETSKI UČINKOVITE OBITELJSKE KUĆE

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Sažetak: *Energetski visoko efikasne obiteljske kuće su se u Sloveniji pojavile oko 2005. godine, u većem broju su počele nastajati 2008.godine. Njihova energetska efikasnost je različita, od pasivnih kuća (godišnja potrebna toplina za grijanje je najviše 15 kWh/(m^{2}a)), do vrlo dobrih niskoenergetskih kuća (15 do 25 kWh/(m^{2}a)) i niskoenergetskih kuća (25 do 40 kWh/(m^{2}a)). Pristupi njihovom planiranju različiti su od ustaljene prakse i moraju poštivati najnovija saznanja i smjernice. Članak predstavlja istraživanje 106 energetski učinkovitih zgrada, u kojima su bile evidentirane: veličina kuće, broj stanara, smještenost u prostor, faktor oblika, vrsta i kvaliteta toplinskog ovoja, godišnja potrebna toplina za grijanje i sanitarnu vodu. Izrađene su također i analize ključnih parametara koji utječu na energetsku učinkovitost zgrada i zadane smjernice, koje su vrlo bitne prilikom njihovog planiranja i optimiranja.*

Ključne riječi: pasivna kuća, niskoenergetska kuća, energetski koncept

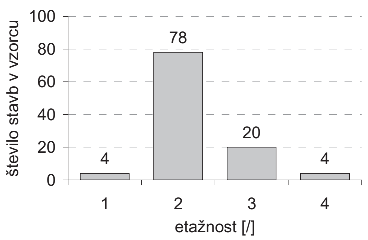
1. UVOD

Energetski učinkovita obiteljska kuća (vrlo dobra niskoenergetska kuća, pasivna kuća) na slovenskom prostoru se počela pojedinačno pojavljivati oko 2005. godine. Razvoj gradnje energetsko učinkovitih kuća počeo je 2008. godine, tako da je u razdoblju od zadnje 4 godine evidentirano [Ekosklad, j.s.] približno 400 takvih projekata. Demonstracijsko značenje tih primjera znatno je utjecalo na širu prepoznatljivost novih pristupa ka omogućavanju energetske učinkovitosti zgrada.
Energetsko učinkovita zgrada u praksi može nastati samo kao posljedica interdisciplinarnog planiranja, koji u svakom koraku projektiranja slijedi i provjerava učinke projektnih rješenja. Za arhitekte i građevinare je pri tom od posebnog značaja dobro poznavanje ključnih pravila, koji vode u oblikovanje projektnog rješenja za energetsko učinkovit i ekonomsko racionalan stambeni objekt.

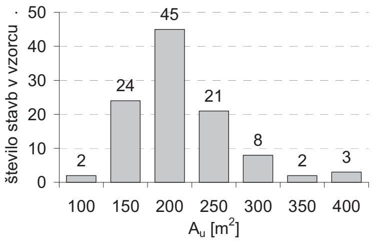
U članku su predstavljeni rezultati, izvedeni na uzorku energetski učinkovitih stambenih zgrada. U istraživanju su bili evidentirani ključni podaci o zgradama, npr. veličina, broj stanara, orijentacija, faktor oblika, sastav toplinskog ovoja, godišnja potrebna toplina za grijanje i sanitarnu vodu. Na osnovu tih analiza osvijetljeni su utjecajni mehanizmi, koji su potrebni za lakše oblizivanje energetski učinkovite zgrade. Istraživanje osvjetljuje načine na koje se odaziva projektno rješenje pri ključnim odlukama, koje je smisleno na pravilan način prenijeti u projekte.

2. PREDSTAVLJANJE UZORKA ISTRAŽIVANJA

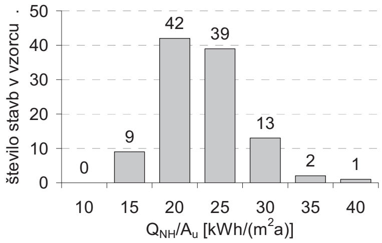
Istraživanje je izvršeno na osnovi uzorka od 106 reprezentativnih obiteljskih kuća, izabranih iz ukupne količine prijavljenih projekata za nepovratne financijske poticaje pri Eko skladu, s godišnjom potrebnom toplinom za grijanje od 10 do 40 kWh/(m^2a). Rezultati istraživanja u nastavku su predstavljeni u obliku analiza bilance i analize parametara, sa analizama i zaključcima. Prikazi rezultata i analiza odnose se isključivo na analizirani uzorak.



Slika 1: Broj etaža



Slika 2: Kondicionirana površina zgrade



Slika 3: godišnja potrošnja topline za grijanje zgrada

Uzorak energetsko učinkovitih novogradnji bio je opsežan, objekti za analizu izabrani su metodom slučajnog odabira, bez prethodne selekcije, dakle kako se i novogradnje pojavljuju u praksi.

U uzorku je 80% jednoobiteljskih kuća, preostali dio su kuće sa dva gospodarstva i dvoobiteljske kuće. 74% stambenih kuća uzorka ima dvije etaže (tipično prizemlje i mansarda ili prizemlje i jedna etaža), 19% tri etaže (tipično prizemlje i dvije etaže ili podrum sa prizemljem i potkrovljem), preostalih 7% predstavljaju prizemni ili objekti sa 4 etaže (slika 1). Kriterij kondicionirane površine (A_u), t.j. ogrijevane i prozračivane površine prostora unutar toplotnog ovoja u uzorku zgrada upravo zato iskazuje (slika 2) obilježja tipične stambene gradnje. Od spomenutih zgrada njih 42% ima površinu između 150 i 200 m^2. Manje od 150 m^2 kondicionirane površine ima 25% zgrada, nad 200 m^2 pa 33% zgrada analiziranog uzorka. Energetska učinkovitost je različita – 8% novogradnji uzorka iskazuje (slika 3) godišnju potrebnu toplinu za grijanje u granicama $Q_{NH}/A_u \leq 15$ kWh/(m^2a) (pasivne kuće), 76% u granicama 15 kWh/(m^2a) $< Q_{NH}/A_u \leq 25$ kWh/(m^2a) (vrlo dobre niskoenergetske kuće) i 16% uzorka u granicama 25 kWh/(m^2a) $< Q_{NH}/A_u \leq 40$ kWh/(m^2a) (niskoenergetske kuće).

3. PRISTUP PLANIRANJU I ANALIZA BILANCE NOVOGRADNJI

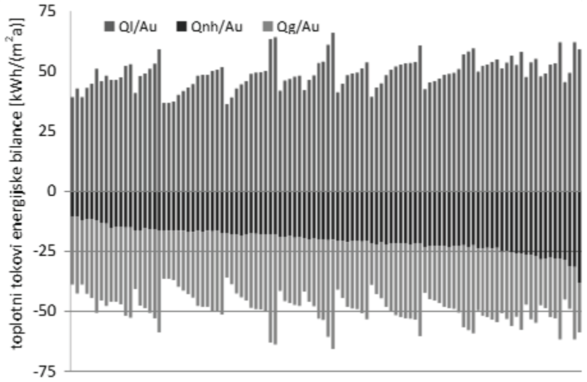
Osnovni koncept energetsko učinkovite novogradnje je kompaktan oblik zgrade i optimalna veličina ostakljenog ovoja glede na orijentaciju, toplinsko zoniranje zgrade i isključivanje neogrijevanih dijelova iz toplinskog ovoja. Sa energetskog vidika su povoljnije, odnosno optimalne manje površine zgrada ili manja kondicionirana površina na korisnika kuće (A_u/P).

U postupku optimiranja projekta energetsko učinkovite stambene zgrade, npr. pasivne kuće, potrebno je osigurati ravnotežu između energetskih tokova preko toplinskog ovoja zgrade, koji je definiran standardima [SIST EN ISO 13789:2007]. U prvom redu, moramo uspostaviti pravilan omjer između tokova toplinskih gubitaka Q_L (transmisijski toplinski gubici Q_T i toplinski gubici nastali zbog prozračivanja Q_V) i tokova toplinskih dobitaka Q_g (dobici sunčanog zračenja Q_s, te unutarnjih izvora topline Q_i), zatim dovedene energije v sistemima aktivnog ogrijevanja Q_{NH}, koji nastaju kao razlika toplinskih gubitaka i iskoristivih dobitaka, te utjecaja mase same zgrade.

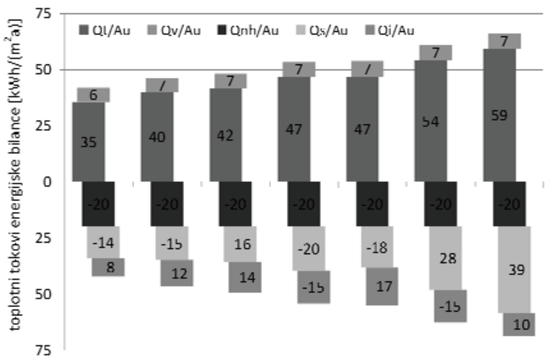
Postupak optimiranja zgrade u ciljni razred energetske učinkovitosti, koji se iskazuje kroz postignutu vrijednost Q_{NH}/A_u, dozvoljava arhitektu traženje rješenja u dva različita smjera. Isti finalni rezultat moguće je doseći na dva načina, dvjema krajnostima:

a) zgrada ima izuzetno reducirane toplinske gubitke te prosječne toplinske dobitke ili
b) zgrada ima prosječne toplinske gubitke te izrazito povećane toplinske dobitke.

Prikaz mogućih rješenja vidljiv je također i na rezultatima optimiranih zgrada iz analiziranog uzorka (slika 4). U primjeru podjele zgrada na parametar Q_{NH}/A_u, koji se postepeno podiže od vrijednosti 10 do 40 kWh/(m^{2}a), unutar pojedinih grupa s istim konačnim rezultatom Q_{NH}/A_u vidljivo je takvo razilaženje. Pri tom se na lijevoj strani svake grupe nalaze zgrade upisane u redu »a)«, na desnoj strani su zgrade opisane pod »b)«. Na primjeru skupine kuća s jednakim rezultatom Q_{NH}/A_u = 20 kWh/(m^{2}a), vidljivo je razilaženje v višim tokovima zajedničkih toplinskih gubitaka i dobitaka čak u omjeru ±20% u odnosu na prosječne skupine (slika 5).



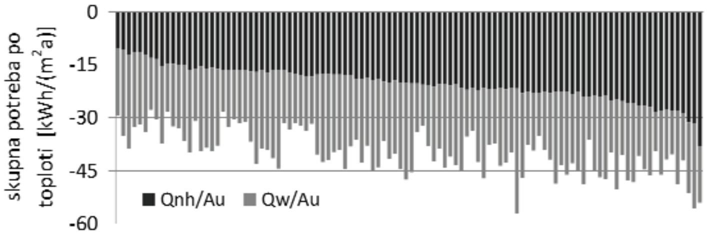
Slika 4: Rezultati projektnog optimiranja na tokovima energetske bilance



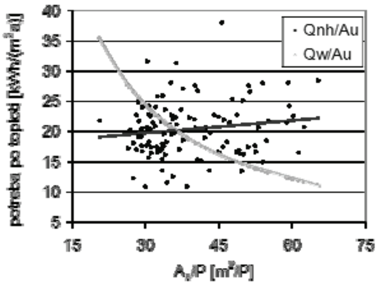
Slika 5: Primeri novogradnji iste učinkovitosti, s prikazom razilaženja tokova toplinskih gubitaka i dobitaka

Kod uobičajenih tj. energetsko manje učinkovitih stambenih zgrada, segment pripreme tople sanitarne vode predstavlja približno 20% ukupne potrošnje topline. Pri energetsko učinkovitih zgrada takvi se znatni omjeri osjetno mijenjaju, kako je i pojašnjeno na analizi uzorka. Prilagođenim dizajnom osigurana je manja godišnja potrebna toplina za ogrijevanje, čija prosječna vrijednost na analiziranom uzorku iznosi Q_{NH}/A_u = 20,4 kWh/(m^{2}a), s minimalnom i maksimalnom vrijednošću 10,9 i 38,1 kWh/(m^{2}a). U segmentu tople sanitarne vode s povećavanjem učinkovitosti instalacija istina je da smanjujemo potrebu za toplinom, ali ne možemo smanjivati samu količinu potrošnje tople vode u kućanstvu, jer je ovisna o broju stanara. Na osnovi toga, topla sanitarna voda zahtijeva količinu toplina koja u prosjeku iznosi Q_w = 19,7 kWh/(m^{2}a), s minimalnom i maksimalnom vrijednosti 11,2 i 35,5 kWh/(m^{2}a).

Kod energetski najučinkovitijih zgrada uzorka (pasivne kuće), udio tople vode u odnosu na toplinu za grijanje predstavlja veći udio (slika 6). Kod ostalih zgrada uzorka segmenti su približno jednakovrijedni, odnosno prevladava opet ogrijevanje prostora. Ovisnost oba segmenta najbolje je prikazana kroz parametre (slika 7), u primjeru ovisnosti toplinskih potreba Q_{NH}/A_u i Q_w/A_u od parametra stambene površine A_u/P. Taj parametar ima na obrađenom uzorku srednju vrijednost 39 m^2/osobu, s minimalnom i maksimalnom vrijednošću 21 i 65 m^2/osobu. Vrijednosti Q_{NH}/A_u i Q_w/A_u su izjednačene kod visine vrijednosti približno 20 kWh/m^{2}a i 35 m^2/osobu. Zgrade s više stanara imaju veći udio toplinskih potreba za zagrijavanjem sanitarne vode. Kod zgrada s manje stanara prevladavaju veće toplinske potrebe za ogrijevanje prostora.



Slika 6: Letne toplinske potrebe – potrebna toplina za grijanje zgrada i pripremu tople vode



Slika 7: Promjene u strukturi toplinskih potreba – toplina za grijanje zgrade i pripremu tople vode

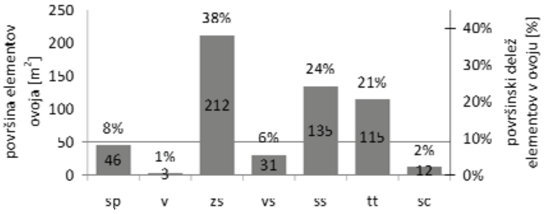
4. ANALIZA ENERGETSKIH TOKOVA S UTJECAJNIM PARAMETRIMA I REZULTATIMA

Analiza na uzorku se U svom prvom dijelu odnosi prvenstveno na ključne energetske tokove godišnje toplinske bilance te spoznavanje ključnih utjecajnih parametara.

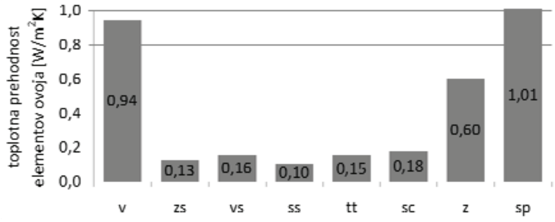
4.1. Toplinski ovoj i transmisijski toplinski gubici

U godišnjoj energetskoj bilanci transmisijski toplinski gubici kroz ovoj predstavljaju najveći pojedini segment. Njihova količina ovisna je od veličine i sastava toplinskog ovoja – dakle od faktora oblika zgrade i toplinske provodljivosti (U) pojedinih elemenata.
Označavanje ključnih elemenata toplinskog ovoja koji su prikazani na slikama je sljedeće: zs – vanjski zid, vs – ukopani zid, ss – krov ili strop, tt – podovi na terenu ali prema neogrijevanom podrumu, sc – zid prema neogrijevanoj zoni, sp – ugrađeni vanjski prozori, z - stakla, v - vanjska vrata.

Na analiziranom uzorku (slika 8) fasade predstavljaju najveći pojedinačni površinski udio (38%), zatim im slijede krovovi/stropovi s 24% i podovi s 21%. Zbog pravilnog toplinskog zoniranja površinski udio ukopanih zidova i elemenata u kontaktu sa neogrijevanim zonama relativno je nizak i iznosi 8%. Vanjski prozori i vrata imaju ukupni udio od 8%. Prosječne vrijednosti toplinske prohodnosti elemenata (slika 9), koji su u kontaktu sa vanjskim zrakom kreću se između U = 0,10 i 0,15 W/(m^{2}K), elementi, koji su u kontaktu sa terenom i neogrijanim zonama su između U = 0,15 i 0,18 W/(m^{2}K). Ostakljenja u toplinskom ovoju imaju u prosjeku toplinsku prohodnost U = 0,60 W/(m^{2}K), te ugrađene vanjske prozore i vrata U = 1,0 W/(m^{2}K).



Slika 8: Prosječne površine i njihovi udjeli u toplinskom ovoju



Slika 9: Prosječne toplinske prohodnosti, po skupinama elemenata ovoja

Prosječni transmisijski toplinski gubici predstavljaju na obrađenom uzorku Q_T/A_u = 42 kWh/(m^{2}a), s minimalnom i maksimalnom vrijednošću 30 i 59 kWh/(m^{2}a). Ugrađeni vanjski prozori i vrata imaju najveći pojedinačni udio od 41%, unatoč učinkovitim tehničkim rješenjima. Navedene toplinske gubitke nadomještaju toplinski dobici koji su opisani u nastavku. Fasade imaju 25% udio, dok stropovi/krovovi imaju 13%. Zbog izloženosti i njihovom velikom udjelu, upravo na tim mjestima tražimo tehnološka rješenja s najnižim toplinskim prohodnostima. Podovi na terenu ali prema podrumima zastupljeni su sa 9%, dok su ukopani zidovi 5%. Toplotni gubici zbog toplinskih mostova predstavljaju preostali udio od samo 3%, zbog toga jer su ti detalji riješeni već u procesu planiranja.

4.2. Prozračivanje prostora, zrakonepropusnost zgrada i ventilacijski gubici

Prozračivanje zgrade predstavlja pored transmisijskih toplinskih gubitaka i važan segment toplinskih gubitaka. Kod energetsko učinkovitih zgrada u okviru obrađenog uzorka oni predstavljaju Q_L/A_u = 7 kWh/(m^{2}a), s minimalnom i maksimalnom vrijednošću 5 i 10 kWh/(m^{2}a), dakle manje od 15% ukupnih toplinskih gubitaka.

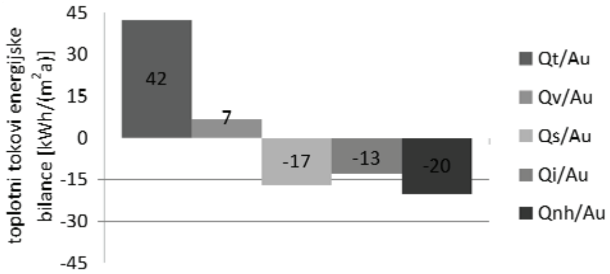
Jedan dio toplinskih gubitaka, koji je nastao prozračivanjem u zgradi, nastane zbog kontroliranog prozračivanja. U zgradu dovodimo određenu količinu svježeg zraka, koji je ovisan od broja ukućana i režima boravka. Istovremeno mi odvodimo iskorišteni zrak. Na analiziranim zgradama je prosječna izmjena zraka $n = 0{,}36\ h^{-1}$, s minimalnom i maksimalnom vrijednošću u uzorku 0,30 i 0,56 h^{-1}, koji pripadaju većim i manjim zgradama. Izmjena zraka protječe mehanički, s pomoću vraćanja topline u napravama s visokom učinkovitošću (tipično 80 do 90%).
Drugi dio gubitaka zbog prozračivanja (prosječno 40% ukupnih gubitaka zbog prozračivanja) nastaje zbog prirodne izmjene zraka s okolinom, tj. (nekontroliranom) infiltracijom kroz nedovoljno zrakonepropustan ovoj zgrade. Sa izuzetno kvalitetnom ugradnjom ovoja zgrade u energetski učinkovitim zgradama dosežemo mjerene vrijednosti za zrakonepropusnost u području $n_{50} \leq 0{,}6\ h^{-1}$, koji su ujedno projektno zadane također za potrebe analize. S tako izvedenim ovojem odražava se infiltracija u prosječnoj prirodnoj izmjeni zraka 0,04 h^{-1}, s minimalnom i maksimalnom vrijednosti u uzorku od 0,03 i 0,09 h^{-1}, što je ujedno i ovisno također i o značajkama mikrolokacije i izloženosti zgrade vjetru.

4.3. Prozirni dio ovoja zgrade i dobici sunčevog zračenja

Dobici sunčevog zračenja mogu pokriti važan udio energetske bilance. Na obrađenom uzorku su vrijednosti tih dobitaka topline prosječno Q_s/A_u = 17 kWh/(m^{2}a), s minimalnom i maksimalnom vrijednošću 5 i 39 kWh/(m^{2}a). Razilaženje tih dvaju vrijednosti ukazuje na izuzetnu važnost prozirnog dijela ovoja zgrade.
Karakteristične vrijednosti ostakljenog dijela toplinskog ovoja možemo prikazati s više parametara, pri čemu ključnu važnost ima broj »z«, tj. odnos površina zastakljenih elemenata zgrade i ukupne površine toplinskog ovoja (A_{sp}/A_u). Prosječna vrijednost na uzorku analiziranih zgrada je z = 0,08, s minimalnom i maksimalnom vrijednošću 0,04 i 0,14. Upravo tako prepoznatljiv je također i odnos, koji prikazuje ovisnost površine staklenog dijela u odnosu na ogrijevanu stambenu površinu. Prosječna vrijednost iznosi A_{sp}/A = 0,24, s minimalnom i maksimalnom vrijednošću 0,14 i 0,46.
Raspored staklenih površina u ovoju glede na orijentaciju, najviše ovisi o smještaju zgrade u prostor, što može biti ograničeno lokacijskim uvjetima i projektnim rješenjima koja su vezana uz funkciju pojedinih prostora zgrade. Uzorak zgrada ima južnu orijentaciju 45% svih staklenih površina, s minimalnom i maksimalnom vrijednošću 11% i 85%.

4.4. Dobici unutrašnjih izvora topline

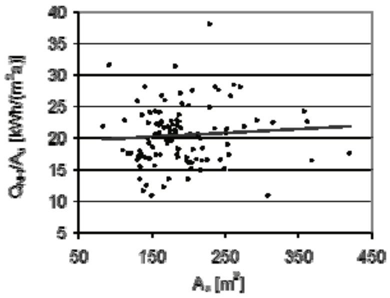
Unutrašnji toplinski izvori predstavljaju drugi dio toplinskih dobitaka, koji udjelom dostižu skoro dobitke sunčevog zračenja. Njihove vrijednosti iznose u prosjeku Q_i/A_u = 13 kWh/(m^{2}a), s minimalnom i maksimalnom vrijednoti 8 i 24 kWh/(m^{2}a).
Toplinske dobitke u energetskoj bilanci zgrada (slika 10) ne može se u potpunosti iskoristiti za ogrijevanje prostora. U tom mehanizmu ključnu ulogu imaju odnos toplinskih gubitaka i dobitaka, te prilagodljivost sistema grijanja odnosno njegovo dinamično prilagođavanje nastalim uvjetima. Kao posljedica tog odnosa, energijsko učinkovite zgrade u prosjeku iskorištavaju 96% toplinskih dobitaka, najmanje 89 i najviše 99%.



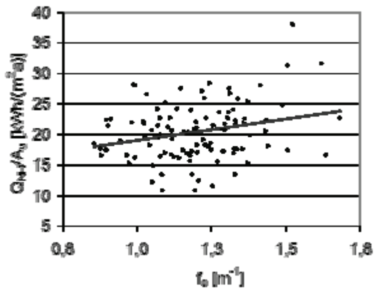
Slika 10: Prosječne vrijednosti energetskih tokova

5. ANALIZA UTJECAJA POJEDINIH KLJUČNIH PARAMETARA

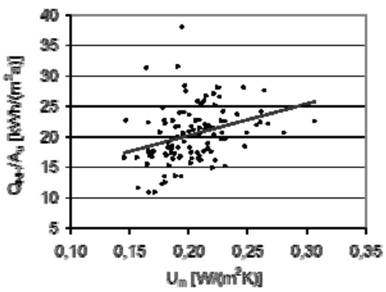
Usporedba nekih značajnih parametara i njihov utjecaj na postignutu energetsku učinkovitost analiziranih zgrada daje nam informacije na osnovi kojih možemo jednostavno tumačiti principe i učinke ključnih mehanizama unutar energetske bilance. Tako oblikovana područja željenih vrijednosti za parametre i poznavanje gibanja tih vrijednosti mogu poslužiti kao pomoć za brzu procjenu energetske učinkovitosti idejnog rješenja. Detaljnija procjena i optimizacija projekta dolazi tek kad su osnove za novogradnju konkretnije oblikovane. U tom trenutku su promjene ključnih idejnih parametara neracionalne, ukoliko procjena ukazuje na neprihvatljive rezultate.



Slika 11: Ovisnost potrebne topline za ogrijevanje i površine kondicioniranih prostora



Slika 12: Ovisnost potrebne topline za ogrijevanje i faktora oblika

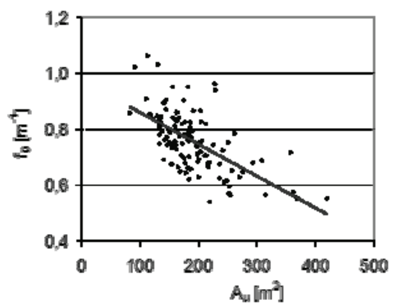


Slika 13: Ovisnost potrebne topline za ogrijevanje i prosječne toplinske protočnosti

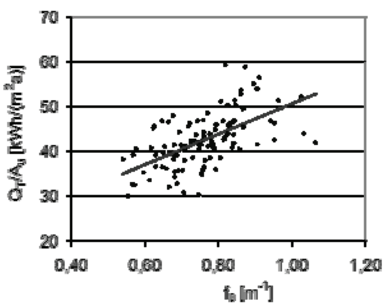
Za energijsko učinkovite stambene zgrade možemo zaključiti, da povećavanje jednoobiteljske ili dvoobiteljske kuće (pri tom mislimo na ogrijevanu površinu prostora A_u ili odnos A_u/P), pri istim karakteristikama i dizajnu zgrade, dovodi do veće potrebe za energijom za grijanje (slika 7 in 11). Taj zaključak ne vrijedi za energetski manje učinkovite zgrade, kod kojih se povećanjem ogrijevane površine potreba za toplinom za grijanje smanjuje. Razlog tom zaključku za energetski učinkovite novogradnje također je i činjenica, da se povećanjem zgrade minimalno smanjuje koncentracija unutrašnjih izvora topline. Povećanjem zgrade se minimalno povećavaju transmisijski toplinski gubici, koji količinski nisu proporcionalni smanjenju unutarnjih toplinskih dobitaka. Većina analiziranih objekata ima kondicioniranu površinu između 100 i 200 m^2 te vrijednost A_u/P od 25 do 40 m^2/osobu.

Rezultati analize ujedno potvrđuju dva zaključka:
- Potrebe za toplinom za grijanje prostora rastu s povećavanjem nekompaktnosti objekta (slika 12) odnosno povećanjem faktora oblika zgrade (f_0);
- potrebe za toplinom za grijanje prostora rastu (slika 13) s povećavanjem prosječne toplinske prohodnosti (U_m).

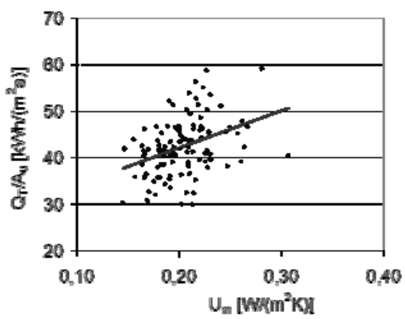
Uzrok za to su transmisijski toplinski gubici, koji kod optimiranih zgrada još uvijek prevladavaju u energetskoj bilanci. Za povećavanje energetske učinkovitosti zgrada smo prethodno drastično smanjili toplinske gubitke prozračivanja (zrakonepropusnost kod izvođenja i učinkovito prozračivanje). Većina analiziranih objekata u području je faktora oblika f_0 = 0,6 i 1,0 m^{-1} te ima srednju toplinsku propusnost ovoja između U_m = 0,15 i 0,25 $W/(m^2K)$.



Slika 14: Ovisnost kondicionirane površine i faktora oblika



Slika 15: Ovisnost transmisijskih toplinskih gubitaka i faktora oblika

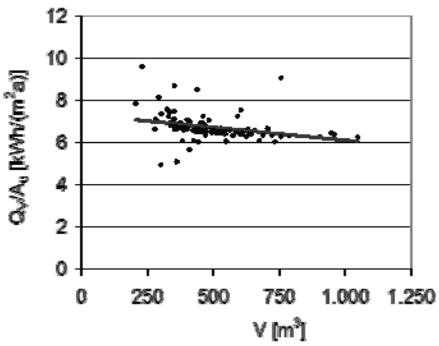


Slika 16: Ovisnost transmisijskih toplomskih gubitaka i prosječne

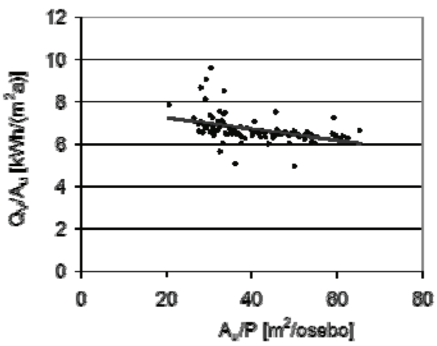
Posebna briga kod optimiranja namijenjena je osmišljavanju što je moguće kompaktnijeg objekta. Prilikom povećavanja zgrade, faktor oblika brzo se smanjuje (slika 14). To bi značilo da nekompaktnost objekta ima bitno veći tj. negativni utjecaj kod (osjetljivijih) manjih zgrada. Kod većih objekata, gdje arhitekt ima više slobode, veći faktor oblika ima manje negativnih posljedica na potrošnju energije za grijanje. Iz prikaza analiziranog uzorka vidljivo je da faktor oblika ima veći utjecaj na transmisijske gubitke (slika 15), kao prosječna toplinska propusnost (slika 16). Kod njega je naime rastresenost uzorka naglašenija i ne ukazuje na tako izrazitu povezanost.

Iz rezultata na uzorku vidljivo je također da se toplinski gubici nastali prozračivanjem smanjuju u sljedećim primjerima:
- pri povećavanju veličine zgrade, te istovremenom povećanju (slika 17) njene neto grijane površine (V);
- pri povećavanju kondicionirane površine na jednog stanara (slika 18).

Uzrok za taj zaključak je činjenica da pri određivanju intenziteta prozračivanja veću važnost ima količina svježeg zraka, koji je ovisna od broja stanara, nego količina zraka kojeg moramo odvoditi iz zgrade.

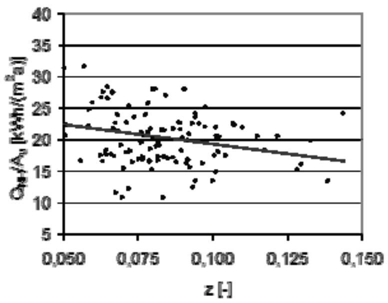


Slika 17: Ovisnost toplinskih gubitaka nastalih prozračivanjem i neto grijane površine zgrade

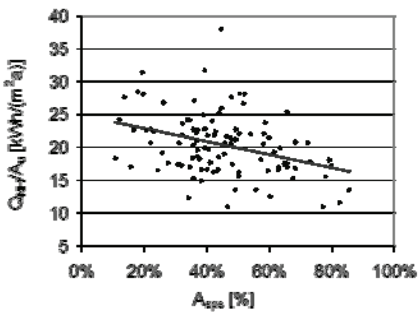


Slika 18: Ovisnost toplinskih gubitaka nastalih prozračivanjem i kondicionirane površine po stanaru

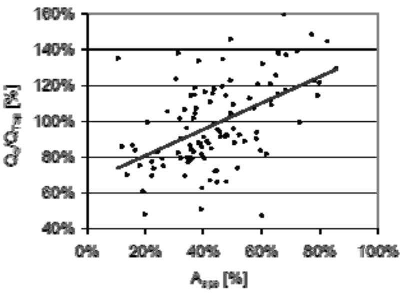
Načela dizajniranja zastakljenog dijela toplinskog ovoja znatno utječu na energetske karakteristike funkcioniranje zgrada, jer dobici sunčevog zračenja u toplinskoj bilanci analiziranog uzorka pokrivaju jednu trećinu ukupnih toplinskih gubitaka. Povećavanjem udjela staklenih površina u ovoju (slika 19) te istovremenim orijentiranjem ostakljenih površina pretežno u smjeru juga (slika 20), rezultat bilance se osjetno unapređuje. Pri tome je važan udio staklenih površina u ovoju zgrade, koji se na većini uzorka kreće između 7 i 10%, odnosno udio staklenih površina u odnosu na ogrijevanu površinu stambene jedinice, gdje je udio između 20 i 30%. Udio južno orijentiranih staklenih površina kreće se između 30 i 70%. Energetsku bilancu zastakljenih površina predstavlja odnos dobitaka sunčanog zračenja i transmisijskih toplinskih gubitaka prozora. Analiza prikazuje (slika 21), da je neutralan rezultat bilance (vrijednost odnosa $Q_s = Q_{Tsp}$) dostignut na približno 50% južnom orijentiranju staklenih površina. U primjeru 20% južne orijentiranosti odnos dobitaka i gubitaka se smanjuje na 80% (negativna bilanca). Pri 80% udjelu staklenog dijela ovoja prema jugu, bilanca postaje pozitivna, s toplinskim viškom u visini od 30%.



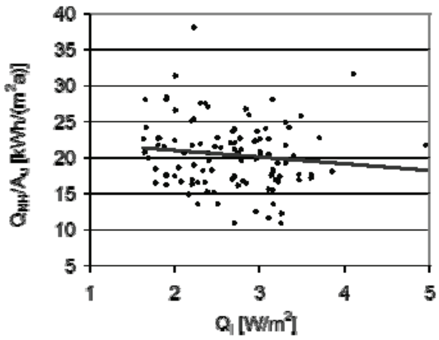
Slika 19: Ovisnost potrebne topline za grijanje i udjela staklenih površina u ovoju



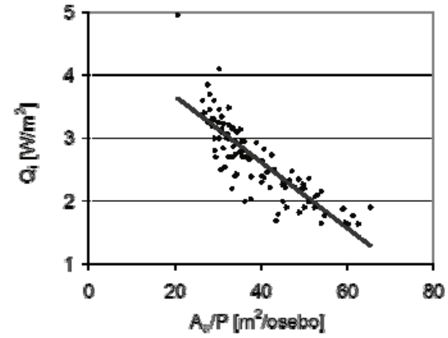
Slika 20: Ovisnost potrebne topline za grijanje i udjela južno orijentiranih površina prozora



Slika 21: Ovisnost energetske bilance prozora i udjela južno orijentiranih površina prozora

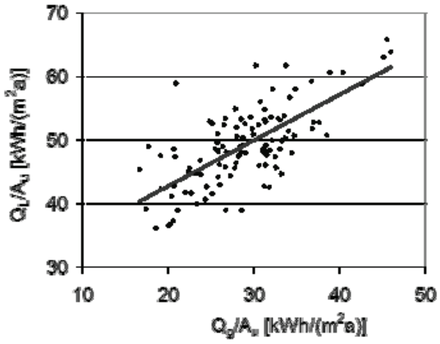


Slika 22: Ovisnost unutrašnjih izvora topline i potrebne topline za grijanje

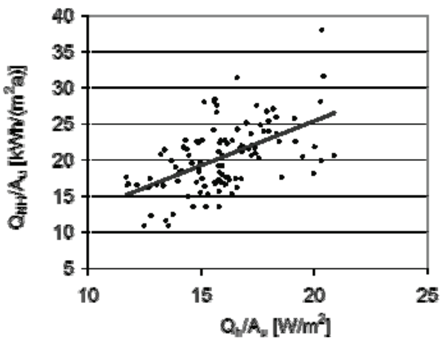


Slika 23: Ovisnost grijane površine o stanarima i unutarnjih izvora topline

Tipične vrijednosti unutrašnjih izvora topline za zgrade uzorka u području između 2,0 i 3,5 W/m^2 (slika 22), pri čemu njihove vrijednosti kod istih osobina zgrade nije moguće bitno povećati, u praksi ih je dugoročno moguće samo smanjiti. Kod primjera povećavanja tih izvora, zgrada bi trebala ili povećati broj stanara od projektiranog broja ili imati bitno manje učinkovite naprave u gospodarstvu, što svakako nije dugoročni razvojni cilj, odnosno trajnosni smjer korištenja zgrada. Budući je intenzivnost korištenja naprava u zgradama ovisna skoro isključivo o broju stanara jasan je trend povećavanja unutrašnjih dobitaka pri smanjivanju površine zgrade na broj stanara (slika 23).



Slika 24: Ovisnost zajedničkih toplinskih dobitaka i toplinskih gubitaka



Slika 25: Ovisnost potrebne toplinske smage za grijanje i potrebne topline za grijanje

Povećavanjem toplinskih gubitaka zgrade, potreba za toplinom za grijanje se povećava, odnosno s povećavanjem toplinskih dotoka se smanjuje. U primjeru manjih vrijednosti energetskih tokova (slika 24), zajednički toplinski dobici mogu doseći manje od pola ukupnih toplinskih gubitaka, dok u primjeru visokih vrijednosti energetskih tokova se udio pokrivanja može podići na tri četvrtine. Taj zaključak podržan je s prethodno identificiranim scenarijima traženja istovrijednih rješenja za energetsko učinkovitu gradnju u dva smjera razmišljanja: niski gubici kod niskim dotoka ili visoki gubici kod visokih dotoka (slika 4 i 5).

Osiguravanje primjerene toplinske snage za grijanje u špici sezone grijanja (slika 25) slijedi potrebama zgrade za toplinom za grijanje, budući je mehanizam određivanja vrijednosti sličan, pri čemu prve vrijednosti u prosjeku gotovo uvijek dosežu 80% druge, u području između Q_h/A_u = 12 i 20 W/m^2. Kod zgrada s Q_{NH}/A_u < 20 kWh/(m^{2}a) izjednačavanje obiju vrijednosti ne bi nužno vodilo u veću pogrešku i lako služi za brzu procjenu.
Za određivanje ukupne potrebne toplinske snage, u pravilu se uzima u obzir i dio rezervne snage za pripremu tople sanitarne vode, koja je neposredno ovisna od broja stanara, sa vrijednostima u istom razredu, tj. između 10 i 20 W/m^2!

6. ZAKLJUČAK

Istraživanje na uzorku od 106 kuća iz razreda pasivnih (godišnja potrošnja energije za grijanje najviše 15 kWh/(m^2a)), vrlo dobrih niskoenergetskih (15 do 25 kWh/(m^2a)) i niskoenergetskih kuća (25 do 40 kWh/(m^2a)) pokazala je da je promišljeno planiranje veoma značajno za dostizanje energetske učinkovitosti. Veći objekti s istim sadržajem manje su učinkoviti. Granica među ogrijevanim površinama i manje ogrijevanim ili čak neogrijevanim pomoćnim dijelom zgrada jasno je postala definirana. Relevantno je optimalno oblikovanje zgrade kod primjera manjih zgrada, koje su s vidika faktora oblika izuzetno osjetljive na promjene. Izvedeni objekti iskazuju zrakonepropusnost $n_{50} \leq 0{,}60\ h^{-1}$, što pored projektnog rješenja, traži i provjerena tehnološka rješenja i dosljedan nadzor gradnje. Vraćanje topline u sistem prozračivanja od velike je važnosti jer je to najutjecajniji parametar toplinskih gubitaka koji nastaju prozračivanjem. Naprave za prozračivanje trebaju, u energetsko učinkovitim zgradama, osigurati najmanje 85% rekuperacije. Usklađivanje toplinskih gubitaka i dobitaka od ključne je važnosti za dostignutu energetsku učinkovitost zgrade. U tom procesu potrebno je u primjeru zgrada s visokim toplinskim gubicima tražiti dodatne mogućnosti za povećavanje toplinskih dobitaka (npr. više zastakljenih površina), pri zgradama s pravilno smanjenim toplinskim gubicima, takve dodatne arhitekturne mjere nisu potrebne. Vrlo je važan smještaj zgrade u prostoru i otvaranje prozirnog dijela zgrade prema jugu. Bilo bi poželjno da je udio zastakljenih površina na ovoju zgrade oko 10%, te ako ih je od toga najviše 50% orijentiranih južno, posljedica je pozitivna energetska bilanca.

LITERATURA

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PARAMETERS FOR OPTIMIZATION OF AN ENERGY EFFICIENT FAMILY HOUSE

Abstract: *Energy efficient family houses have appeared in Sloveniaaround year 2005., and their amplified building has begun at 2008. Their energy efficiency is quite different, from passive houses (annual heat energy max 15 kWh/(m^2a)), to very good low-energy houses (15 do 25 kWh/(m^2a)) and true low-energy houses (25 do 40 kWh/(m^2a)). Methodology for planning of such houses are quite different from common practice and the latest aknowledges and guidelines must be folowed. This paper presents the research of 106 energy efficient buildings, for which were recorded: the size of the house, number of residents, placedness in space, shape factor, quality of heat insulation, annual energy for heating and DHW. Also, the analisys is made of key parameters which influence on energetic efficiency of buildings, and other guidelines which are very important for planning and optimizing of such buildings.*

Keywords: passive house, low-energy house, energy concept

MODEL SOLARNE OZRAČENOSTI GRAĐEVINA

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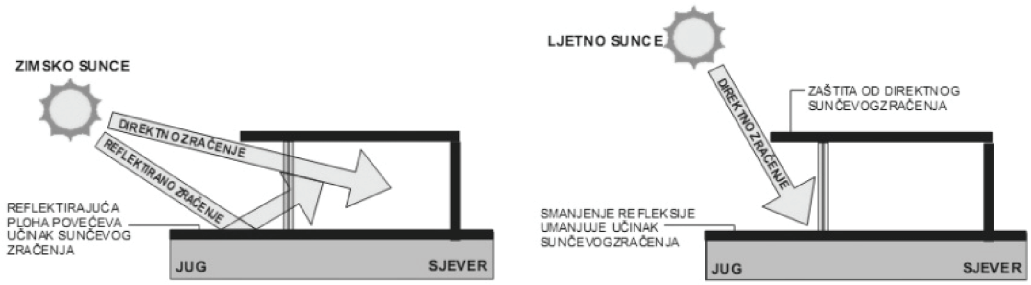
Sažetak: *Sunce kao praktički neiscrpan izvor energije ima značajnu stavku u toplinskoj ravnoteži objekta; svakodnevno dozračuje proračunski osjetnu količinu topline koja sudjeluje u nestacionarnom toplinskom toku kroz zidove a u standardnim izračunima fizike zgrade taj bitan faktor se većinom zanemaruje.U ovom radu opisat će se precizni anizotropni modeli koji služe za predikciju ozračenosti nagnute plohe, te integracija njihovih rezultata sa svojstvima objekta. Korišteni su Muneerov model i Klucherova modifikacija Temps-Coulsonovog modela, tzv. „all-sky model" za proračun raspršene komponente Sunčevog zračenja. Izvedeni model dozračene energije je u zavisnosti o lokaciji objekta, vremenu na razini dana i godine, svojstvima objekta poput orijentacije plohe, apsorpcijskom koeficijentu (boji i teksturi) i nagibu plohe, te reflektiranom zračenju od okolnog terena.Napravljeni su proračun i njegova analiza na reprezentativnom modelu jednostavnog kvadratičnog oblika objekta (cubus); te mogućnosti pospješenja dobitka Sunčeve energije ovisno o potrebama promjenom svojstava i karakteristika plohe. U svrhu proračun razvijen je skriptni program PSGCalculus (Passive Solar Gain Calculus) u programskom jeziku Python. Princip i pravila korištena u ovom radu predstavljaju dobru podlogu za temeljne smjernice već kod idejnog projektiranja objekta gdje se prije daljnjeg razvoja projekta i izračuna fizike zgrade može doći do zaključka u kakvoj će interakciji biti svojstva objekta sa dozračenom Sunčevom energijom i odaziv učinka promjene nekih od svojstava.*

Ključne riječi: Solarna Ozračenost, Pasivna Energija, Obnovljivi Izvori, Anizotropni Model, Muneer, Klucher.

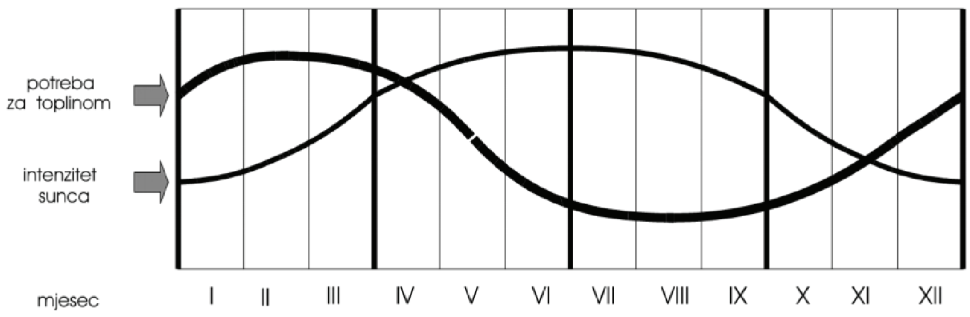
1. UVOD

Za pasivno korištenje Sunčeve energije nastoje se uskladiti geometrijske karakteristike objekta (najčešće stambeni objekti) pravilnim projektiranjem oblika i orijentacije ploha sa optimalnim smještajem na parceli, te time povećati efikasnost korištenja Sunčevog zračenja kao izvora topline. Na taj način smanjuje se korištenje konvencionalnih izvora energije što dovodi do financijskih ušteda i zdravije životne okoline (Bukarica et al., 2008.)
Potencijalni problem kod projektiranja i procjene troškova potrošnje objekta sa uključenim faktorom dozračene energije od Sunca predstavlja nesrazmjer inteziteta i potreba toplinskog toka zimi i ljeti. Zimi, kad su jače izražene potrebe za grijanjem; intezitet Sunčeva ozračenja je manji. Ljeti, kad su jače izražene potrebe za hlađenjem; intezitet Sunčeva ozračenja je veći (Koški, 2010.)



Slika 1.1 (Koški, 2010.) Korištenje istaka (streha) za manipulaciju Sunčeva ozračenja

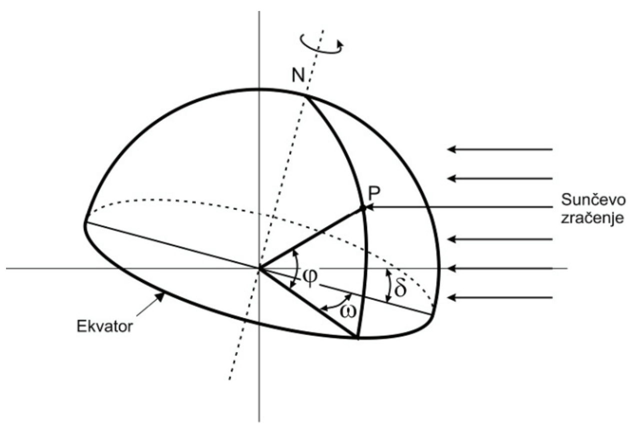
Upravo zato je potrebno provesti analizu potencijalnog poboljšanja učinkovitosti iskorištenja dozračene Sunčeve energije, npr. promjenom boje fasadne obloge ili samom orijentacijom objekta i funkcionalnih grupa unutar njega.



Slika 1.2 (Koški, 2010.) Prikaz nesrazmjera potreba za toplinom i inteziteta Sunca po *mjesecima*

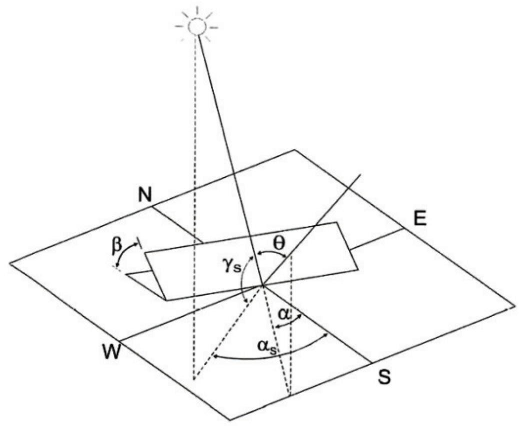
2. ZEMLJA I SUNCE

Da bi se odredio položaj Sunca u odnosu na promatrača na Zemljinoj površini koriste se tri osnovna kuta; *zemljopisna širina [ ] , deklinacija Sunca [ ], satni kut Sunca [ ].*



Slika 1.3 (Matić, 2007.) Zemljopisna širina, deklinacija Sunca i satni kut Sunca u odnosu na promatranu točku

Iz prethodno opisana tri osnovna kuta mogu se odrediti i sve ostale veličine vezane uz kretanje Sunca na nebu; *visina Sunca [γs]* , *zenitni kut Sunca [ζs]* , *azimut plohe [α], upadni kut [θ]* .



Slika 1.4 (Matić, 2007.) Prikaz kuteva za računanje zračenja na nagnutu plohu

3. MODEL DOZRAČENE ENERGIJE NA ZID

3.1 Procjena prosječnih satnih vrijednosti Sunčevog zračenja

Modeli koji se koriste za estimaciju dozračene energije na nagnutu plohu ovise o satnom kutu Sunca; samim time ovise dobu dana za koje se računa količina dozračene energije. Podaci poput prosječne satne ozračenosti rijetko kad su dostupni i takva mjerenja nisu ustaljena niti potpuna. Parametar koji se koristi iz literature su tablične vrijednosti prosječnih mjesečnih vrijednosti dnevne (ukupne [$(G_d)_m$],direktne [$(B_d)_m$] ili raspršene [$(D_d)_m$]ozračenosti.

Procjena prosječnih satnih vrijednosti Sunčevog zračenja temelji se na modelima za dekompoziciju dnevnih vrijednosti pomoću udjela satnog u dnevnom ukupnom ozračenju.

Prema Europskom atlasu Sunčevog zračenja, jednostavan Liu-Jordanov model razvijen na temelju podataka za sjevernu Ameriku, bolji je od složenijih europskih modela kao što su Olsethov ili Beyerov (Matić, 2007.)

Liu i Jordan predlažu sljedeći analitički izraz za odnos satnih i dnevnih vrijednosti raspršenog zračenja (Matić, 2007.):

$$r_{0d}(t) = \left(\frac{\pi}{24}\right) \times \frac{\cos(\omega(t)) - \cos((\omega_s)_m)}{\sin((\omega_s)_m) - (\omega_s)_m \times \cos((\omega_s)_m)} \tag{1}$$

$$(D_h)_m(t) = (D_d)_m \times r_{0d}(t) \tag{2}$$

Gdje je $(\omega_s)_m$ srednji dnevni kut zalaska Sunca za pojedini mjesec, $\omega(t)$ satni kut Sunca u ovisnosti o pravom Sunčevom vremenu koje je između izlaska i zalaska Sunca, $r_{0d}(t)$ koeficijent dekompozicije, a $(D_h)_m$ srednja mjesečna vrijednost satne raspršene ozračenosti.

Za ukupno zračenje koristi se gornji izrazi (1, 2) prošireni sa strane Collares-Pereire i Rabla (Noorian, 2008):

$$\left(G_h\right)_m = \left(G_d\right)_m \times \left(\frac{\pi}{24}\right) \times \frac{\cos(\omega(t)) - \cos\left(\left(\omega_s\right)_m\right)}{\sin\left(\left(\omega_s\right)_m\right) - \left(\omega_s\right)_m \times \cos\left(\left(\omega_s\right)_m\right)} \times \left[a + b \times \cos(\omega(t))\right] \tag{3}$$

$$a = 0{,}4090 + 0{,}5016 \times \sin\left[\left(\omega_s\right)_m - \frac{\pi}{3}\right] \tag{4}$$

$$b = 0{,}6609 + 0{,}4767 \times \sin\left[\left(\omega_s\right)_m - \frac{\pi}{3}\right] \tag{5}$$

$$\left(B_h\right)_m = \left(G_h\right)_m - \left(D_h\right)_m \tag{6}$$

Gdje je $(G_h)_m$ srednja mjesečna vrijednost satne ukupne ozračenosti a $(B_h)_m$ srednja mjesečna vrijednost satne direktne ozračenosti.

3.2 Podjela ozračenosti po članovima

Općenit izraz ukupnog ozračenja zida (Matić, 2007):

$$G_{hPLOHA} = B_{hPLOHA} + D_{hPLOHA} + R_{hPLOHA} \tag{7}$$

Gdje je:

G_{hPLOHA}– ukupno satno ozračenje na plohu
B_{hPLOHA}– izravno (direktno) satno ozračenje na plohu
D_{hPLOHA}– difuzno (raspršeno) satno ozračenje na plohu (izraz ovisan o odabranom modelu)
R_{hPLOHA}– reflektirano (odbijeno) satno ozračenje na plohu
ρ_g – koeficijent refleksije okolnog terena
β – kut nagiba plohe

$$B_{hPLOHA} = \frac{\cos(\vartheta)}{\sin(\gamma_s)} \times \left(B_h\right)_m \tag{8}$$

Konačan izraz dobiven kombinacijom modela dobiva oblik:

$$G_{hPLOHA} = \frac{\cos(\vartheta)}{\sin(\gamma_s)} \times \left(B_h\right)_m + D_{hPLOHA\,(Muneer)} + R_{hPLOHA\,(Temps-Coulson)} \tag{9}$$

Iz izraza za G_{hPLOHA} (9) dobiva se najbitniji podatak; ukupno satno ozračenje zida u ovisnosti o više varijabli izraženo u [Wh/m^2].

Izbor modela je raznolik, svrstani su u dvije glavne skupine; izotropni i anizotropni modeli. Svaki od njih daje rezultate ovisno o klimatskim prilikama, no smatra se da su anizotropni modeli precizniji zbog približavanja realnim uvjetima raspršenja Sunčeva zračenja prolaskom kroz atmosferu u svim smjerovima, kad izotropni pretpostavljaju raspršenje u jednom smjeru. Odabrani su Muneerov anizotropni model i Klucherova modifikacija Temps-Coulsonovog anizotropnog modela tzv. „all-sky model“. Muneerov model je novije generacije i korišten je pri izradi Europskog solarnog atlasa te se preporučuje za ovo područje (Matić, 2007.). Temps-Coulsonov je stariji model i daje slične rezultate kao i Muneerov. Ovi modeli se najviše referenciraju na raspršenu komponentu ozračenja, ali za potrebe ovog rada za komponenetu reflektiranog ozračenja odabran je Temps-Coulsonov model (15) u kombinaciji Muneerovog modela (10-14) za komponenetu raspršenog ozračenja.

Muneerov model, (Matić, 2007.)

Za osunčane površine na vedrom nebu:

$$\gamma_s \geq 0{,}1\,\mathrm{rad}[5{,}7°]$$

$$D(\beta,\alpha,t) = D(t)\left\{f(\beta)\times(1-K_B)+K_B\times\frac{\cos(\vartheta)}{\sin(\gamma_s)}\right\} \tag{10}$$

$$\gamma_s < 0{,}1\,\mathrm{rad}[5{,}7°]$$

$$D(\beta,\alpha,t) = D(t)\left\{f(\beta)\times(1-K_B)+K_B\times\frac{\sin(\beta)\times\cos(\alpha)}{0{,}1-0{,}008\times\gamma_s}\right\} \tag{11}$$

Za osunčane površine na tmurnom nebu i površine u sjeni:

$$D(\beta,\alpha,t) = D(t)\times f(\beta) \tag{12}$$

Gdje je K_B mjera dostupnog izravnog zračenja (ili oblačnosti):

$$K_B = \frac{(B_h)_m}{G_{0h}} \tag{13}$$

Funkcija *f(β)* uzima u obzir distribuciju raspršenog zračenja. Za objekte izložene Sunčevom zračenju u uvjetima vedrog neba; što je energetski najvažnija situacija, Muneer predlaže relaciju:

$$f(\beta)=\frac{1+\cos(\beta)}{2}+\left\{\sin(\beta)-\beta\times\cos(\beta)-\pi\times\sin^2\left(\frac{\beta}{2}\right)\right\}\times \\ \left\{a_0-a_1\times K_B-a_2\times K_B{}^2\right\} \tag{14}$$

Gdje koeficijenti imaju vrijednosti; a_0=0,00263, a_1=0,71200, a_2=0,6883, a G_{0h} je satna ukupna ekstraterestička ozračenost vodoravne plohe

Temps-Coulsonov (Klucherov) model, (Klucher, 1978.)

$$R_{hPLOHA} = \rho_g\left((B_h)_m\right)\times\cos(\zeta_s)+\left((D_h)_m\right)\times\sin^2\left(\frac{\beta}{2}\right) \tag{15}$$

3.3 Proračun i reduciranje dozračene energije

Kao rezultat prethodnih izraza (9) dobiva se ozračenost zida [Wh/m^2] u ovisnosti o lokaciji, orijentaciji i nagibu plohe te vremenskom intervalu. Da bi se dobio ključan pokazatelj za analizu dozračene energije, ta ozračenost se integira po površini plohe da bi se izrazila jedinica za energiju [Wh] ili [J], ovisno o korištenim mjernim jedinicama za vrijeme (Šimić, 2010.)

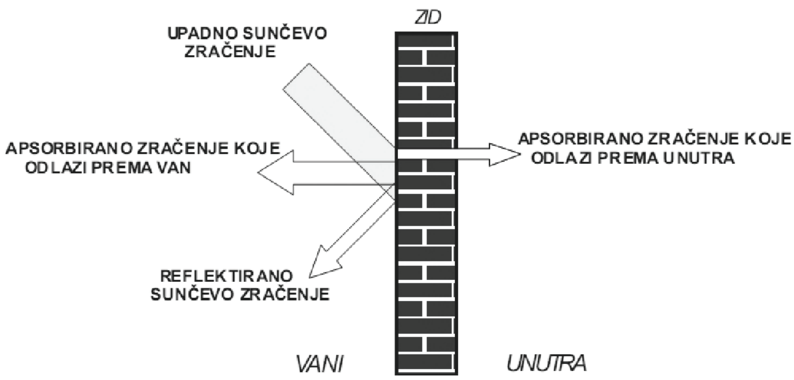
$$Q = G_{hPLOHA} \times A \tag{16}$$

$$(Q)_a = G_{hPLOHA} \times A \times a \tag{17}$$

Gdje je Q dozračena energija [Wh], A površina ozračene plohe [m^2] i a apsorpcijski koeficijent (0-1).

Kao što je opisano u prethodnim poglavljima, albedo površine ima utjecaj na zračenje koje se reflektira u svim smjerovima te je nužno u proračun uključiti posljedičnu refleksiju energetskog toka, vrijednosti se kreću od 0 (savršeno crno tijelo) do 1 (savršeno bijelo tijelo). Smatra se kako je zanemariva greška ukoliko se pretpostavi izotropno raspršenje reflektiranog zračenja.

Zbog zagrijavanja plohe sa vanjske strane dolazi do temperaturne razlike i dio apsorbiranog zračenja konvekcijom predaje toplinu okolišu. Preostali dio ulazi u nestacionaran toplinski tok i interakcija te energije sa objektom ovisi o svojstvima presjeka plohe (Šimetin, 1983.)



Slika 3.1 (Koški, 2010.) Utjecaj koeficijenata refleksije i apsorpcije

Na osnovi zakona o održanju energije vrijedi (Galović, 1997.):

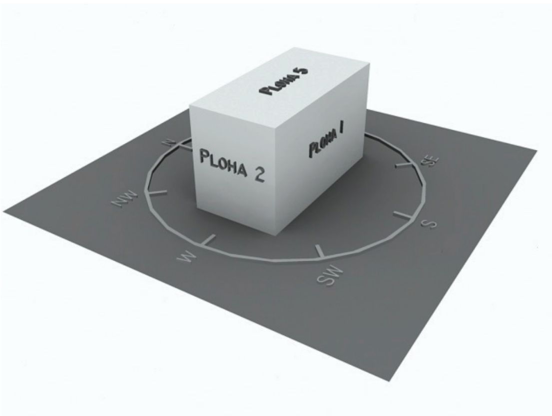
$$Q = rQ + aQ + dQ \tag{18}$$

Gdje su; *r – koeficijent refleksije*, *a – koeficijent apsorpcije (upijanja)*,
d – koeficijent dijatermije (za toplinske zrake većina čvrstih tijela su adijatermna; d=0)

4. REZULTATI PRORAČUNA I ANALIZA

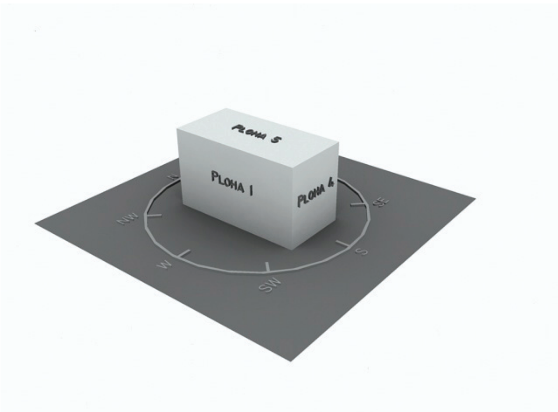
Da bi se demonstrirao značaj proračuna dozračene energije odabran je grad Varaždin sa dva različita tipska objekta. Zbog pojednostavljenja obrađen je proračun za dan u lipnju i prosincu jer u tim mjesecima postoje vršni periodi deklinacija i prosječnih dnevnih vrijednosti ozračenosti. Budući kako je Varaždin grad na sjeveru države, uvriježeno je kod takvih gradova istaknuta potreba za grijanjem. Odabran je objekt jednostavnog kvadratičnog izgleda (cubus) koji u naturi možda i ne bi egzistirao, ali zbog svoje pretpostavljene homogenosti biti će dobra podloga za proračun. Nakon unosa parametara svake plohe u PSGCalculus dobiveni su detaljni rezultati ozračenja plohe, ali i dozračene energije u ovisnosti o površini plohe i završnom izgledu plohu. Na temelju tih rezultata vrši se optimiranje cjelokupnog sustava u ovisnosti planiranih ušteda.

Slučaj I



Slika 4.1 Shematski prikaz objekta i njegove orijentacije – Slučaj I

Slučaj II

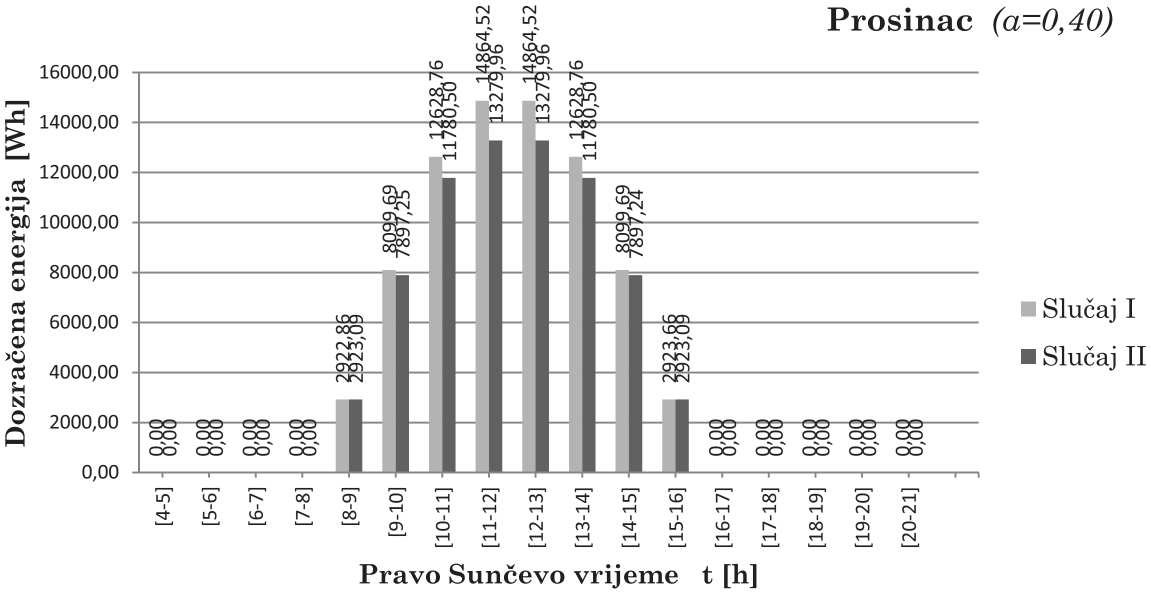


Slika 4.2 Shematski prikaz objekta i njegove orijentacije – Slučaj II

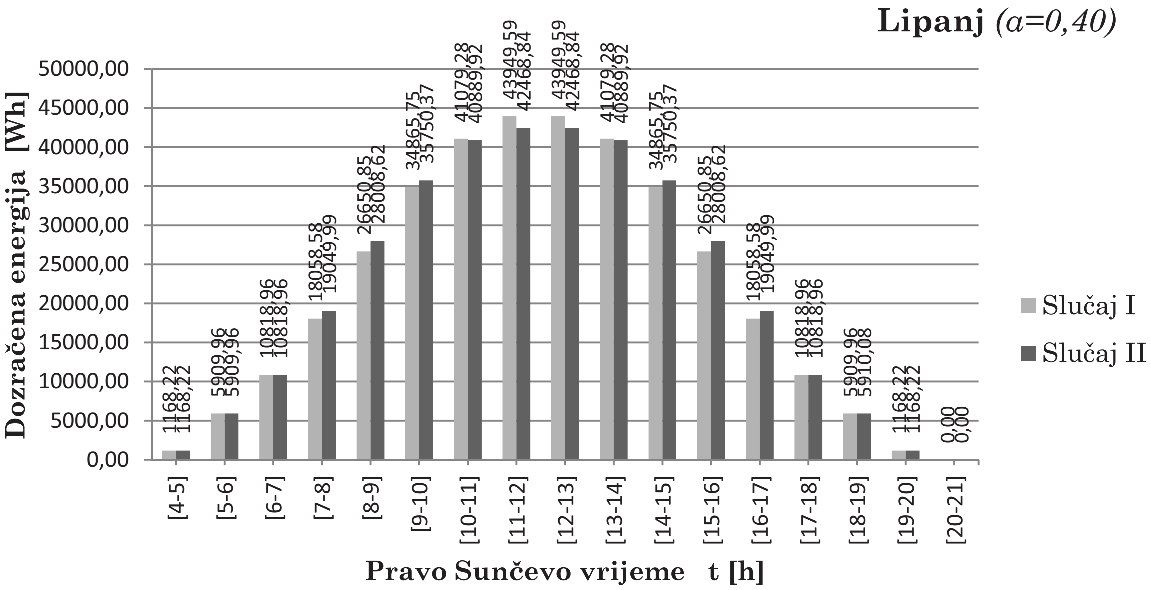
Početni uvjeti proračuna su za apsorpcijski koeficijent aproksimativne vrijednosti a=0,40 (npr. siva boja) i za albedo okoline ρ=0,20. Za prosinac redni dan je j=345, a lipanj j=162. Za takve uvjete proračunom kumulativnog dozračenja za karakterističan dan u mjesecu je dobiveno:

Tablica 1. Dozračena reducirana energija za a=0,40

Q [Wh]	Slučaj I	Slučaj II
Prosinac	77032,46	71761,60
Lipanj	365002,39	368129,90



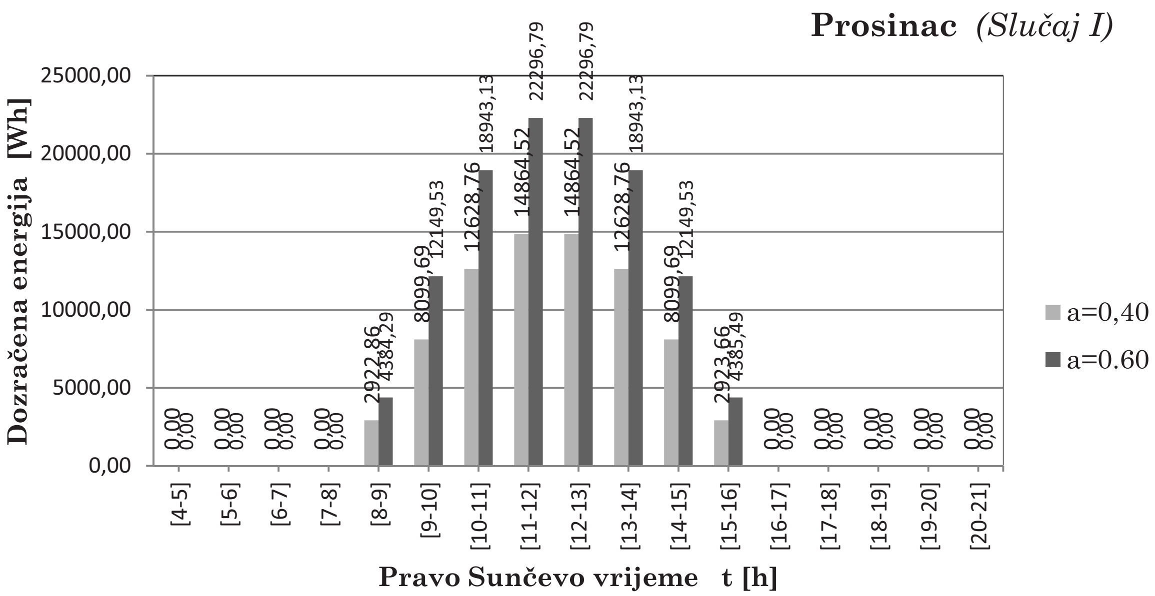
Slika 4.3 Graf hoda dnevne ozračenosti objekta za mjesec prosinac (a=0,40)



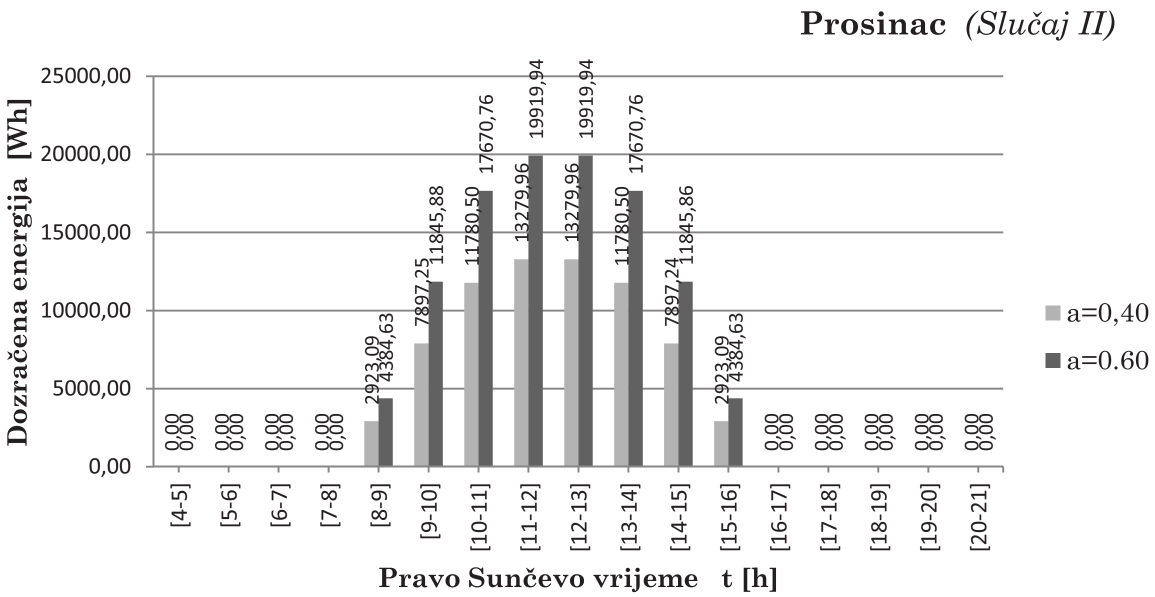
Slika 4.4 Graf hoda dnevne ozračenosti objekta za mjesec lipanj (a=0,40)

Iz prethodnih rezultata može se uvidjeti kako promjenom orijentacije ploha može doći do manipulacije dozračene energije ali u manjem postotku; praktički zanemarivom. Razlog tomu je da unatoč što se mijenja orijentacija površina, na njih utječe samo direktna komponenta ozračenja, jer raspršena komponenta i reflektirana imaju relativno isti utjecaj na sve površine tokom dana.

S druge strane, ukoliko se promjeni apsorpcijski koeficijent aproksimativne vrijednosti sa a=0,40 na a=0,60 (npr. crvena boja) dolazi do značajnog povećanja apsorpcije energije koja ima proračunski osjetan utjecaj u izračunu nestacionarnog toka, bez obzira na konvekciju topline prema okolišu.



Slika 4.5 Graf hoda dnevne ozračenosti objekta za mjesec prosinac (a=0,40; 0,60), Slučaj I



Slika 4.6 Graf hoda dnevne ozračenosti objekta za mjesec prosinac (a=0,40; 0,60), Slučaj II

Tablica 2. Dozračena reducirana energija za a=0,40; 0,60, prosinac

Q [Wh]	Slučaj I	Slučaj II
a=0,40	77032,46	71761,60
a=0,60	115548,68	107642,39

Ukoliko se želi efikasno promijeniti energetsko povećanje (za grijanje u hladnijim krajevima) ili smanjenje (za hlađenje u toplijim krajevima) Sunčevog zračenja, uz osvrt na orijentaciju objekta, pažnju treba posvetiti boji i teksturi završnog sloja jer proračunom je pokazano kako parametar koeficijenta refleksije ima značajan utjecaj na toplinsku ravnotežu ploha (Taha et al., 1992.). Za *Slučaj I* i *Slučaj II* dolazi do povećanja od cca. 50% dozračene energije. Iako ta energija ne predstavlja energiju u obliku koju objekt efektivno u potpunosti koristi za utjecaj na toplinsku ravnotežu, povećanjem te energije manipulira se konačnim izračunom nestacionarnog toplinskog toka.

5. ZAKLJUČAK

Sumirajući trenutnu energetsku bilancu, odavno se prešla granica iza koje se nije trebalo minuciozno proučavati nove izvore energije i njihovu efektivnu i efikasnu implementaciju u sustav industrijalizirane civilizacije.

Relativno brza potrošnja zaliha fosilnih goriva ubrzala je proces izučavanja i proizvodnje energije iz obnovljivih izvora. Vrsta takvog principa prikazana je u ovom radu gdje su opisane i obrađene mogućnosti manipulacije dozračenom toplinom od strane Sunca.

Uzevši u obzir lokaciju objekta, karakteristike njegovih ploha poput orijentacije, površine, nagiba i boje kao i albeda njegovog okruženja te korištenjem anizotropnih preciznih modela predikcije Sunčevog zračenja, opisani su i proračunom dokazani funkcionalni temeljni principi korištenja pasivne energije koji pokazuju realnu mogućnost primjene u zgradarstvu. Promjenom boje i vrste završnog sloja obloge objekta dolazi do značajnog utjecaja na teoretski iskoristivu energiju. Opisani model dozračene topline biti će uključen u nestacionarni izračun toplinskog toka kroz zidove što će omogućiti preciznije određivanje toplinske ravnoteže građevinskog objekta, odnosno, utroška energije za grijanje i hlađenje.

U praktičnoj primjeni uz sve veći trend projektiranja energetski samodostatnih objekata, proračun egzaktnog nestacionarnog toplinskog toka uz faktor dozračene Sunčeve energije bi trebao postati neizostavna stavka projekta.

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MODEL OF SOLAR IRRADIANCE OF BUILDINGS

Abstract: *The Sun as an practically insatiable source of energy has an important role in the heat balance of every object; everyday irradiated heat which participates int he heat flux through the walls, which is neglected in the majority of standard calculations. This paper describes precise anisotropic models which can be used for prediction of irradiance of inclined surfaces, and integration of results with the object's properties. Muneer model has been used and Klucher's modification of Temps-Coulson model, a.k.a. „all-sky model“ for calculation of dispersed component of Sun's radiation. The model is developed in dependance with object's location, time (day and year), object's properties like orientation, apsorption coefficient, inclination, and reflected radiation from the surrounding terrain. The calculation and it's analisys is done on a representative model of a simple cubus shape. A script programme has also been developed, the PSGCalculus (Passive Solar Gain Calculus) by using the Python programming language. This paper presents the guidelines which can be useful at design stage of an object for determination of Solar irradiated heat on the object, as well as interaction of object's properties and location on irradiated solar energy.*

Key words: Solar Irradiance, Passive Energy, Renewable Energy Sources, Anisotropic Model, Muneer, Klucher.

IMPROVING THE ENERGY EFFICIENCY OF MASS WALLS: WORK BY HISTORIC SCOTLAND

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Abstract: *The reduction of greenhouse gas emissions in Europe and other developed countries is now part of the mainstream political and social agenda, with particular focus on the performance of the built environment. Traditional and historic domestic buildings are under significant pressure to reduce the carbon emissions associated with their operation. Following direction from Scottish Government, Historic Scotland is taking a lead in the provision of guidance and advice for the thermal upgrade of traditionally built structures of all types in Scotland. Its programme of research has looked at the thermal performance of the traditional building envelope and how it can be improved by sensitive and appropriate intervention; key processes and initial findings for wall elements are presented. Other related factors such as thermal comfort, passive benefits of older properties and sustainability issues are also considered together with an outline of the future research programme. While the trials were carried out on Scottish residential housing stock, the lessons learnt and some of the intervention techniques will apply to mass walled structures in all parts of Europe and elsewhere.*

Key words: Energy efficiency, traditional buildings, thermal upgrade.

1. INTRODUCTION

As a result of the potential impacts of climate change, significant attention is being paid to the energy efficiency of older buildings. Legislation passed by The Scottish Government (The Climate Change (Scotland) Act 2009) has set the most demanding reduction targets in Europe, and the built environment (especially housing) has some challenging targets to reach. In all sectors, an 80% reduction of CO2 emissions is required by 2050, with an intermediate target of a 42% reduction by 2020, now set in law. In addressing energy efficiency improvements to any property Historic Scotland believes that a hierarchy should be followed – addressing occupant behaviours first, then heating and lighting efficiencies, only then followed by fabric improvements. Micro renewables also have a place, but only following these prior actions. This sequence of action, as well as wider considerations, are described in the Historic Scotland Climate Change Action Plan, released in March 2012 [1] which forms the higher level guidance for the approach to managing Historic Scotland's Estate.

This paper will concern itself with improvements to the walls of stone built domestic structures. It will describe key types of intervention that have been tested and initial results, seeking to demonstrate that improvements can be achieved without losing or compromising existing fabric. Some of the interventions described are suitable for buildings of all types, including those with statutory protection. The article secondly considers wider non fabric specific issues concerning retrofit such as indoor air quality and the delivery of thermal comfort. It concludes with a summary of planned future research work.

2. IMPROVING THE ENERGY EFFICIENCY OF TRADITIONAL BUILDINGS

Historic Scotland refers to traditional buildings generally, but not exclusively, as those structures in Scotland built before 1919. Such structures were normally constructed with double pitched roofs and solid masonry load-bearing walls, built from a limited palette of largely natural materials thought of in general as being vapour permeable. These structures, comprising an estimated 19% of Scotland's housing stock, include tenements, terraces, semi-detached houses, detached villas and cottages (Fig. 1). While some older structures are protected (2% of the total) most of these buildings have no statutory heritage protection and are therefore vulnerable to interventions as a result of thermal upgrading, especially with regard to wall insulation, window replacement and other changes where large amounts of historic material are at risk of wholesale removal.

Figure 1. 19C tenements in Edinburgh (Historic Scotland).

As attention focussed on upgrade options for the traditional stock, it became apparent that there was little accurate data on the actual thermal performance of traditional building elements. The construction sector has always relied on calculated U values. This omission resulted in a research schedule for testing of building fabric elements by Historic Scotland that has allowed better baseline performance information to be established. This work was carried out in partnership with Glasgow Caledonian University [2], and The social enterprise Changeworks [3] and Napier University in Edinburgh [4]. Generally these results indicate that calculated performance values (especially of walls) suggested a poorer performance than what was actually measured, sometimes by as much as 25%. The new data allows a more modest intervention to bring the fabric performance within acceptable tolerances. In addition the measured values obtained for building elements can now be used as input into assessment methodologies in the building assessment processes. How older structures are assessed is a developing area of which the Energy Performance Certificate (EPC) is possibly the best known method in the UK to date and required under European Legislation since 2009. Work by Changeworks for Historic Scotland on assessment methodologies has outlined the respective attributes of the different systems used in the UK and how they assess traditionally built structures [5]. It is clear that further work is required in this area to allow certain benefits of older structures to be realised. In addition to a lack of evidence on the thermal properties of mass walls, there is a lack of understanding of how such walls handle liquid water and water vapour. Generally many incorrect assumptions have been as to their ambient moisture levels and humidity buffering especially with regard to the addition of insulation. In the sector of building conservation there is general acceptance that the principle of vapour permeability, in all areas of the fabric, should be maintained during repair and retrofit work. The broad principles of this are shown in Fig. 2.

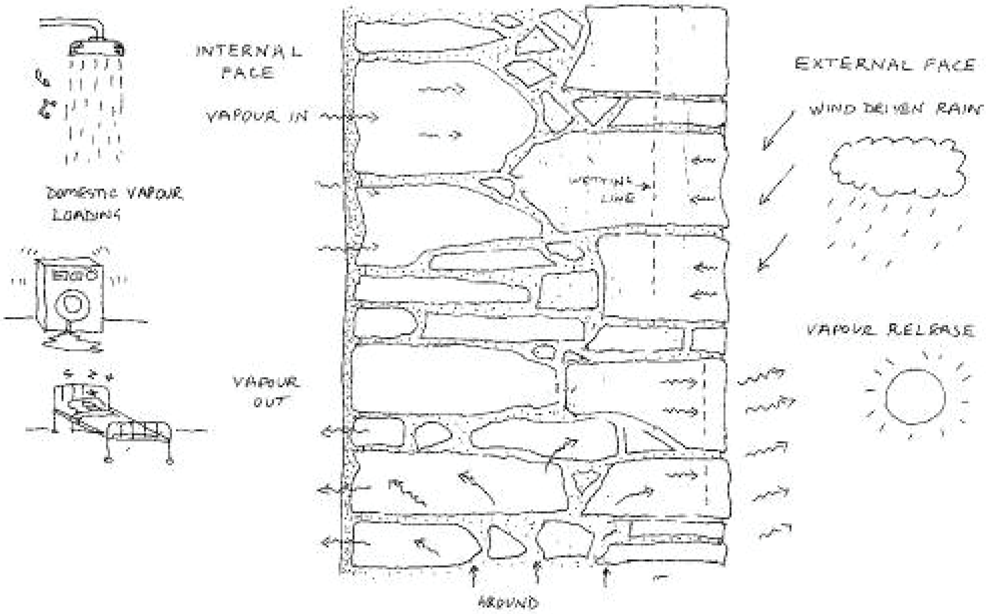

Figure 2. Vapour movement in a mass wall.

In order to trial interventions and improvements a set of pilot refurbishments were set up by Historic Scotland and other stakeholders in the summer of 2010. The projects were funded by internal research funds and additional support from the Scottish Government Energy Efficiency Team. The pilot projects included work on tenement flats, detached rural cottages (Fig. 3) and other buildings described as "hard to treat", that is, where standard insulation techniques were not suitable or too expensive.

Figure 3. One of the homes used in the trials programme. (Historic Scotland)

Work on all the pilots has followed a principle of modest intervention in the fabric and retaining vapour permeability in the and materials used for any improvements. Currently in the UK refurbishment is a fairly invasive process, with much existing sound and usable material being typically disposed of. One of the wider sustainability goals of the trials was to demonstrate that upgrades to older buildings were possible without excessive waste, through retention and re-use of existing facings and finishes.

3. WALL IMPROVEMENTS AND RESULTS

Background Research

Prior to this research the thermal performance of mass masonry walls, common in Scotland and many parts of England and Wales, seemed especially unclear, with a lack of measured data and many assumptions among designers and regulatory bodies as to the actual thermal properties of traditional mass masonry.

Historic Scotland therefore commissioned a programme of basic research by Glasgow Caledonian University that measured the thermal performance of a wide range of walls across Scotland. Beginning in 2008 this used *in situ* heat flux meters in a similar manner to the method used for the glazing tests. The results gave a generally better performance than expected (calculated U-values for a typical mass wall of 600 mm in thickness range from 1.5 to 2.5 W/m^2K) and it appears that a dry mass wall of around 600 mm in thickness (very common in Scotland in buildings of all types) generally had a U-value of 1.2 – 0.7 W/m^2K [6].

Knowing that the real thermal performance of a mass wall is better than expected allows more modest intervention – and giving an opportunity for improving the existing linings rather than removing them. In terms of building physics, it is generally accepted that the insulation should be applied to the exterior surface of a wall, but that has a range of practical and architectural limitations. Internal insulation up to now has been considered an expensive and often destructive process, requiring the wholesale removal of internal linings and replacement with modern insulated materials, an approach that Historic Scotland does not generally support. From a building and materials conservation point of view, removal of traditional linings such as lath and plaster should be a last resort. However, in buildings where such finishes have been removed in the past and replaced by modern materials greater intervention is clearly possible. In these cases U Values that reach current UK building codes for new structures are achievable (a U-value of 0.28 Wm^2K is required for current UK building Codes in the domestic sector) using some of the techniques trialled.

Blown Insulants behind existing linings

In order to retain original and historic linings, techniques were tried to insert internal wall insulation in the void behind the lath and plaster (the traditional internal lining technique used since the 17^{th} C) where it still is extant. Site trials over the winter of 2010/2011 involved the use of various forms of blown materials into the cavity space. Such blown materials will reduce volume advection of air in the cavity, but due to the nature of the insulation material will not compromise the ability of water vapour to disperse through the structure – which remains vapour permeable in both directions, inside and out. Various types of insulation material have now been trialled in such cavities in a range of properties, in both rural and urban locations. In one detached stone cottage in Edinburgh a post intervention U Value of

0.6 Wm^2K was recorded, an improvement of 50% against a measured pre-intervention U Value of 1.2 Wm^2K. It has also to be accepted that this is still short of the target figure quoted above. To date the wall appears to functioning normally, humidity probes within the wall recorded variations between 60% and 80% Rh. Should the dew point have been reached it appears the permeable nature of lime construction has wicked and dispersed any moisture. This project is described in more detail in Refurbishment Case Study 2 [7]. Subsequent case studies will describe the techniques and results in other similar situations. It is considered that in a largely mild maritime climate, where steady state situations are rare, that the interstitial condensation risk as modelled using steady state methodologies is minor. Additional work is ongoing within Historic Scotland on the hygrothermal modelling of mass walls with proprietary software to assess how modelled simulations match situations on site. Technical Paper 15 makes some initial observations [8]. Questions also remain about the evenness of fill and subsequent settling of the blown materials, but these are questions of practice not principle. Infra red thermography and borescopes can quickly check the fill density and spread to ensure even coverage. Newer materials suitable for this approach are still coming into the marketplace and it is likely that installation in this way will become easier as industry responds to demand with an increasing range of products. Reversibility is sometimes an important consideration in building conservation and it is accepted that materials blown into cavities are not reversible in any practical sense. This must be considered against the situation with most traditional buildings in Scotland that have no formal protection - thus if this technique was not available the linings would have to have been removed anyway to install more conventional insulation.

Figure 4. Application of blown cellulose insulation (Historic Scotland).

Thin insulants onto an existing surface

In cases where there were concerns about the filling of the air gap behind the plaster linings, a thin insulant was applied onto the surface of the plaster instead. This consisted of a thin aerogel matt, 10mm thick, which was secured against the wall using an expanded steel mesh and thermally decoupled fastenings (Fig 4). On top of this sandwich were applied two coats of plaster to produce a smooth finish; the total thickness of the layers was 20mm, thin enough to not affect facings and cornices. Thus internal features were unaffected and U-value improved while retaining an air gap behind the linings; U-values achieved with this measure were 0.8 W/m^2K against a pre intervention reading of 1.3 W/m^2K [9], an improvement of 38%. This option is reversible as the insulation, the mesh and the plaster coating can be removed back to the original plaster layer.

Figure 5. Application of a thin aerogel matt. Note the cornice is unaffected.

New insulated linings

In many cases old linings have already been removed, and an opportunity arose to test a range of internal insulation products in six flats in a Glasgow tenement dating from *c*. 1900. The existing walls were tested for thermal performance before removal of the existing modern plasterboard (giving a measured U Value of 1.2 W/m^2K) and the rear rooms of the flats were then retrofitted with a range of six different insulation materials. Some materials were applied directly onto the inside masonry face while others were fitted between new timber strapping. The insulation materials, ranging from a silica-based insulant to a wood fibre board, achieved the designed U-value of 0.33 W/m^2K (with minor variation between products). In terms of moisture and potential condensation in the improved walls, initial results from March 2012 indicate that wall moisture levels (using relative humidity measurements as a proxy) are within tolerance in the masonry core and on the inside edge. Full results of this trial are published in Refurbishment Case Study 4, [10].

In some traditional walls in Scotland there is plaster directly on the masonry, referred to as being “on the hard”. This was tested in a stone built property using a proprietary calcium silicate board applied directly onto the existing plaster surface and finished with a skim coat of plaster. This measure achieved a U Value of 0.5 W/m^2K a 60% improvement against a measure pre intervention baseline of 1.3 W/m^2K, details are described in Refurbishment Case Study 3 [9].

Figure 6. Application of calcium silicate board to an existing plastered surface.

4. AIR TIGHTNESS AND INDOOR AIR QUALITY

In refurbishment achieving a good balance of natural ventilation and air tightness is important, for the benefit of the occupants and the fabric. Many commentators have raised concerns about ventilation rates in housing of all types and ages, and Historic Scotland has funded a scoping study [10] by GAIA Research to look at some of the issues. Others have commented on the health effects of low air change rates; for example, Howieson [11] considers why asthma rates in Scotland are now many times higher than they were in 1960 and suggests that reduced ventilation rates in the Scottish housing stock may have been responsible for this trend. And these concerns are not limited to the United Kingdom, in Australia, where there have been longstanding energy efficiency programmes; the nutritionist Peter Dingle considers the internal environment in his book "Is your home making you sick" [12].

The often held rule that older buildings are more air permeable or "leaky" than new ones has also been questioned by recent site work. Tests commissioned by the Society for the Protection of Ancient Buildings (SPAB) in 2010 showed that some 19^{th} C properties in the north west of England had the same air leakage rates as those of some modern buildings [13]. However, a modest increase in the air tightness of older properties is entirely appropriate and was achieved at an Historic Scotland pilot property by draft proofing of the windows, the existing doors and new laid floors in the ground floor. The existing chimneys and flues in the pilots were retained as a key part of the ventilation strategy although temporary chimney balloons were used for isolation of the flue when a reduction in ventilation was required, such as during extreme weather. This aspect of the works to this property are described in Refurbishment Case Study 7 [14].

Traditional construction practice can offer many benefits in air quality management, especially that of humidity control - traditional finishes such as limewash and distemper are able to absorb excess water vapour in times of high humidity load – the principle of humidity buffering. Modern materials such as clay paint and modern distemper can be used in refurbishment and are equally effective. These have been used on one of the pilot cottages and the indoor climate will be monitored when occupancy re-commences. To consider some of the wider issues of internal air quality and traditional construction Dr Richard Hobday was commissioned by Historic Scotland to compare historic ventilation practice with preferences today [14] and consider the benefits of well ventilated (and lit) living spaces.

5. THERMAL COMFORT

In addressing how to improve thermal loss through the fabric, we should also remember that the ultimate objective of a dwelling is to provide a comfortable living environment for the occupants. Delivering thermal comfort by warm air is one way of doing that, but not the only way. Traditional heating methods from the earliest times achieved this by increasing the temperature of the surrounding fabric and by the use of radiant heat, giving thermal comfort for the occupants while the air temperature remained modest by modern expectations of comfort. In a paper by Heriot Watt University, commissioned by Historic Scotland these themes are considered in more detail [15] where the current assumption that thermal comfort is directly linked to internal air temperature is questioned. These principles are being trialled on side in an occupied rural cottage where radiant heat is provided by heated electric panels. The objective is to assess if thermal comfort can be delivered at lower cost than that provided by a conventional wet system with a boiler.

Figure 7. Radiant heat panel (the "mirror" above the fireplace) being trialled in a rural cottage.

6. FUTURE WORK AND SITE TRIALS

Historic Scotland, as part of the Scottish Government, is actively involved with other government departments in developing a range of improvement options for a variety of housing types in Scotland. Historic Scotland will continue its work on energy efficiency in the non-domestic and domestic sector through a second phase of site interventions and evaluation.

Further trials will be conducted in a range of traditionally built properties to further develop simple and cost-effective interventions that are replicable across housing and other built stock in Scotland. Such site projects will include further tenement upgrades in Glasgow and Aberdeen and other rural properties. The details and techniques for the methods discussed above have been published as part of the Historic Scotland Short Guide Series under the title *Improving Energy Efficiency in Traditional Buildings* [16].

7. CONCLUSION

Work by Historic Scotland in quantifying the thermal properties of the traditional building envelope has allowed a more informed specification of measures that are suitable for older and historic properties. Through its on-site and laboratory-based research programme, Historic Scotland has identified a range of ways by which traditional mass walls can be upgraded to nearly modern thermal standards while retaining original fabric and without compromising the essential vapour dynamic that characterizes traditional construction. These upgrades do not losing the integrity of historic structures and firmly place traditional buildings as part of the solution to carbon management and resource issues, and not, as it is often assumed, part of the problem. This work has also led to further questions of indoor climate and air quality as well as the best ways of delivering thermal comfort which has relevance in all sectors of construction.

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Online Resources

All the Technical reports and Refurbishment Case Studies mentioned in the text are available free as PDF's from the Historic Scotland Website: http://www.historic-scotland.gov.uk/conservation-research

POBOLJŠANJE ENERGETSKE UČINKOVITOSTI MASIVNIH ZIDOVA: RAD HISTORIC SCOTLAND

Sažetak: *Smanjenje emisije stakleničkih plinova u Europi i drugim razvijenim zemljama sada su dio programa političke i društvene srednje struje, s posebnim naglaskom na učinkovitost izgrađenog okoliša. Tradicionalne i povijesne zgrade su pod značajnim pritiskom radi smanjenja emisija ugljičnog dioksida vezanih uz njihovu namjenu. Slijedeći naputke škotske vlade, Historic Scotland prednjače u pružanju vodstva i savjeta za toplinsko unapređivanje tradicionalno izgrađenih objekata svih vrsta u Škotskoj. Njihov program istraživanja je pregled toplinskih performansi tradicionalnih ovojnica zgrada te kako se one mogu poboljšati osjetljivom i prikladnom intervencijom; prikazani su ključni procesi i početna saznanja o zidnim elementima. Ostali povezani čimbenici, poput toplinske ugodnosti, pasivnih prednosti starijih imanja i održivosti, također su razmatrani zajedno s okvirnim pregledom budućeg istraživačkog programa. Dok su ispitivanja provođena na škotskom lokalnom stambenom fondu, naučene pouke i neke od tehnika intervencije su primjenjive na strukture koje rabe toplinsku masu zidova, u svim dijelovima Europe i drugdje.*

Ključne riječi: energetska efikasnost, tradicionalne zgrade, nadogradnja toplinske izolacije

STEP BY STEP IMPLEMENTATION OF ENERGY EFFICIENCY IN PUBLIC BUILDINGS

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***project MINUS3 was cofinaced by European Commisison**

Abstract: *Municipalities play a key role in final energy consumption and its environmental consequences in EU member states. Increased costs of energy in recent years coupled with the economic downturn bring a greater motivation to focus on the demand side of energy management, especially in the public sector. The public sector is one of the largest energy consumers in the EU and subsequently has the most to gain from increased energy efficiency. These facts are reflected in EU energy policy, strategy, action plans and Directives, especially the EU Directive on the Promotion of energy end-use efficiency and Energy Services (2006/32/EC). The fact that most of the municipalities are lacking financial resources creates an additional motivation and a huge market potential for the application of energy services as public-private partnerships. In the frame of EU co-financed project Minus 3% the guide how to achieve 3% yearly savings was prepared. The content is structured using the experiences gained during the implementation of the Minus 3% project in the six participating cities. Step-by-step approach towards the energy efficiency in public sector is mainly addressed to local authorities and municipal energy managers as key stakeholders who are involved in creating an energy efficiency action plan for the City, in the decision process and in the implementation of energy-efficiency measures. The first part focuses on describing the step-by-step process of the Minus 3% approach – how to implement energy management at municipal level, the commitment of City, roles and responsibilities of the energy manager and their team, how to set up an energy baseline, how to prepare an energy-efficiency action plan and implement its measures. The second part is dedicated to national shining examples from already implemented projects in the participating Cities [1].*
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Key words: energy management, public sector, monitoring, guide, implementaion

1. INTRODUCTION

Energy is a variable cost that can be controlled. Energy management within buildings generally results in an absolute reduction in the use of energy. The interventions can save energy, reduce costs, and preserve natural resources while reducing environmental pollution. There are not only immediate benefits for the building owner and user but long-term public benefits when energy consumption is managed better for buildings. Energy management therefore makes business sense as well as broader economic, social and environmental sense. For these reasons, local and national governments have set energy efficiency targets related to buildings. Energy management benefits are cumulative over time. Each day opportunities to save energy and minimise the energy demand are lost without realising these benefits if energy management is not implemented [2].

Municipalities play a key role in final energy consumption and its environmental consequences in EU member states. Increased costs of energy in recent years coupled with the economic downturn bring a greater motivation to focus on the demand side of energy management, especially in the public sector. The public sector is one of the largest energy consumers in the EU and subsequently has the most to gain from increased energy efficiency. These facts are reflected in EU energy policy, strategy, action plans and Directives, especially the EU Directive on the Promotion of energy end-use efficiency and Energy Services (2006/32/EC). The fact that most of the municipalities are lacking financial resources creates an additional motivation and a huge market potential for the application of energy services as public-private partnerships.

The Minus 3% project is an international project supported by the Intelligent Energy Europe Program (IEE) of the European Commission. Its goal is to address the difficulties in implementing the EU Directive on the Promotion of energy end-use efficiency and Energy Services (2006/32/EC). The role of Minus 3% is to start the reduction in energy end-use among the municipalities of the participating Cities towards 3% per annum over the duration of the program and in the long term to reach minus 30% by 2020 through different activities, mainly:

- The establishment of energy action teams on a municipal level;
- Analyzing the current situation and setting up an energy consumption baseline;
- Development of an energy efficiency action plan which allows Cities to show progress towards energy reduction of 3% per annum;
- Setting up a methodology to monitor and evaluate energy savings;
- Promotion of energy services through the analysis of market conditions;
- Implementation of energy saving measures in the participating Cities;
- Collection of experiences and shining examples gathered during implementation;
- Raise awareness of City staff, other Cities, developers, financial institutions, technology suppliers and other target groups.

The Minus 3% project has been implemented in the following Cities with assistance of local energy agencies: Dublin, Derry, Malacky, Maribor, Teruel and Graz.

¶

2. IMPORTANCE OF ENERGY EFFICIENCY AT THE MUNICIPAL LEVEL

Energy efficiency (EE) is part of the broader targets of energy and environmental policy of the European Union. Increases in energy efficiency play an important role towards achieving the targets of the Kyoto Protocol. EU Member States must adopt and achieve an indicative energy saving target of 9% by 2016 within the framework of a national energy efficiency action plan (NEEAP). Requirement to increase EE is a logical consequence of environmental protection and security of energy supply. Aims and tools to support energy efficiency do not differ in EU countries very much. However, Member States must ensure that the public sector adopts measures to improve energy efficiency, inform the public and businesses of these measures and promote the exchange of good practice. The public sector should act as exemplars of this good practice. Examining the current situation in the public sector, municipalities lack a combination of:

- Systematic monitoring and evaluation of energy consumption
- Energy management with clear responsibilities on preparing an action plan
- Capacity to identify and implement possible EE measures and action plans

- Motivation and stimulation to implement EE measures by decision makers
- Systematic education of City employees in energy management
- Awareness-raising activities for the wider public on communal level
- Information on the importance of decreasing energy consumption for sustainable development and environmental protection

From the experiences of Minus 3%, the most important step for a municipality that makes the decision to decrease its energy consumption is to introduce systematic energy management on a City level with clearly defined tasks and responsibilities. There is a crucial role to play by energy agencies as they have the organisational and technical Capacity and experiences to assist the municipalities. This may be done by the establishment of an energy management structure, the preparation of an action plan and helping municipalities to take the decision about necessary investments and searching for possible financial resources.

3. HOW TO IMPLEMENT MINUS 3% APPROACH [1]

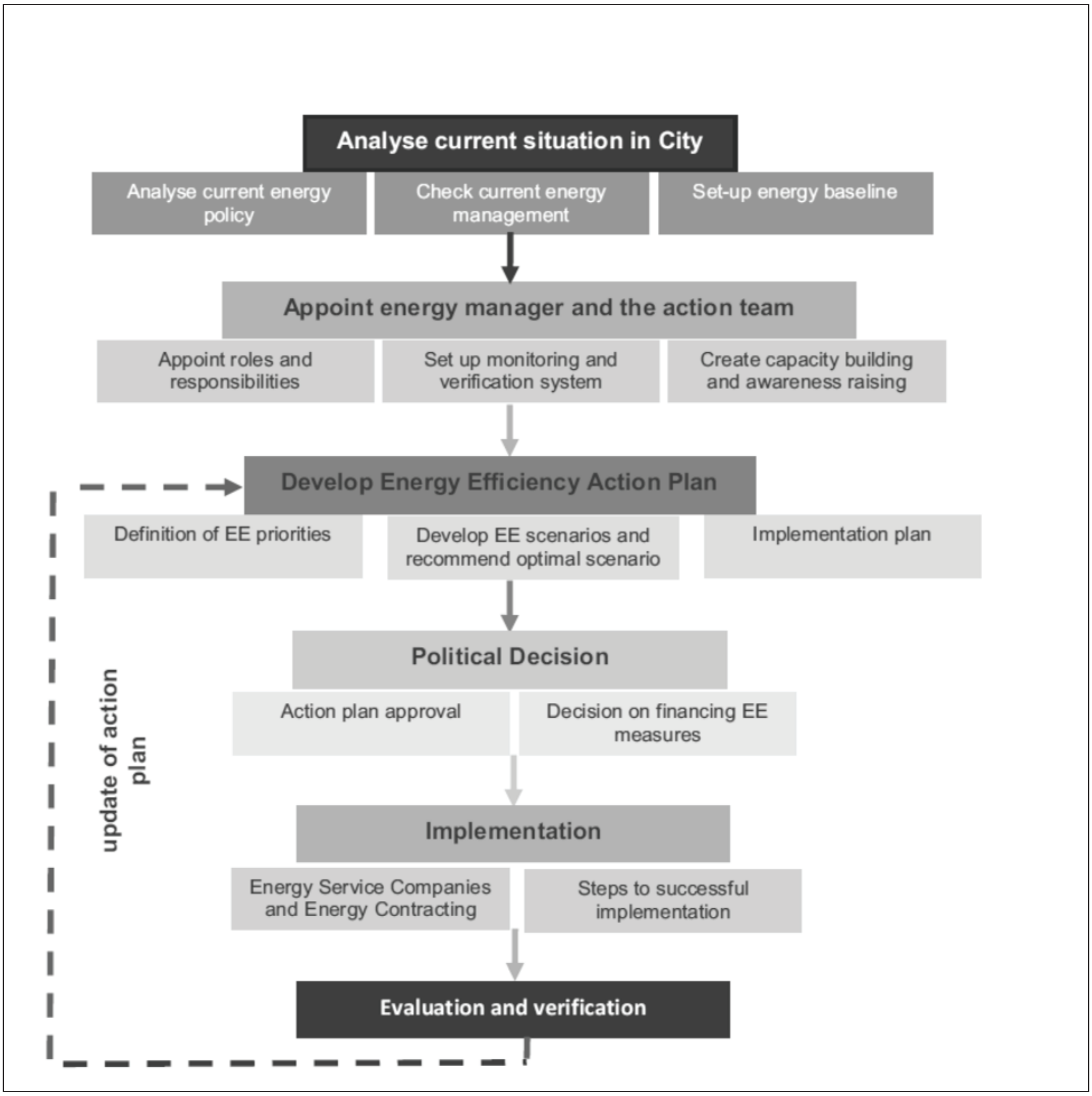
The aim of the Minus 3% approach is to create effective energy-management systems leading to sustainable energy consumption reduction. The main principle in the proposed approach is the management of those energy consumption areas which are directly under municipal responsibility i.e. where the City is paying for energy bills and can directly influence energy consumption. Generally in municipalities the energy management includes the following consumption areas:

- Buildings
- Public lighting
- Transport
- Waste collection and disposal
- Water and wastewater treatment etc.

The Minus 3% approach consists of the following main components:

- An effective system of energy consumption monitoring and its evaluation in all consumption areas
- Assessment and regular revision of energy consumption baseline according to consumption areas
- Establishment of energy management structure (appointment of an energy manager and an energy management team, definition of roles and responsibilities)
- Creation of Capacity-building systems and systems of information dissemination
- Methodology for energy-savings monitoring and verification
- Development and regular update of an energy efficiency action plan with a list of measures, tasks and responsibilities, assessment of investment, preparation of comparative scenarios and identification of priorities
- Decision making (political and financial)
- Support of energy services
- Implementation

Picture 1 shows the schematic diagram of Minus3 approach. The procedure is presented on



Picture 1: Diagram of the implementation phases of good energy management system at municipal level

4. IMPLEMENATION IN MARIBOR CITY, SLOVENIA

Since the start of the Minus 3% project in October 2008 the City of Maribor started the cooperation with Energy Agency of Podravje to implement systematic monitoring and energy management in the city. In the first stage the main energy consumption areas were identified, baseline consumption of the city set-up and the main energy indicators evaluated. Energy action teams were set-up and an energy action plan developed. In the next stage the city has implemented energy management by means of CEMS. Central energy management system (CEMS) as an on-line energy management tool is user friendly tool, which enables the city to:

- log into the system through internet access;
- input, evaluate and control energy consumption – electricity, natural gas, heat, water

- display outputs in user-friendly format – tables and graphs in timeframe selected by user;
- collect information & documents coupled with energy consumption and measures applied in municipal facilities i.e. energy bills, energy audits, project documentation, and etc. The data collected is useful as the benchmark for evaluation of energy efficiency improvements once energy management measures have been implemented;
- using the data collected, begin to put together preliminary energy balances. The data analysis can provide a useful summarised energy picture for the building in the form of an 'energy profile' for the current status of the building as indicated in the graph adjacent;
- assessing energy savings potential by benchmarking or comparing the energy performance values or indicators of a particular building's energy use against similar ones [3].

5. CONCLUSIONS

The practical step by step guide How to increase energy efficiency in a city is structured using the experiences gained during the implementation of the Minus 3% project in the six participating Cities. The goals of the guide are to:

- share national experiences with other municipalities in the EU
- to aid in implementing energy management at municipal level, planning energy efficiency measures
- build motivation for further project development towards the achievement of 3% energy savings yearly.

This step-by-step guide is mainly addressed to local authorities and municipal energy managers as key stakeholders who are involved in creating an energy efficiency action plan for the City, in the decision process and in the implementation of energy-efficiency measures. The first part focuses on describing the step-by-step process of the Minus 3% approach – how to implement energy management at municipal level, the commitment of City, roles and responsibilities of the energy manager and their team, how to set up an energy baseline, how to prepare an energy-efficiency action plan and implement its measures. The second part is dedicated to national shining examples from already implemented projects in the participating Cities. As one of the shining example of involved city Maribor's approach was presented. The energy management system in Maribor is based on four management principles:

- Plan – establish the objectives and processes necessary to deliver results in accordance with the energy policy at EU, national and local level by using action plans;
- Do – implement the proposed action plans
- Check – monitor and measure processes against the policy, objectives, targets, legal obligation, reports to the policy makers;
- Act – continually to improve performance and influence lifetime planning process.

The Central energy management system was prepared and treated with all the data to produce energy performance certificates that are required for all the buildings owned by the Municipality of Maribor. According to this, energy performance certificates for administrative buildings, for all schools and kindergartens in the Municipality of Maribor and several other individual public buildings: sports facilities, cultural facilities, health centre, are already made and visible through monitor screen – live energy performance certificate. The monitor provides transparent and up to date figures that are available. Monitor was installed in the premises of the Municipality of Maribor, so the data are accessible to the Mayor and other citizens of Maribor. The benefits of implementation of MINUS3 step by step approach in Maribor are:

- possibility to compare invoiced energy consumption and real consumption;
- have a tool to identify potential energy savings;
- provides municipality energy data for long-term energy planning;
- good decision making tool for future investments;
- best practice example in the state and awareness raising.

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IMPLEMENTACIJA ENERGETSKE UČINKOVITOSTI U JAVNIM ZGRADAMA „KORAK-PO-KORAK"

Sažetak: *Općine igraju ključnu ulogu u potrošnji energije i njezinim posljedicama po okoliš u zemljama članicama EU. Povećani troškovi energije posljednjih nekoliko godina zajedno s gospodarskom krizom potičuusredotočavanje na potrošačku stranu gospodarenja energijom, posebice u javnom sektoru. Javni sektor je jedan od najvećih potrošača energije u EU, pa stoga ima najviše koristi od povećanja energetske učinkovitosti. Te se činjenice ju u energetskoj politici EU, strategiji, akcijskim planovima i direktivama, posebice u direktivi EU o poticanju energetske učinkovitosti u krajnjoj potrošnjii energetskim uslugama (2006/32/EZ). Činjenica da većina općina nema financijskih sredstava dodatno motivira i veliki tržišni potencijal za primjenu energetskih usluga kao javno-privatnog partnerstva. U okviru projekta Minus 3%, kojeg je sufinancirao EU, pripremljen je vodič s preporukama za postizanje godišnjih ušteda od 3%. Njegov je sadržaj strukturiran koristeći se iskustvima stečenim tijekom provedbe projekta Minus 3% u šest gradova sudionika. Pristup „korak-po-korak" prema energetskoj učinkovitosti u javnom sektoru uglavnom je namijenjen lokalnim vlastima i voditeljima općinskih službi za gospodarenje energijom kao ključnih dionika koji su uključeni u izradu akcijskog plana energetske učinkovitosti za grad, u procesu odlučivanja i provedbe mjera energetske učinkovitosti. Prvi dio fokusira se na opisivanje procesa „korak-po-korak" pristupa Minus 3% - kako implementirati upravljanje energijom na općinskoj razini, definirati obveze grada, ulogu i odgovornost voditelja službi za gospodarenje energijomnjegova tima, kako postaviti osnovicu potrošnje energije, kako pripremiti akcijski plan energetske učinkovitosti i implementirati svoje mjere. Drugi dio posvećen je odličnim nacionalnim primjerima već provedenih projekata u gradovima sudionicima [1].*

Ključne riječi: energetski menadžment, javni sektor, monitoring potrošnje, implementacija

ASSESSMENT OF DOMESTIC ENERGY CONSUMPTION AND GDP TRENDS[1]

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Abstract: *A major concern of our days is the burden of our energy consumption imposed on our environment. Consequences are multiple, primarily global warming and increasing concerns over sustainability of our economic growth has to be mentioned. For the concise assessment of future energy consumption and economic development tends it is vital to develop a model which helps to understand the long term interaction between these macroeconomic variables. The task is significant as a properly founded model on energy-economic development can aid us in the solution of energy consumption related challenges without endangering economic growth. In our analysis we are examining the concept of energy consumption and economic development's cointegrated movement, and the possible direction of casuality. Internationally many good examples exist, here we present the results for Hungary. The developed model will be used to forecast economic growth based on energy consumption patterns in Hungary.*

Key words: energy consumption, economic growth, cointegration analysis

1. INTRODUCTION

Hungary became a member of the European Union in 2004. The country has a strong dependence on imported energy and the new energy policy of the Hungarian government places emphasis on changing this situation to the largest extent possible.

The understanding of the relationship between long-term transitions in energy use and growth trajectories is an important step towards establishing sustainable development in a globalising world economy. Impact assessment of energy-economic transitions can be undertaken, as economic transitions, transitions from extensive to intensive resource management or modernisation with green energy technologies to replace and expand capital stock to meet growing energy demand will become more and more important for policymakers.

Significant changes in energy consumption and technology can be observed across countries and over time and analysis and improved understanding of the differences is also vital in tackling global climate change issues and developing optimal mitigation strategies.

[1] The authors would like to express their gratitude for the support of the TÁMOP-4.2.1.B-11/2/KMR-2011-0003 project titled „"Az oktatás és kutatás színvonalának emelése a Szent István Egyetemen"

This paper aims to investigate the link between energy consumption and GDP utilising co-integration analysis. Besides, Granger-casuality links are assessed, that is which is more likely to cause changes in the other variable, GDP or energy consumption.

Furthermore the application of cointegration analysis to Hungary's energy consumption and economic growth can help answer the question: is there a decoupling of energy consumption from economic growth? The novum of the article is a comprehensive analysis with more recent data since we endeavour to build an error-correction model (ECM) as well.

Several important issues can be addressed by developing a good model. For example having a better view on link between energy consumption and GDP can help answer the question to which extent economic growth can be sustained under various energy availability scenarios. Another important question could be about the pathway of meeting the energy consumption challenges without interrupting economic growth within a country.

Furthermore conclusions for Hungary may be relevant for other countries including Croatia, which have to follow a similar development path, increasing the pressure on already scarce energy resources. Many studies highlight that the problem is also acute for Croatia (see e.g. Feretić et al (1998), Kovačević et al., 2000) This paper is also timely, as demonstrated by the current historic high oil and energy carrier prices.

The paper is organised as follows. Section 2 presents the international relevant experience and reviews important work on co-integration analyses similar to the results gained herewith. Section 3 discusses the method used, while Section 4 presents the data and discusses the results of the analysis. Section 5 contains some concluding remarks.

2. RELEVANT INTERNATIONAL EXPERIENCE

An overview of recent literature shows various applications of co-integration analysis in the field of energy and economic development, in some cases extended with casuality analysis.

Stern (1993) used annual data over the period 1947-1990 for the United States to show casuality link between a corrected energy consumption measure and economic growth. In a similar framework Stern (2000) undertook a co-integration analysis to conclude that energy is a limiting factor for growth, as shocks to energy tend to reduce output. For the United States Yu and Jin (1992) explained the link between energy consumption and GNP using employment as a third variable. Based on monthly data for the period of 1974:1-1990:4 no evidence was found for co-integration. This supports the earlier notion that energy restrictions do not impair US economic growth and that energy saving measures have no clear impact on employment

For Taiwan an analysis by Yang (2000) uses different types of energy carriers (oil, gas, and coal, power) for energy consumption to test for the causal relation of energy consumption with GDP. Annual data for the period of 1954-1997 is used to conclude that various directions of casuality exist between GDP and energy carrier consumptions.

For Korea a VECM-model was applied by Glasure (2002) to study the causality between GDP and energy consumption. Government expenditure, money supply and oil prices together with two structural breaks for oil price peaks are included in his model to explain casuality for the period 1961.1990. A bi-directional connection is derived for casuality and the oil price had the biggest effect on economic growth and energy consumption. Another analysis for Korea by Oh and Lee (2004) consider the period 1970-1999. In their approach a classical production function is applied (as recommended by Stern (1993)). Energy, labour and capital are used as variables for the function which generating macroeconomic output and a vector-ECM is established to confirm the conclusion of bi-directional causation between energy and GDP.

A study for Greece by Hondroyiannis et al (2002) examined the link between the consumer price index (CPI), energy consumption and GDP. Annual data over the period 1960-1996 was used to demonstrate bidirectional causality between energy consumption and GDP.

For Turkey Lise and Van Montfort (2005) provides a thorough co-integration analysis where after the examination of casuality and development of a VECM model an environmental Kuznets-curve is assessed. Soytas et al (2004) also study the causality between energy consumption and GDP for Turkey, using a cointegration analysis. They use annual logarithmised data over the period 1960-1995 and find that energy consumption Ganger-causes GDP unidirectionally. Altinay and Karagöl (2004) studied the existence structural break of energy consumption

3. METHODOLOGICAL BACKGROUND FOR THE ANALYSIS OF COINTEGRATION

A time-series model can only be built for stationary series and in most cases of practical interest data series are not like that. Moreover working with transformed series makes it difficult to interpret the results or impossible to use the model for forecasting. (Kovács et al. 2010), To overcome this problem Engle and Granger (1987) showed that if independent series are integrated of the same order *d*, denoted by I(*d*), and if the residuals of the linear regression among these series are integrated of the order *d*–*b*, I(*d*–*b*), then the series are said to be co-integrated of the order *(d, b)*, denoted as CI(*d,b*).

Cointegration is therefore a generalization of unit roots to vector systems. Assume that two time series are each integrated, i.e. have unit roots, and therefore can be represented with moving averages as follows where L denotes the lag operator:

$$\begin{aligned}(1-L)y_t &= a(L)\delta_t \\ (1-L)x_t &= b(L)\nu_t\end{aligned} \tag{1}$$

In general, linear combinations of y and x also have unit roots. However if there is some linear combination of the two time series which is stationary (for example $y_t - \alpha x_t$) then x and y are *cointegrated*, and [1-α] is called their cointegrating vector.
Some possible examples can be considered as follows: log *GDP* and log *consumption* each probably contain a unit root. However, the consumption/GDP ratio is stable over long periods, thus log consumption - log GDP is stationary, and log GDP and consumption are cointegrated. The same holds for any two components of GDP (investment, etc). Also, log stock prices certainly contain a unit root; log dividends probably do too; but the dividend/price ratio is stationary. Money (as a monetary variable) and prices are another example.

There is a great advantage in finding (long-term) co-integration relationships, as the series need no longer be transformed and, hence, the forecasting power increases substantially.

Several steps can be distinguished in undertaking a co-integration analysis on time series (see e.g. Hondroyiannis et al, 2002, Beki et al, 1999). For ease of exposition, but without loss of generality, we consider two time series only, namely xt and yt. First, the order of integration of xt and yt has to be established. Non-stationary series are particularly problematic when they have a unit root, which is equal to being integrated of the order one, I(1). This series is a random walk (possibly with drift), where the future value is equal to the past value (possibly with drift) with an error. The difficulty in using a random walk series is that it is typically heteroscedastic and cannot be used for forecasts. It is possible to test for a unit root using the Augmented Dickey-Fuller (ADF) test (Said and Dickey 1984) or the Phillips-Perron (PP) test (Phillips and Perron 1988). For instance, the ADF produces a tstatistic, which needs to cross a critical value above which the series can be confirmed to be stationary. This test needs to be run for different orders of integration, with trend and/or intercept and a number of lags. In this manner the order of integration can be determined.

Second, let us assume that xt and yt are integrated of the order one: I(1). By running a simple ordinary least squares (OLS) estimation, it can be verified whether these series are co-integrated. This is the case once the residuals are stationary. This can be verified by undertaking either the Johansen maximum likelihood cointegration test or by determining the order of integration of the residuals by using the same ADF as before again.

$$y_t = \phi x_t + \varepsilon_t \tag{2}$$

Once the residuals εt of Eqn.(2) are white noise, then there is one co-integrating factor (as established by the OLS), which is a good predictor of the long-term relationship among the variables (Harvey 1990). In general, when more variables are considered, it is possible to find multiple cointegrating vectors.(Edelmayer, 2011)

Third, a vector error-correction modeling approach is needed to test for the exogenity of the variables (Hatvani, 2011). The short-term variation can be predicted by using an error correction model (ECM). For instance, by using the following model:

$$\Delta y_t = \alpha + \sum_{i=1}^{k} \Delta x_{t-i+1} + \sum_{j=1}^{m} \Delta y_{t-j} + \delta ECT_{t-1} + \varepsilon_t \tag{3}$$

where α, β, γ, δ are coefficients which need to be estimated from a VAR regression, Δ is the difference operator, and φ is the co-integrating factor, which can be derived through OLS in a first stage. ECT stands for error correction term, which can be established by Equation (2). Fourth, the causality between variables can be established. It is then possible to verify whether, say, energy Granger-causes economic growth, the other way around, or both. Moreover, once a co-integration relation is established between xt and yt then either xt has to (Granger) cause yt, or the other way around, or both.

4. RESULTS OF THE ANALYSIS

In the followings we try to justify or refuse the hypothesis that energy consumption goes hand-in-hand with economic development, and an attempt is made to identify long term cointegration between the two macroeconomic variables. An error-correction model is also developed according to the methodology described in the previous chapter. This is undertaken in the context of Hungary, but can be generalised to any country (or region).

The relationship between domestic energy consumption and GDP is examined in the following steps: assessment of stationarity, unit root test, identification of degree of integration, identification of a co-integrating equation and a formulation of a vector-error correction model.

4.1. Source data used for analysis

Data on domestic GDP was made available by the ECOSTAT division of the Hungarian Central Statistical Office (HCSO), energy consumption data come from Molnár S. (1997). The GDP time series is a nominal price series beginning from 1950. Although the methodology for calculation of GDP changed significantly in 1995 we still maintained the use of a longer data series (which thus includes GDP data calculated by two different methodologies) as an analysis restricted to the period after 1995 would result in a critically low element number already after two difference operations, furthermore it would not have given satisfactory significance for the unit root test and cointegration test. Time series were logarithmised due to their different dimensions and scales. Figure 4.1. demonstrates the similar behaviour of GDP and energy consumption in Hungary. Note that on the figure the time scale is also asymmetric, it is more detailed for the last two decades.

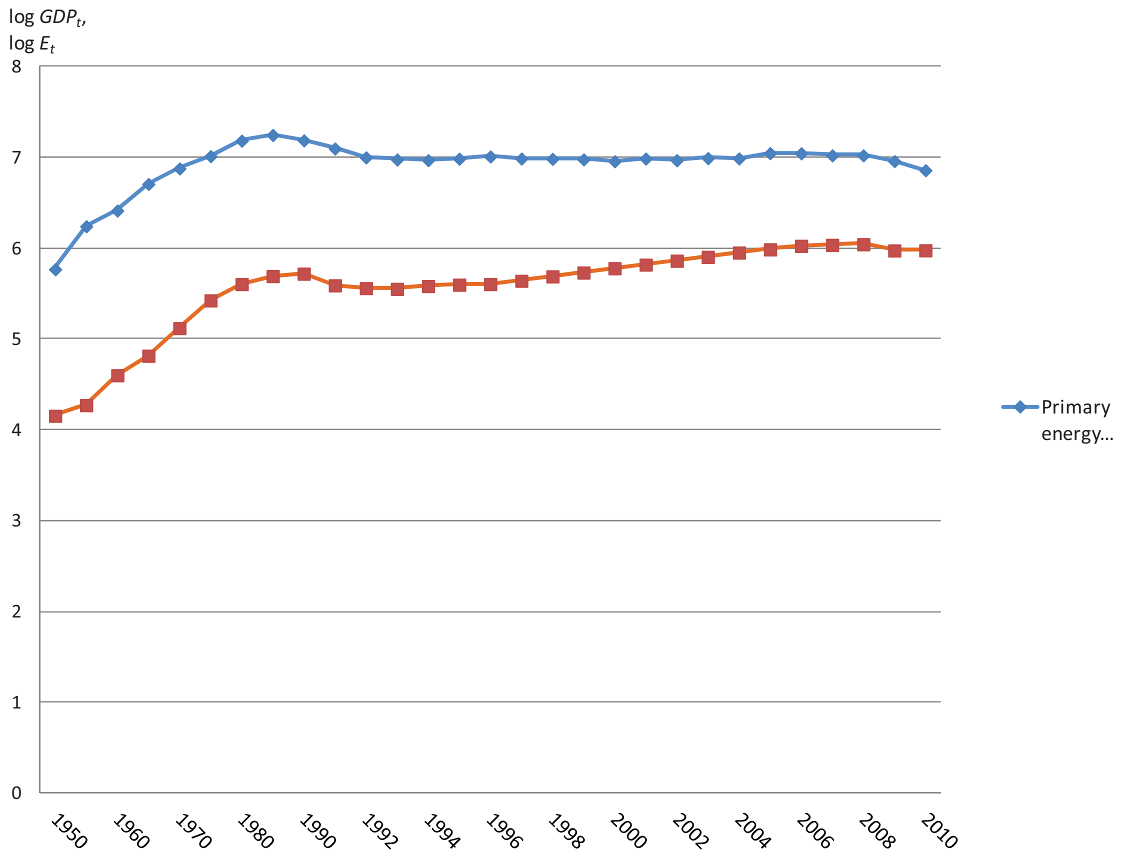

Figure 4.1. Domestic primary energy consumption and GDP trends on a logarithmised scale (1950-2010[2])

source: Ecostat, own ed.

[2] 2010: 4th quarter estimated from interim annual figures available

4.2. Results

The fundamental area of our analysis was the relationship between GDP and energy consumption: is the earlier a function of the latter (or vice versa)? What is the long term interdependence between these two variables? These are basically the questions we try to answer. Once we have firmly established a cointegration relationship between EC and GDP, then we know that there is (Granger) causality at least in one direction (but possibly both). Continuation of the cointegration analysis can establish the direction of causality. Hence, we leave the decision of causality to the analysis.

In the first step the order of integration was identified by a unit root test (Augmented-Dickey Fuller test or ADF). The results show with 95% confidence that both processes are of I(2) types, that is of second order of integration.

Performing the Johansen-test for cointegration the following cointegrating equation is gained on a confidence level of 95%:

$$\ln E_t = 0.603442 \cdot \ln GDP_t + 3.89389 + u_t \tag{4}$$

where E_t , E_{t-1}, etc. denotes energy consumption in the t^{th} period, and GDP_t denotes the gross domestic product in the t^{th} period. The equation definitely underlines our expectation on energy consumption being strongly dependent on the level of our gross domestic product.

A vector-error correction model explains deviation from the long term equilibrium by the lagged variables where a plain vector-autoregressive model would give a bad specification even if it would have a better fitting (better explanatory strength). Selecting the optimal number of lags according to the Schwarz-information criterion renders the following VECM-model:

$$\begin{aligned}\Delta \ln E_t = &-0.0892950 \cdot (\ln E_{t-1} - 0.603442 \cdot \ln GDP_{t-1} - 3.89389) - 0.384743 \cdot \Delta \ln E_{t-1} - \\ &-0.08482 \cdot \Delta \ln E_{t-2} + 0.332045 \cdot \Delta \ln GDP_{t-1} + 0.09607 \cdot \Delta \ln GDP_{t-2} - 0.011946 + \varepsilon_t\end{aligned} \tag{5}$$

The estimated model has the required strength and the residuals are stationary: $R^2_{adj} = 0.937621, \varepsilon_t \sim I(0)$. If we select the other direction (we try to explain changes in economic growth with changes in energy consumption) then the explanatory strength decreases but still remains quite significant (R_2^{adj} =0.7548).

It can be stated from these findings that the relationship is significant and the changes in macroeconomic output (GDP) strongly influences energy consumption.

Using estimations from the error-correction model we can derive the equation describing adjustment to the long term equilibrium as follows:

$$\begin{aligned}\ln E_t = &\,0.3030942 \ln GDP_{t-1} - 0.235975 \ln GDP_{t-2} - 0.09607 \ln GDP_{t-3} + \\ &+0.525962 \ln E_{t-1} + 0.299923 \ln E_{t-2} + 0.08482 \ln E_{t-3} + 0.35965 + \varepsilon_t\end{aligned} \tag{6}$$

From the above equation it follows that energy consumption in a specific year is strongly influenced by the GDP and energy consumption in the previous year and the energy consumption and the GDP of two periods before (with respectively negative and positive sign). The influence of variables lagged with three years is not significant and thus can be ignored.

Performing the Granger-casuality tests using a delay of l=(1,1) in the variables (one-period lag) results in GDP (Granger-) causing energy consumption, if a delay of l=(2,2) in the variables (two-period lag) is assumed than a bidirectional probability can be expected with high probability.

4. CONCLUSIONS

This paper undertook a quantitative analysis of development and energy transitions for the energy situation in Hungary. A cointegration analysis was undertaken to answer the following question: What is the link between energy consumption and GDP in Hungary? The analysis shows that energy consumption and GDP are co-integrated. This means that there is a causality relationship between the two variables. We found that causality runs unidirectionally from GDP to energy consumption but a model with more lags shows bidirectional relationship. An important conclusion is that the decoupling of economic development from energy consumption is not possible under the present economic framework. This also means that the Hungarian economy along with typical OECD economies is still very sensitive to energy prices and energy supply. This sensitivity can be considered critical and should therefore be one of the highest priorities for the government. There are definite signs in the new Hungarian energy strategy that strong awareness exists among our decision makers about the size and importance of the problem.

In the long term equilibrium we find that the amount of GDP and energy consumption in the previous two years is a good predictor for the amount of energy consumption in the current year. We see that energy consumption in the previous two periods has a larger weight then GDP in defining energy consumption in the current period. This possibly shows that the energy consumption patterns have a large inertness and a switch to a less energy intensive economy is still ahead of us. This has important policy consequences as it suggests that energy policy should definitely focus on energy conservation and energy efficiency measures primarily.

Areas for future research might be to undertake a sectoral cointegration analysis to verify in which sectors the results of this paper are valid. This could lead to a more precise policy recommendation as to where energy conservation policies would not harm the economy.

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PROCJENA TRENDOVA RAZVOJA DOMAĆE POTROŠNJE ENERGIJE I KRETANJA BDP-a[3]

Sažetak: *Glavna briga naših dana jest utjecaj naše energetske potrošnje na okoliš. Posljedice su višestruke, prvenstveno treba spomenuti globalno zatopljenje i povećanu zabrinutost zbog održivosti našega gospodarskog rasta. Za sažetu procjenu trendova buduće energetske potrošnje i gospodarskoga razvoja, bitno je razviti model koji pomaže u razumijevanju dugoročna međudjelovanja između tih makroekonomskih varijabli. Zadatak je značajan jer nam ispravno postavljeni model energetsko-ekonomskog razvoja može pomoći u rješavanju izazova povezanih s energetskom potrošnjom bez ugrožavanja gospodarskoga rasta. U našoj analizi ispitujemo koncept kointegracije kretanja energetske potrošnje i gospodarskoga razvoja, te moguće posljedice. Postoje mnogi dobri međunarodni primjeri a ovdje ćemo predstaviti rezultate za Mađarsku. Razvijeni će se model koristiti za prognozu gospodarskoga rasta temeljena na obrascima energetske potrošnje u Mađarskoj.*

Key words: energy consumption, economic growth, cointegration analysis

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NACIONALNI INFORMACIJSKI SUSTAV ZA GOSPODARENJE ENERGIJOM

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Sažetak: *Informacijski Sustav za Gospodarenje Energijom (ISGE) je web aplikacija za praćenje i analizu potrošnje energije i vode u zgradama javne namjene (sektor zgradarstva), te kao takva predstavlja neizbježan alat za uspostavu Sustavnog gospodarenja energijom (SGE). Koristi ga većina objekata kojima troškove za energiju i vodu plaćaju Gradovi, Županije, Ministarstva i ostale državne agencije.*

Ključne riječi: energetska efikasnost, sustavno gospodarenje energijom, informacijski sustavi, energetika, okoliš, održivi razvoj, potrošnja energije i vode, automatizirana očitanja brojila

1. UVOD

Sustavno gospodarenje energijom (SGE) obuhvaća strateško planiranje i održivo gospodarenje energetskim resursima. Primjenjuje se u zgradama javne namjene, npr. zgrade u vlasništvu Gradova, Županija i Ministarstava. Stručnjaci odgovorni za SGE u informacijski sustav unose važne informacije o objektima u njihovoj nadležnosti. Korisnici se u sustav mogu prijaviti s bilo kojeg računala s pristupom internetu unoseći dodijeljeno im korisničko ime i lozinku.

Unutar baze podataka Informacijskog sustava za gospodarenje energijom (ISGE) korisnici mogu unijeti statičke podatke o svakom objektu; tzv. općeniti, konstrukcijski i energetski obrazac. Unosi se i dinamička potrošnja energije i vode koja uključuje praćenje potrošnje s mjesečnih računa za pojedine energente te praćenje stanja mjernih uređaja na objektu. Također, sustav prihvaća i automatska daljinska mjerenja s objekata koji su takvim sustavima opremljeni.

Podaci u ISGE-u koriste se za razne izračune i analizu koja je potrebna kako bi se u potpunosti razumio način korištenja energetskih resursa i vode na objektu. Aplikacija omogućava usporedbu pojedinih objekata s objektima sličnih karakteristika te pomaže prilikom identificiranja povećane i nerazumne potrošnje energije i vode. Dio analiza i praćenja potrošnje obavlja se automatski (npr. na drastično povećanje potrošnje energije ili vode sustav će nas upozoriti odmah nakon unosa). Tim putem sprječavaju se neželjeni i nepotrebni troškovi.

ISGE uvelike pojednostavljuje uspostavu SGE-a u zgradama javne namjene. Omogućava brzi pristup podacima o potrošnji energije i vode te ih grafičkim ili tabličnim putem prikazuje na zaslonu. U sustav je integrirana i temeljita analiza koja olakšava prikazivanje podataka nužnih za stvaranje lokalnih planova u vidu poboljšanja energetske učinkovitosti. Povrh toga, ISGE omogućava kvantifikaciju pozitivnih i negativnih utjecaja na okoliš putem analize CO_2 emisija.

2. RAZVOJ ISGE-A

Razvoj inicijalne verzije ISGE-a datira iz 2006. godine kada se ideja o informacijskom sustavu pojavila kao dio radnog paketa pilot projekta „Uvođenje sustavnog gospodarenja energijom u gradu Sisku“ [1]. Implementacija pilot projekta obavljena je uspješno, realizirano je nekoliko projekata na kojima su postignuti zacrtani ciljevi energetski učinkovitijeg korištenja energije (godišnja ušteda od 10% energetskog proračuna grada Siska). S uspješnim pilot projektom grada Siska iza sebe, ostali gradovi također su počeli iskazivati interes za uspostavom sustavnog gospodarenja energijom u javnim zgradama. Sve veći interes i potreba gradova za energetskim projektima, a time i uštedama, dovela je do razvoja nacionalnog projekta „Sustavno gospodarenje energijom u gradovima i županijama u RH“ (u daljnjem tekstu: SGE projekt). SGE projekt službeno je počeo u prosincu 2007. Godine [2], a glavni mu je fokus bio uspostavljanje sustavnog i kontinuiranog gospodarenja energijom u zgradama javne namjene (sektor zgradarstva) u vlasništvu gradova i županija. Uspjeh SGE projekta postavio je temelje i za uspostavu drugog nacionalnog projekta; „Dovesti svoju kuću u red“ („House in order“, u daljnjem tekstu: HIO projekt). HIO projekt počeo je s radom u svibnju 2008. godine, a za fokus potrošnje uzima zgrade u vlasništvu RH, odnosno ministarstva i ostale vladine organizacije. ISGE se pokazao ključnim alatom prilikom uspostave sustavnog gospodarenja energijom. Jednom kad je ISGE instaliran, a baza podataka popunjena, ISGE omogućava jednostavan pristup podacima o potrošnji energije i vode, provjeru postignutih rezultata te identifikaciju mjesta pogodnih za brojne energetske, a time i iznimno značajne financijske uštede.

Povod daljnjem razvoju ležao je u potrebi za optimizacijom sustava na sve veći broj subjekata koji koriste sustav. Dva nacionalna projekta, potpisana Pisma namjere o sudjelovanje u nacionalnom projektu od svih gradova i županija, a samim time i prilagodba sustava svim različitostima tih subjekata, iziskivala su razvoj sustava i njegovih funkcionalnosti. Tako je uspostavljena centralna verzija ISGE-a s mogućnošću pristupa aplikaciji s bilo kojeg računala s pristupom internetu.

Kontinuirani rast i razvoj projekata inicirao je razvoj nove verzije ISGE-a na kojoj je veći naglasak bio upravo na analitičkim funkcionalnostima koje bi omogućile agregiranje podataka sve do nacionalne razine. Naravno, analitika se zadržala i za najmanju lokalnu razinu (na razini samog brojila). U rujnu 2009. raspisan je međunarodni natječaj na koji se javilo osam razvojnih tvrtki, od čega su tri bile strane kompanije. Kumulativnom analizom odabrana je tvrtka koja je postigla najveću kombinatornu ocjenu koja se temeljila na tehničkoj evaluaciji i ponuđenoj cijeni. Nakon potpisanog ugovora potpuno funkcionalna ISGE aplikacija isporučena je i instalirana na centralni server u travnju 2011. godine. Tijekom 2011. godine, testiran je rad aplikacije i provjerena točnost prebačenih podataka sa stare na novu verziju, a paralelno su educirani korisnici i unašani novi podaci o potrošnji energije i vode.

Kroz spomenuti period otvoreno je preko 2.000 korisničkih računa, te je u ISGE sustav uneseno preko 6.000 objekata kroz oba nacionalna projekta. Kako unos podataka javnih ustanova i dalje traje, broj unesenih objekata i otvorenih korisničkih računa u stalnom je porastu. Za svaki objekt prikupljaju se podaci o energetskim trošilima na objektu, kao i dinamički podaci o potrošnji energije i vode s mjesečnih računa i očitanja sa samih brojila.

3.STRUKTURA I ORGANIZACIJA

3.1. Hardverska i softverska struktura sustava

Pristup ISGE-u moguć je s lokalnog servera, stolnog ili prijenosnog računala, mobitela, odnosno s bilo kojeg uređaja koje ima pristup internetu. Hardver ovog sustava čine server, VPN router s firewallom (dual WAN, DMZ/WAN), gigabitni switch preko kojega su serveri spojeni međusobno na router. Softversku stranu ISGE-a čini Oracle baza podataka te web aplikacija. Sami korisnici ISGE-a zaštićeni su korisničkim imenom i lozinkom kojim se prijavljuju na sustav na stranici https://www.isge.hr gdje je promet enkriptiran. Backup baze podataka radi se jednom tjedno, dok se inkrementalni backup radi svaki dan. Tako konfiguriran sustav trenutno komunicira s informacijskim sustavima poput sustava daljinskih očitanja, sustavom DHMZ-a s kojeg dobiva meteorološke podatke, bazom podataka energetskih certifikata, a uz postojeće postoji mogućnost spajanja i s brojnim drugim pametnim sustavima.

3.2. Struktura korisnika sustava

Organizacija uloga unutar ISGE-a pomno prati organizacijsku strukturu cijelog koncepta SGE-a. Kroz Funkcijsku specifikaciju na temelju koje je razvijena trenutna verzija ISGE-a definirano je pet funkcionalno različitih uloga, a svakoj ulozi prilagođeno je sučelje sustava. One ovise o položaju i odgovornosti samog korisnika, a upravo se ta odgovornost može uspostaviti kroz koncept SGE-a. Uloge grupiramo u dvije cjeline; administratorska i korisnička. Ovisno o pravima korisnika, isti prolazi posebnu edukaciju za svoju ulogu nakon koje dobiva jedinstveno korisničko ime i lozinku. Za svaku korisničku ulogu napisani su i priručnici za korištenje ISGE-a [3], koji su javno dostupni na početnoj stranici aplikacije. Administratorske uloge čine Administrator Sustava (AS), Energetski Administrator (EA) i Energetski Menadžer (EM), dok korisničke uloge dijelimo na ulogu Korisnika (K) i Gosta (G).

<u>Administrator sustava (AS).</u> AS nadzire rad sustava, prati kreiranje novih objekata, korisnika i podataka koje korisnici unose. Zadužen je za definiranje svih administrativnih cjelina kao i korisnika koji koriste objekte javne uprave. Isto tako, u opis posla ulazi i definiranje svih energetskih karakteristika zgrada, kao npr. dodavanje novih sustava za grijanje ili unos novih vrsta energenata. Zadužen je i za uređivanje dobavljača koji distribuiraju energiju i/ili vodu.
AS odgovoran je za rad samog sustava, njegovih korisnika i stabilnost svih funkcionalnosti sustava. Također, on nadgleda sve niže rangirane uloge u aplikaciji na način da upozorava na neispravne unose, korigira neispravne podatke i postavlja granične vrijednosti na koje sam sustav reagira alarmirajući korisnika na primjerice prevelik ili premali iznos jedinične cijene za električnu energiju.

Uz sam nadzor, AS radi i globalne izvještaje na razini cijele države ili pojedinog korisnika grupe objekata kao što je primjerice Ministarstvo zdravstva ili Grad Osijek. Također, objavljuje i statističke podatke iz sustava kao što su broj objekata u pojedinom Ministarstvu ili broj trenutno aktivnih korisnika, popunjenost podacima i slično.

Energetski administrator (EA). EA bavi se prije svega energetskim dijelom administracije pojedinih objekata, kreiranjem energetskih troškovnih centara (ETC) tj. povezivanjem karakteristika zgrade s brojilima potrošnje energije i vode, odnosno korisnicima objekata.
EA se najčešće nalaze u regionalnim uredima u kojima nadgledaju potrošnju energije i vode za pojedinu regiju kao što je primjerice Slavonija koja se sastoji od 5 županija i 22 grada. Republika Hrvatska je kroz ISGE i centre za analizu potrošnje energije i vode u javnom sektoru podijeljena u šest regija: Slavonija, Sjeverozapadna Hrvatska, Centralna Hrvatska, Istra i Kvarner, Sjeverna Dalmacija i Lika, te Južna Dalmacija.
Također, ulogu EA imaju i EE timovi koji se bave isključivo analizama potrošnje energije i vode u svom Gradu, Županiji ili Ministarstvu. Takvi timovi se najčešće sastoje od kombinacije jednog EA i EM.

Energetski menadžer (EM). EM bavi se analizom potrošnje energije i vode. Potreba za timom takvih kadrova dolazi tek nakon što se cijeli sustav konfigurira i ispuni podacima. Osoba mora dobro poznavati potrošnju energije i vode ETC-ova koje prati jer će donositi bitne zaključke za provođenje daljnjih mjera prilikom implementacije efikasnijih sustava.

Korisnik (K). Korisnicima, kojih je najveći broj i obavljaju najveći broj unosa podataka u sustav, sučelje je pojednostavljeno, a opet dovoljno funkcionalno da bi kvalitetno gospodarili energijom na svom objektu, bilo kroz unos podataka, bilo kroz analizu istih. Svaki objekt ili skup objekata ima osobu (najčešće domar ili tajnica) koja kroz očitanja mjerila i unos mjesečnih računa u sustav kontinuirano prati potrošnju energije.

Gost (G). Čest je slučaj da primjerice ravnatelji objekta ili skupa objekata želi imati uvid u potrošnju energije i vode. Kroz ulogu G na jednostavan način može se dobiti uvid u potrošnju energije i vode na svom objektu bez ikakvih drugih ovlasti u smislu izmjene podataka ili brisanja istih. G isključivo ima omogućeno vidljivost podataka i ispis tih podataka kroz predefinirane izvještaje.

3.3. Organizacijska struktura korisnika u RH

Kroz aktualni nacionalni program SGE-a, u većini regija trenutno postoji uspostavljen koncept praćenja potrošnje i unosa iste u ISGE.

Regionalni EE uredi. Izuzetno važan faktor u samoj strukturi imaju regionalni EE uredi (uloge EA i EM). Oni su poveznica lokalne razine (EE timova) i centralnog ureda s ciljem koordiniranja EE ureda na svom području, agregacije podataka te izrade izvještaja trenutnog stanja, kao i prijedloga budućih mjera prema nacionalnoj razini. Regionalni administrator mora poznavati posebne karakteristike područja, ljude, te mora posjedovati odlične vještine komuniciranja prema korisnicima, ostalim EE timovima, različitim distributerima energije itd. Ovisno o broju objekata (ETC-ova) koje regija obuhvaća, regionalni ured zapošljava više ili manje regionalnih administratora, menadžera i njihovih asistenata.

Lokalni EE uredi. Koncept lokalnog EE ureda identičan je konceptu regionalnog EE ureda. Jedina je razlika u opsegu objekata koje pojedini ured nadzire. Idealno bi bilo da postoje sistematizirana radna mjesta unutar pojedinih gradova/županija/ministarstava kako bi zaposleni u tom uredu potpuno posvetili uspostavljanju SGE-a. Tada bi uz komunikaciju s korisnicima na objektima (što je posebno bitno), tehničku pomoć, punjenje baze podacima, više vremena mogli provesti analizirajući podatke. Pomoću analiza mogu pisati izvještaje, predlagati objekte s izrazito lošim indikatorima potrošnje za provedbu energetskih pregleda i na posljetku investicija koje bi dugoročno koristile zajednici u kojoj djeluju.

Korisnici na objektu. Na razini samog objekta zadužuje se tehnički obrazovna osoba (uloga K) za komunikaciju s lokalnim EE uredom. Poželjno je objektu dodijeliti i jednu gostujuću ulogu koja prati potrošnju objekta (a samim time i aktivnost) kroz sustav (uloga G). Tehnička osoba na razini objekta prošla je svu potrebnu edukaciju za korištenje sustava, a samim time je upoznata i sa svim aktivnostima koje je na razini objekta potrebno obavljati (očitanja i unos potrošnje sa brojila dvaput tjedno, unos mjesečnih računa, prikupljanje osnovnih karakteristika pojedinog energetskog sustava, konstrukcijskih elemenata, itd.). Naravno, za sve poteškoće na usluzi korisnicima stoje EE lokalni i regionalni uredi.

4. PRIKUPLJENI PODACI

Cilj prikupljanja podataka i ispunjavanje obrazaca unutar ISGE-a je dobivanje uvida u strukturu potrošnje energije i vode u javnim zgradama RH [4]. Na temelju svih ulaznih podataka moguće je kroz ISGE na jednostavan način donijeti konkretne prijedloge vezane uz moguće uštede energije i vode.
Set podataka koji se prikuplja u ISGE-u dijeli se u dvije osnovne skupine: statički i dinamički podaci. Statičkim nazivamo one koji se rijetko ili nikada ne mijenjaju, dok su dinamički oni koje za objekt dobivamo na dnevnoj, tjednoj ili mjesečnoj bazi, a riječ je o očitanjima samih mjerila, mjesečnim računima i meteorološkim podacima.

4.1. Statički podaci

Statičke podatke čine oni podaci koji se nikada ili vrlo rijetko mijenjaju. Prije svega služe u ISGE-u kao osnova za proračun indikatora kojima se na jednostavan način mogu uspoređivati građevine sličnih karakteristika, ali i informativno kako bi korisnik sustava brzo mogao saznati o kakvom se objektu radi.
Osnovnu podjelu statičkih podataka čine opći podaci, energetski podaci, konstrukcijski podaci, dokumenti te meteorološki parametri.
Unutar općeg obrasca nalaze se najosnovnije informacije vezane uz geografsku poziciju samog objekta, način korištenja tog objekta, kontaktni podaci odgovornih osoba i osnovne dimenzije objekta (površina, volumen i slično). Energetski obrazac služi za prepoznavanje karakteristika sustava potrošnje energije i vode kao što su sustav grijanja, hlađenja, ventilacije, potrošne tople vode, vodovodni sustav, sustavi vanjske i unutarnje električne rasvjete te ostalih potrošača električne energije. U okviru konstrukcijskih podataka upisuju se podaci vezani uz vanjsku ovojnicu građevine i općenito građevinski dio objekta. Također uz obrasce postoji mogućnost pridruživanja objektu odgovarajućih dokumenata kao što su projektna dokumentacija, energetski pregledi, fotografije i sl.

Meteorološki parametri uzeti su iz priloga E Tehničkog propisa o racionalnoj uporabi energije i toplinskoj zaštiti u zgradama (NN110/08). U tom su Prilogu sadržane meteorološke veličine za mjerodavne meteorološke postaje potrebne za proračun fizikalnih svojstava zgrade glede racionalne uporabe energije i toplinske zaštite. ISGE automatski povezuje svaku zgradu s odgovarajućom meteorološkom postajom i na taj način koristi odgovarajuće meteorološke parametre za proračune.

4.2. Dinamički podaci

Dinamičke podatke nazivamo one podatke koji se na mjesečnoj bazi unose u sustav. Oni su promjenjivi i predstavljaju podatke koji nam služe za analizu realne potrošnje energije i vode na objektu za koji su uneseni.
Osnovnu podjelu dinamičkih podataka čine mjesečni računi, tjedna očitanja brojila, daljinska očitanja brojila te meteorološki parametri.
Mjesečne račune u sustav unose sami korisnici objekata iz mjeseca u mjesec. U sustav su retroaktivno uneseni svi računi za potrošenu energiju i vodu od 2007. godine za većinu objekata unesenih u sustav. Na taj način dobila se izuzetno dobra slika potrošnje na mjesečnom nivou kroz zadnjih 6 godina i pojednostavila se analiza potrošnje za svako pojedino brojilo jer se na jednostavan način mogu uspoređivati mjesečne potrošnje.
Uz mjesečne račune bitno je pratiti i samu potrošnju s tjednih očitanja brojila. Veliki dio brojila očitava se ponedjeljkom i petkom kako bi se dobio uvid u potrošnju kroz radni dio tjedna od ponedjeljka do petka, ali i neradni dio tjedna, odnosno vikend od petka do ponedjeljka. Na taj su se način uočila brojna puknuća cjevovoda i curenje vode koje bi se primijetilo tek nakon izdavanja mjesečnog računa. Također, kroz samu analizu potrošnje vikendom može se na jednostavan način uočiti postoji li određeno opravdano ili češće neopravdano povećanje potrošnja toplinske ili električne energije.
Kod većih objekata instaliran je automatski sustav očitanja brojila koji podrazumijeva uvid u trenutno stanje brojila u ISGE-u. To znači da je na satnoj razini moguće nadzirati potrošnju energije i vode. Kroz analizu je utvrđeno više anomalija u potrošnji kao što su curenje vode u noćnim satima, loša regulacija sustava grijanja ili primjerice neopravdano povećana potrošnja električne energije radi uključene rasvjete u noćnim satima.
Osim statičkih meteoroloških podataka kao što su tridesetogodišnji prosjeci i srednje mjesečne temperature, meteorološki parametri se od DHMZ-a dobivaju i daljinskim putem na mjesečnoj i satnoj razini. Kao takvi služe za iscrtavanje E-t krivulja i proračun ušteda putem CUSUM analize. Za sam proračun se prema bitnosti uzimaju prvo lokalni podaci sa sustava daljinskih očitanja ukoliko ga objekt posjeduje, zatim baza DHMZ-a, a tek onda statički podaci iz baze podataka ISGE-a uneseni iz Priloga E Tehničkog propisa NN110/08.

5. METODE ANALIZE

Analiza potrošnje energije i vode [5] kroz ISGE vrši se putem tabličnih ili grafičkih prikaza. Kako su tablični prikazi u potpunosti fleksibilni, na jednostavan se način mogu dobiti agregirani podaci vezani uz potrošnju energije ili vode za pojedini objekt, grupu objekata sortiranih po određenom parametru ili nešto drugo prema želji korisnika. Rezultati koji se dobiju nakon provedenog filtriranja i sortiranja podataka na jednostavan se način mogu eksportirati u tabličnom formatu i na taj način bilo kojim programom za tablično računanje dalje obrađivati. Uz tablični prikaz podaci o potrošnji energije i vode mogu se prikazati i grafički u modulu Grafovi.

Grafički se mogu analizirati prikupljeni podaci s mjesečnih računa za bilo koji energent i vodu, ali i sama očitanja s brojila. Temperature koje služe za regresijsku analizu i proračun ušteda u potrošnji na temelju određene referentne godine dobivene su od DHMZ-a i automatski se ažuriraju kada se pojave novi podaci o temperaturi.
Grafičke metode analize potrošnje energije i vode također su široke, a sam tok analize provodi se sljedećim redoslijedom kroz grafove: analiza apsolutne potrošnje, analiza indikatora potrošnje, regresijska analiza (E-t krivulja), CUSUM analiza.
Potrošnja se grafički može prikazati za jedno brojilo, dio zgrade, cjelovitu zgradu ili kompleks koji sadrži veći broj brojila, ali i za neki skup zgrada kojeg povezuje vlasnik zgrade ili neki drugi proizvoljni parametar.

5.1. Analiza apsolutnih vrijednosti potrošnje energije i vode

Analiza potrošnje u određenim vremenskim intervalima predstavlja prvi korak prema razumijevanju potrošnje promatranog objekta. Sam objekt može biti jedno mjerilo, dio neke zgrade s više mjerila, cijela zgrada, kompleks s više zgrada, skup specifičnih zgrada ili cijeli grad, županija ili ministarstvo. Na taj se način jednostavno mogu uočiti kretanja potrošnje u odabranim funkcijskim intervalima. Vremenski intervali mogu biti od satnog kretanja potrošnje, ukoliko se daljinski očitavaju brojila, pa sve do tjednog, mjesečnog i godišnjeg. Potrošnja energije može se prikazati u kWh, ali i količinski u m^3, kg, litrama i slično.

5.2. Analiza indikatora potrošnje energije i vode

Analiza potrošnje energije i vode korištenjem indikatora potrošnje predstavlja korak analize koji omogućuje jasnu procjenu energetske efikasnosti objekta. Indikatori omogućuju samu klasifikaciju po pojedinim razinama energetske efikasnosti te uspoređivanje više objekata međusobno. Indikator potrošnje daje odnos izmjerene potrošnje i odabranog mjerljivog parametra koji je proizvoljno odabrana izlazna veličina kao što je razina okupiranosti, površina objekta ili volumen grijanog prostora.

5.3. Analiza potrošnje u ovisnosti o vanjskoj temperaturi (E-t krivulja)

Metoda analize energije putem E-t krivulje omogućuje kontinuirano praćenje samo potrošnje energije (bez vode) u ovisnosti o vanjskoj temperaturi. E-t krivulja daje mogućnost praćenja potrošnje kroz duže razdoblje nevezano za godišnja doba i vrste energenata koje promatrani objekt koristi. Sama krivulja se sastoji od dva pravca; jedan koji opisuje zimski period i predstavlja ponašanje potrošnje zimi, dok drugi pravac predstavlja ljetni period. Svaka točka na pravcima može se ručno postaviti u željeni period, dok sustav sam predefinirano uzima prijelaznu vrijednost temperature od 15°C. O odabiru točaka ovisit će i izrada CUSUM grafa kojim se verificiraju uštede na promatranom objektu.

5.4. Određivanje ušteda (CUSUM analiza)

Završni korak u uvođenju SGE-a te implementiranju mjera energetske efikasnosti je određivanje ostvarenih ušteda. Najčešće korišteni statistički alat za vrednovanje ušteda u zgradama implementiran je u ISGE i naziva se metoda CUSUM grafa (engl. Cumulative Sum). Izračunata ušteda uzima u obzir vanjsku temperaturu i radi proračun uštede ostvarene u nekom trenutku s obzirom na proizvoljno odabranu baznu godinu ili neki drugi bazni period potrošnje.

6. VANJSKI SUSTAVI

ISGE koristi brojne vanjske sustave za dobivanje preciznih podataka o primjerice vanjskoj temperaturi za izradu E-t krivulja od Državnog hidrometeorološkog zavoda, o službenim podacima kao što je ploština korisne površine zgrade iz informacijskog sustava za upravljanje energetskim certifikatima ili sustavom daljinskih očitanja brojila za precizna mjerenja i mogućnost detaljnije analize podataka o potrošnji energije i vode.

6.1. Meteorološki parametri

Baza ISGE-a povezana je sa sustavom Državnog hidrometeorološkog zavoda (DHMZ) i na taj način dobiva sve potrebne meteorološke parametre. Meteorološki parametri integrirani u sustav su srednja mjesečna temperatura zraka, stupanj-dan grijanja i hlađenja, broj dana grijanja i hlađenja te datumi početka i kraja ogrjevne sezone. Podaci su prebačeni za povijesni period od početka 2007. do kraja 2010. godine, dok se od 2011. godine prikupljaju ne samo mjesečni podaci već i satna temperatura zraka za sve glavne meteorološke i klimatološke postaje Republike Hrvatske.

6.2. Informacijski sustav za upravljanje energetskim certifikatima (ISEC)

Informacijski sustav za upravljanje energetskim certifikatima (ISEC) je sustav za evidentiranje zgrada, osoba koje vrše energetsko certificiranje i energetski pregled zgrada, kao i sam proces certificiranja zgrada te vođenje evidencije ovlaštenih osoba. ISEC je centralno mjesto gdje se nalaze svi podaci o certificiranim objektima kao i objektima u postupku certifikacije te informacije o njihovom stvarnom energetskom stanju.
Kako vrijednosti u energetskom certifikatu predstavljaju službene vrijednosti o primjerice oplošju grijanog dijela zgrade, unutrašnjoj projektnoj temperaturi grijanja, i još mnogim drugim parametrima, sinkronizacija baza omogućuje preuzimanje tih podataka na temelju kojih ISGE radi daljnju obradu, proračune i prezentaciju istih.

6.3. Sustav daljinskih očitanja

Sustavom daljinskih očitanja ISGE je povezan s otprilike 300 mjernih uređaja. Uređaji su spojeni na centralni server za prikupljanje daljinskih mjerenja koji dalje obrađene podatke provjerava i prosljeđuje u bazu ISGE-a. Kroz samu aplikaciju moguće je pratiti satnu razinu potrošnje energije i vode za sve objekta na kojima je ugrađen ovakav sustav. Interes javnih

objekata za ugradnju sustava daljinskih očitanja mjerila postaje sve veći, a time i broj malih i srednjih poduzetnika koji ugrađuju takvu specifičnu opremu.
Detaljan uvid u potrošnju daje i puno bolje rezultate analize potrošnje energije i vode, kao i preliminarna upozorenja ukoliko je došlo do primjerice puknuća cjevovoda u vodovodnom sustavu ili primjerice povećane potrošnje toplinske energije uslijed pogrešne regulacije sustava grijanja tokom vikenda.

6.4. EE paneli

EE panel je dio sustava daljinskog očitanja koji služi za prikazivanje mjerenih rezultata na objektu te omogućava kontinuiranu edukaciju i poticanje krajnjih korisnika na primjenu mjera energetske efikasnosti. Panel se sastoji od LCD televizora i računala na kojem radi aplikacija za prikazivanje potrošnje i savjeta energetske učinkovitosti. Aplikacija dobiva već pripremljene podatke od ISGE-a.

7. DALJNI RAZVOJ

Svakoj suvremenoj aplikaciji kao što je ISGE potreban je kontinuirani razvoj ne samo radi što bolje prilagodbe krajnjim korisnicima koji ju koriste već i radi stalnog napretka tehnologije i potrebe da ovakav jedan nacionalni sustav taj napredak i prati. Konačan cilj je potpuna automatizacija svih procesa vezanih uz prikupljanje ulaznih podataka čime bi se minimizirala mogućnost pogreške ručnog unosa. Takva automatizacija podrazumijeva automatsku sinkronizaciju ISGE-a sa sustavima naplate i očitanja brojila svih distributera energije i vode u Republici Hrvatskoj. Također, automatizacija podrazumijeva i daljinska očitanja svih mjerila čime bi podaci o potrošnji za sve javne objekte bili trenutni, odnosno, frekventniji.

Na tu trenutnu informiranost nadovezuju se i napredniji moduli za alarmiranje korisnika objekata, kao i predviđanja buduće potrošnje na temelju detaljnih analiza svih podataka koji su pristigli u sustav. Takovo predviđanje omogućilo bi i rezerviranje sredstava za pokrivanje troškova koji su u stalnom porastu. U tom dijeli analitike svakako bi pomogla i predikcija vremenske prognoze gdje bi sustav na temelju klimatoloških parametara mogao predvidjeti potrošnju nekoliko dana unaprijed.

Jedna od ideja je i sinkronizacija ISGE-a s geografskim informacijskim sustavom (GIS) radi poboljšanja vizualne preglednosti potrošnje s obzirom na geografsku rasprostranjenost objekata. Na taj bi se način, osim tablično, mogli i na dodatan grafički način prezentirati podaci prikupljeni i analizirani kroz ISGE.

8. ZAKLJUČAK

Sustavno gospodarenje energijom (SGE) temeljeno na promjeni ponašanja ljudi, izmjenama unutar postojećih organizacijskih struktura i primjeni tehničkih mjera poboljšanja energetske efikasnosti ključan je preduvjet razvoja svih vještina i znanja potrebnih za ostvarivanje postojećeg potencijala poboljšanja energetske efikasnosti i razvoja društva na održiv način. Potpun uspostavljen SGE u konačnici pretpostavlja da se maksimalno iskorištava potencijal poboljšanja energetske efikasnosti. Dosadašnja iskustva ukazuju da je ostvarivi potencijal smanjenja potrošnje energije do 30 posto ukupne neposredne potrošnje energije, no taj potencijal nije jednostavno ostvariti.

Uspostava SGE-a danas je nezamisliva bez korištenja modernih informatičkih sustava te SGE i ISGE čine nerazdvojnu cjelinu. Uvođenje SGE-a i ISGE-a u javnom sektoru otvara mogućnost i pruža donositeljima odluka potrebne alate i informacije nužne za kvalitetno provođenje aktivnosti smanjenja neposedne potrošnje energije. ISGE je pritom osnovni alat koji uvelike olakšava gospodarenje energijom jer krajnjim korisnicima, koji su najbliže mjestu neposredne potrošnje energije, omogućava jasan uvid u potrošnju energije, kao i u potencijale poboljšanja, a time znatno olakšava ostvarivanje ušteda. Bez ISGE-a koji omogućava uključivanje i komunikaciju s korisnicima koji se nalaze na mjestu neposredne potrošnje energije i vode vrlo je teško ostvariti sve postavljene ciljeve poboljšanja energetske efikanosti.

Uvođenje ISGE-a u konačnici je usmjereno ka značajnom poboljšanju trenutnih praksi gospodarenja energijom te definiranja, provođenja i potvrđivanja uspješnosti projekata poboljšanja energetske efikasnosti.

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NATIONAL ENERGY MANAGEMENT INFORMATION SYSTEM

Abstract: *Energy Management Information System (EMIS) is a web application for monitoring and analyzing energy and water consumption in public sector buildings. Thereby it represents an inevitable tool for Energy Management (EM). EMIS is used by most of the public buildings owned by Cities, Counties, Ministries and other Governmental agencies in the Republic of Croatia.*

Key words: energy efficiency, energy management, information system, energy consumption, water consumption, sustainable development, automatic meter readings

THE STUDY OF FAÇADE DESIGN IMPROVEMENT OF THE BUILDING USING DOUBLE SKIN FAÇADE SIMULATION

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Abstract: *Recently, various studies to realize the low energy consuming, eco-building have been proceeding globally. The first thing decision makers needs to do is energy efficiency improvement with building envelop for reduction of building energy consumption. A Double-Skin Facade (DSF) is one of the reformations of aforementioned problem in green building industries. DSF is comprised of two windows and the intermediate space between two windows, shading and ventilation damper. DSF which has variety merits is regarded as alternative to satisfy social need by the thermal or ventilation performance control in the intermediate space. For this study, real hospital building was selected in South Korea. The authors investigate the way to design improvement of existing double-skin façade system in hospital building. The authors suggest the improvement method by analyzing the performance, (1) Air-stream analysis velocity according to elevation shape, (2) an intermediate space environment simulation change in blind position, and (3) thermal characteristic with DSF opening shade. Fluent, Computational Fluid Dynamics (CFD) simulation, was used.*
The purpose of this study is to provide meaningful information to the decision maker about double-skin façade design and application of building energy simulation in real building.

Key words: double-skin façade design, Fluent simulation(CFD), envelopment of hospital

1. INTRODUCTION

Improving the energy efficiency of buildings with their facades is the primary way to reduce their energy consumption. Walls and windows that form the building facades must be excellent heat insulators. In particular, energy use caused by heat gain and loss through windows accounts for the largest proportion of the total energy used by commercial buildings (22% of heating energy and 32% of cooling energy) (DOE, 2009).
Through energy simulations on buildings, this study aims to diagnose energy consumption of double-skin facades on buildings and evaluate various energy-saving alternatives.
This paper is a study on finding ways to improve the existing design of the corridor-access type double-skin facade which are to be installed on the southwest-facing side of the hospital building located in City Seongnam of Gyeonggi Province, Korea. By carrying out three simulation processes, the study sought to examine the design, efficiency and comfortability which are regarded as problems in the existing designs.

2. OVERVIEW OF THE TARGET BUILDING

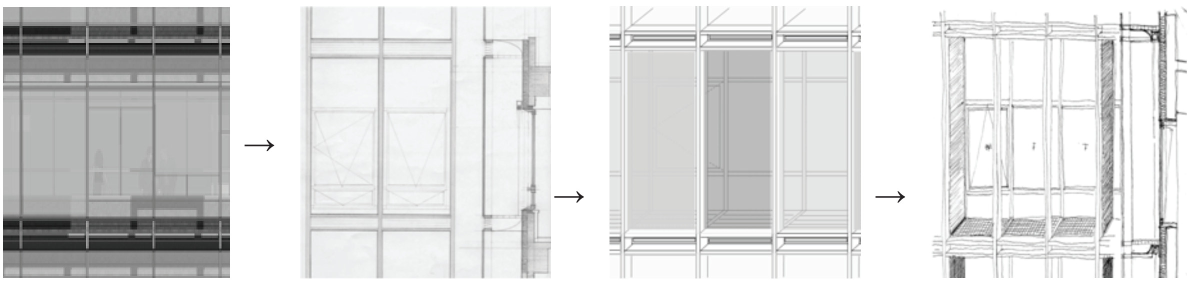
On the site with an area of 120,660m, the new block with 10 stories above ground and 3 below and 388 beds will be built. The block will have a total floor area of 53,075m^2. Its main visual directions will face east and west

Double-skin facade designs proposed in the early stage was based on a corridor-access type structure where the facades would be made separately for each story. In this structure, the air inlets and air outlets were designed to be installed at the top and bottom of each floor and the air inlets and air outlets were perpendicularly arranged in sequence.

3. WAYS TO IMPROVE DOUBLE SKIN FACADES THROUGH SIMULATION

Based on the previous double-skin facade designs, this study sought alternatives which can meet the efficiency needs while maintaining the existing design concepts. Figure 1 below shows the changes and improvements made in the initial plans, first, second and final revised versions of the plans, for each problem identified. This section will compare the specific considerations for each suggestion by using the Fluent simulation.

In the first simulation, the effect of solid shapes on the middle air layer was examined. In the second simulation, the environment of the middle air layer for different window shade positions was reviewed. Finally, the third simulation attempted to derive optimum designs by reviewing the middle air layer environment that change in accordance with the changes in the openings at the tops and bottoms of the double-skin facades.



(a)Initial plan (b) First revised version (c) Second revised version (d)Final Plan

Figure1. The change and improvement step

3.1 The simulation modeling and boundary condition

Functional units of corridor-access type double-skin facades are divided into floors. Each unit has a width of 6.6m, and height of each floor is 4m, and the width of each middle air layer is 700mm.
This was based on the Seoul's meteorological data published by the Korea Meteorological Agency. When evaluating the efficiency of the double-skin facades, it was assumed that wind will blow straight inside. The annual mean wind speed in Seoul is 2.4 m/s, and the city's mean wind speed is the highest in spring (2.8 m/s).
In the simulations, the outside and room temperatures were set for summer and winter. Since there was a cooling load almost all year in the existing buildings of the hospital, only air conditioners that cause a solar radiation load were used in the simulations(July). When the air conditioner was used, the outside temperature was set at 30° and the room temperature was set at 25°.
The low-E double-layer glass and tempered glass for the double-skin facades' windows and doors. The heat transmission coefficients were set at 1.74W/m^{2}K for the low-E double-layer glass and 5.8W/m^{2}K for the exterior tempered glass. The solar radiation was set based on solar radiations of days with high longitudes, latitudes and temperatures, by setting the Fluent's Radiation Model. The simulation time was set between 3pm and 4pm during which sunlight comes in from the west. The sunlight penetration and reflection ratios for different materials are stated in Table 1.

Table 1. Sunlight penetration and reflection ratios for different materials

	Visible ray (%)		Infrared rays (%)	
	Penetration ratio	Reflection ratio	Penetration ratio	Reflection ratio
Low-e glass	75	11	43	24
Tempered glass	88	8	79	7

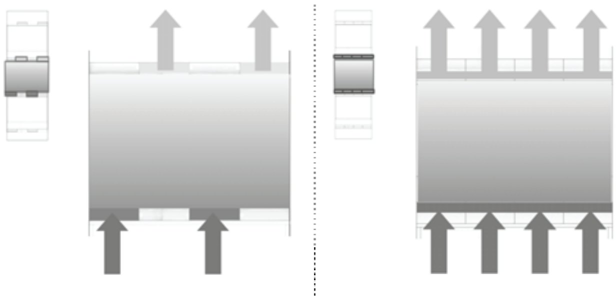
3.2 First simulation

The first simulation was conducted case by case by using three stories as models. The purpose of this was to identify the effects of the arrangement of the air inlets and outlets and the air current of through the opening on the double-skin facade of each story.

Table 2. Efficiency of the double-skin facades in accordance with the solid shapes

	Opening Height	Wind direction	Season	Wind speed (m/s)	window shade	Windows	
						Top	Bottom
Case 1	200 mm	Vertical	Summer (July)	2.24/2.4	Inner	On	On
Case 2							

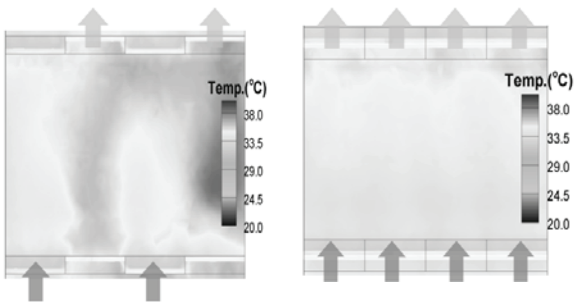
Figure2(a) shows the Case in which the inlets and the outlets have been cross-arranged, with the temperature ranging from 30 to 40°C. In this simulation, the temperature on the top right increases as the outdoor air flowing in through the inlet is discharged through the outlet at the top. This means that rises in the temperature affects the thermal environment of the indoors.



(a) Case 1 (b) Case 2

Figure 2. The air inlet and outlet for the first simulation

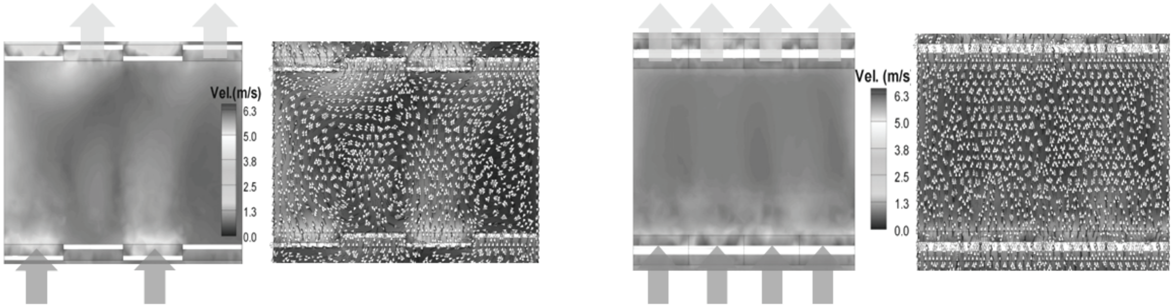
In Figure 2(b), air inlets are located throughout the bottom and air outlets are throughout the top, and the temperature ranges from 30 to 35°C. Unlike in Case 1, the outdoor air flowing in through the inlets covering the entire bottom side will flow out through the outlets at the top, causing no increases in the temperature.



(a) Case1 (b) Case2

Figure 3. Temperature distributions for the cases in the first simulation (2nd floor)

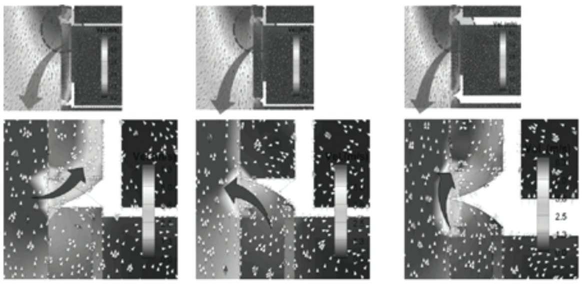
Figure 3 (a) there is a large temperature deviation between the right and left space. This deviation is about 6 °C.



(a) Case1 (b)Case2

Figure 4. Velocity distribution (Right: Vector distribution)

Figure 4 (a) shows the velocity distribution in Case 1. The air flow velocity in the middle layer ranges from 0.1 to 1.5 m/s, and the air is stagnant on the right part. (b) shows that the velocity distribution in Case 2 is even compared to Case 1 and ranges between 0.2 and 1.1 m/s.



(a) Case 1. inlet (left) / outlet (right) (b) Case 2

Figure 5. Velocity distribution in the cases in the first simulation

Figure 5 shows the velocity distribution of the air flowing in and out. Since the air inlets and outlets are cross-arranged, the air flow is hardly affected by the top and bottom in case1. In Case 2, the air discharged through the outlet re-enters through the inlet.

While Case 1 can offer an independent middle air layer environment, stagnation in some parts may increase the temperature inside. This will affect the outdoor environment. On the contrary, the sequential arrangement of the air inlets and outlets enables active air circulation in the middle air layer, decreasing the temperature inside this layer. Case 2 would be a more effective option than Case 1 for buildings with large cooling loads, such as hospitals.

3.3 The second simulation

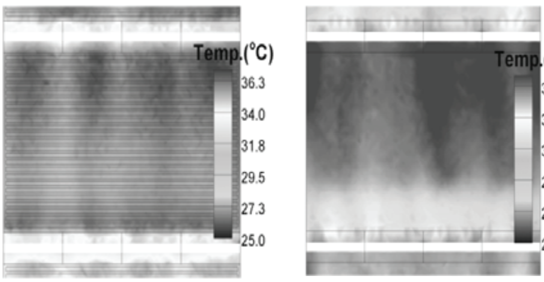
The solid shape of the double-skin facade was determined through the first simulation. Then, in the second simulation, the thermal environment of the facades' insides was examined for different positions of the window shade.

Table 3. Effectiveness of the double-skin facades depending on the window shade

	Opening Height	Wind direction	Season	Wind speed (m/s)	Window shade	Windows	
						Top	Bot-tom
Case 1	200 mm	Vertical	Sum-mer (July)	2.24	Inner	On	On
Case 2					Outer		

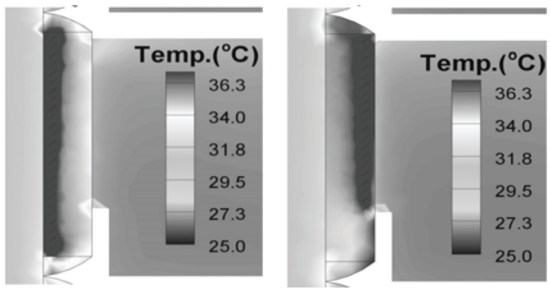
In Figure 6(a), the window shade in the double-skin facade was installed close to the outer window pane. The temperature range of the part where the air does not collide with the window shade is 33.8 to 34.3°C. It was assumed that the temperature increase inside the middle air layer was due to the outside temperature and the sunlight. In Figure 6(b), the window shade was installed close to the inner window pane, and the temperature in the air passage was 34.2~35.8°C. This temperature range was higher than in Case 1.

Figure 7(a) is a cross section of the area in Case 1. It was identified that the temperature around the window shade installed close to the outer window pane was at least 37°C, which was higher than the other parts of the middle-air layer. Yet, the area round the inner window pane showed a temperature 2 to 3°C lower than the other parts of the middle-air layer, having a smaller influence on the indoors environment. Figure 7(b) shows the cross-section of the area in Case 2. It was identified that the temperature around the window shade installed close to the inner window pane was above 37°C, which was 3 to 4°C higher than the other parts of the middle-air layer.



(a)Case1 (b) Case2

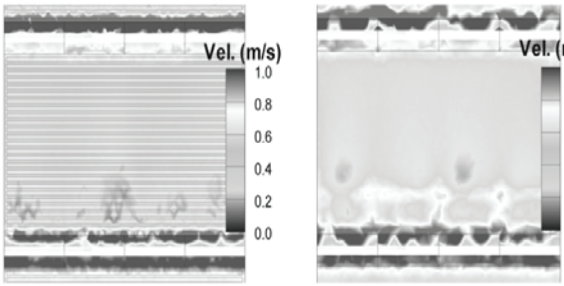
Figure 6. Front view of the temperature distribution



(a)Case1 (b) Case2

Figure 7. Temperature distribution for the cross section

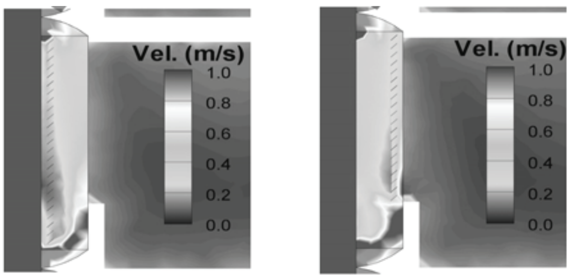
Case 1 clearly shows that the temperature around the inner window pane was lower than that around the window shade installed on the outer window. In Case 2, this resulted in an increase in the temperature and a higher overall temperature distribution. Such change is resulted from the heat generated from the reaction between the sunlight with the window shade, affecting the heating environment of the surroundings.



(a)Case1 (b)Case2

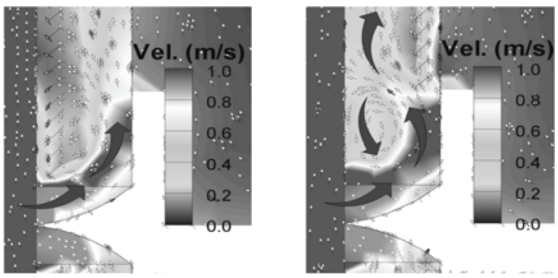
Figure 8. Front view of the velocities in the second simulation (2nd floor)

Figure 8(a) shows that in Case 1 the velocity distribution outdoor air flowing in through the air inlets at the bottom. This air was discharged at velocities of 0.2 to 0.6 m/s through the outlets at the top. This air was discharged without colliding with the window shades. Figure 8(b) shows the front view of the air flow velocity distribution for Case 2. As the air flowing in through the air inlet collided, its velocity rapidly decreased from 0.8 m/s to 0.2 m/s.
Figure 9(a) shows the cross-section of the space in Case 1, where you can see the outdoor air flowing in through the air inlet and then being discharged after rising in a natural manner. By contrast, in Figure 9(b), which shows the cross-section of the space in Case 2, the air which flowed in through the air inlet collided with the bottom of the window shade, causing a rapid change in the air flow.
Through the second simulation, ways for effective location of the window shades have been examined. The window shades should be installed on the outer window pane like in Case 1. This will prevent hindrance to the movement of the outdoor air which has flowed inside, will keep the indoor temperature low, and will prevent the window shades from shaking and causing noise.



(a)Case 1 (b)Case2

Figure 9. Air flow in the second simulation (2nd floor)



(a)Case 1 (b)Case2

Figure 10. Enlarged version of the air flow diagram in Figure 11(2nd floor)

3.4 The third simulation

In the third simulation, the effectiveness of the double-skin facades for different heights of the inlets and outlets located at the tops and bottoms of the double-skin facades. The ranges of these heights were set at 50 to 450mm, with an increment of 50mm.

Table 4. Effectiveness of the double-skin facades for different opening sizes

	Opening Height	Wind direction	Sea-son	Wind speed (m/s)	Window shade	Windows	
						Top	Bottom
Case 1	50mm	Vertical	Sum-mer (July)	2.24	Outer	On	On
Case 2	100mm						
Case 3	150mm						
Case 4	200mm						
Case 5	250mm						
Case 6	300mm						
Case 7	350mm						
Case 8	400mm						
Case 9	450mm						

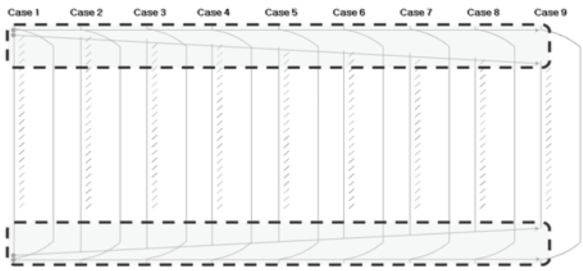


Figure 11. Changes in the opening sizes shown in the third simulation

Figure 12. shows the temperature and velocity of the air when the opening has a height of 50mm. The range of the inside temperature was 34.3~36°C. While the air current velocity ranged from 0.6 to 0.8 m/s in the lower air layer, this decreased to 0.1~0.2 m/s in the upper layer.
Figure 13. shows the result for the opening with a height of 100mm. The temperature range of the middle air layer was 33.7~35°C, and the air current velocity ranged between 0.1 and 1.0 m/s. While this velocity range ware higher than that when the opening's height ware 50mm.

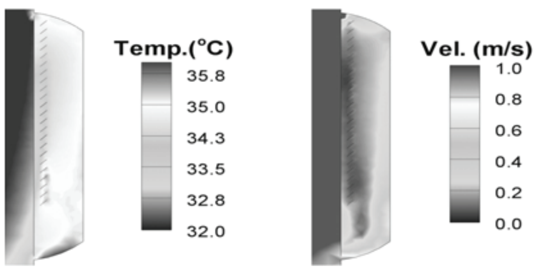


Figure12. Case 1 of Simulation 3
(Opening height: 50mm)

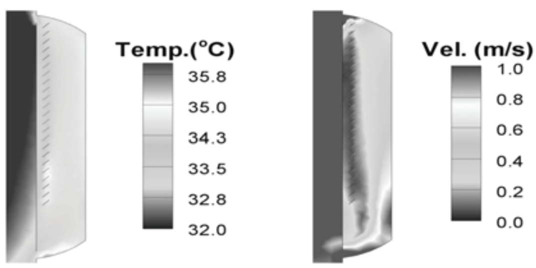


Figure 13. Case 2 of Simulation 3
(Opening height: 100mm)

Figure 14 shows the result for the opening with a height of 150mm. The temperature range of the middle air layer was 33.5~34.5°C, which are lower than the two preceding cases, and the air current velocity increased from 0.1 m/s to 1.0 m/s. However, there was a difference of 0.6 m/s between the air current velocity of the upper part and that of the lower part. Hence, the decline of the air current from the upper part may lead to temperature increases.

Figure 15 shows the result for the opening with a height of 200mm. The temperature range of the middle air layer ranged from 32.8 to 33.7°C, and the air current velocity was about 1.0 m/s.

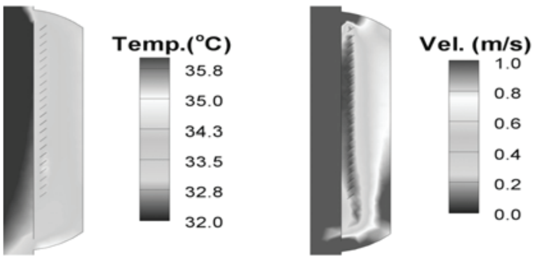


Figure14 Case 3 of Simulation 3

(Opening height: 150mm)

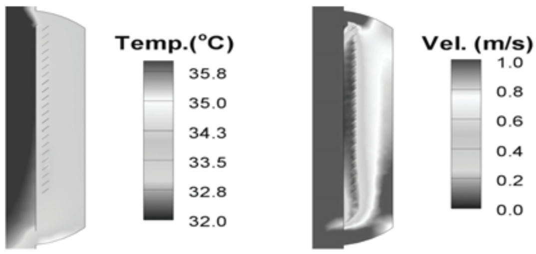


Figure 15 Case 4 of Simulation 3

(Opening height: 200mm)

From the opening heights of 250mm upwards, virtually no difference was found between the air velocities around the inlet and the outlet. Hence, the result values have not been stated in detail.

Figure 16 shows a comparison between all the cases. In Cases 1 to 3, decreases in the air flow velocity cause the temperature to rise. This leads to an increase in the cooling load. In Case 5 to 9, the temperatures were relatively low considering that the middle air layer is affected by the sunlight. However, the high air flow velocity caused the window shades to shake and produce noise, creating displeasure on patients living inside the block. Thus, it has been concluded that the heights of 200mm of the openings (Case 4) is the optimum.

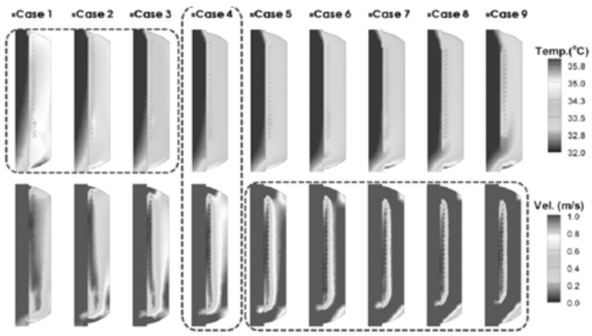


Figure 16. Comparison and analysis of the cases in the third simulation

4. CONCLUSION

This study explained ways to improve the design of the double-skin facade which have been applied in hospital buildings. The result of the simulation, which involved effective solid shape plans and set positions of window shades in the middle air layer and appropriate sizes of the openings are as follows.

Effects of double-skin facade systems vary depending of the solid shape. The double-skin facade system used on the Seoul National University Bundang Hospital buildings has a structure under which no windows can be opened or closed, causing no effect on the middle air layer inside these buildings. Hence, if you only consider the effect of the interior heating environment on the overall indoor environment, Case 2 will have a better influence on the indoor environment than Case 1 which has a much more unbalanced temperature distribution than Case 1. Case 2 seems to be more effective in summer when the overall air flow is active and Case 1 may be a more suitable option in winter as it can lead to temperature increases. However, the temperature around the air inlets and outlets during winter may cause discomfort to patients who will live inside the block. Hence, it has been concluded that Case 2 is the most suitable for Seoul National University Bundang Hospital.

After analyzing the simulations of cases with different window shade positions, it was discovered that installing window shades on the outer window pane showed less temperature stratification in the middle air layer than when the window shades were installed on the inner window pane, also reducing any negative effects on the adjacent rooms. Case 1, this will prevent hindrance to the movement of the outdoor air which has flowed inside, will keep the indoor temperature low, and will prevent the window shades from shaking and causing noise. The simulation results based on the installation location window shades are installed inside the case than those installed on the outside, the temperature stratification within the junggongcheung decreased the influence of adjacent rooms was reduced. When installing the indoor side window shades the diffuser coming from the bottom of the upper layer of air emissions at the bottom of the window shade in the process of clinflict and loss of the flow rate and the turbulence occurs. The window shade part of this phenomenon and the fluctuation of the temperature rise and noise resulting in patients living in the indoor environment is not pleasant. Thus, as shown in Case 1, the outdoor window shades installed at the location of the migratory path of the supply air no longer fails to install the interior sides of the window shades at the same time, lowering the temperature fluctuation can be suppresse and the noise is expected.

Through the simulation in which the effectiveness of the double-skin facades for different air inlet and outlet sizes, the most ideal temperature and air flow distributions were created and the air flow stagnation zone was the smallest when the current planned sizes of 200mm was applied. In Cases 1 to 3, decreases in the air flow velocity cause the temperature to rise. This leads to an increase in the cooling load. In Cases 5 to 9, the temperatures were relatively low considering that the middle air layer is affected by the sunlight. However, the high air flow velocity caused the window shades to shake and produce noise, creating displeasure on patients living inside the block. Thus, it has been concluded that the heights of 200mm of the openings (Case 4) is the optimum.

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In general, double-skin facade not only saves cooling energy by blocking sunlight, but also maximizes the natural ventilation effect during winter. In particular, as the building in this study will be used as a hospital, applying double-skin facades is very significant for the building. Since top-quality double-skin facades were developed entirely through decisions of Korean architects and technicians on all areas from the construction and engineering designs, the results of this study shall have a significant impact.

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STUDIJA UNAPRJEĐENJA DIZAJNA FASADE ZGRADE UPORABOM SIMULACIJA DVOSTRUKE FASADE

Sažetak: *U zadnje su vrijeme diljem svijeta provedene različite studije s ciljem postizanja niske potrošnje energije u zgradama. Prva stvar koju donositelji odluka moraju učiniti kako bi se smanjila potrošnje energije jest poboljšanje energetske učinkovitosti vanjske ovojnice zgrade. Dvostruka fasada predstavlja jedno od rješenja spomenuta problema u industriji zelenih zgrada. Dvostruka se fasada sastoji od dvaju prozora i središnjega prostora između njih, sjenila i ventilacijskih zaklopki. Dvostruka fasada, koja ima razne prednosti, smatra se alternativom koja zadovoljava društvene potrebe glede kontrole učinkovitosti uporabe topline ili ventilacije u središnjem prostoru. Za ovu je studiju odabrana zgrada bolnice u Južnoj Koreji. Autori istražuju način dizajniranja poboljšanja postojećega sustava dvostruke fasade u zgradi bolnice. Autori predlažu metodu poboljšanja analizirajući: (1) promjenu brzine strujanja zraka s visinom, (2) simulacije promjene okoliša u središnjem prostoru sa zatvorenim sjenilima, i (3) toplinska svojstva dvostruke fasade s otvorenim sjenilima. Korišten je softver Fluent, odnosno simulacije temeljene na računalnoj dinamici fluida (CFD). Cilj ovoga rada jest dati smislene informacije donositelju odluka o dizajnu dvostruke fasade i primjeni simulacija potrošnje energije u stvarnoj zgradi.*

Ključne riječi: dvostruka fasada, Fluent simulacija(CFD), izolacijska ovojnica bolnice

APPLICATION OF WOOD AS AN ECOLOGIC MATERIAL IN CONTEMPORARY ARCHITECTURE AND ITS IMPACT ON THE ENVIRONMENT

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Abstract: *The world trend of re-use of wood and wood products like materials for construction and covering of architectural structures is present not only because of the need to meet the aesthetic, artistic and formal requirements or to seek inspiration in the return to tradition and nature, but also because of its ecological, economic and energetic feasibility. Furthermore, the use of wood fits into contemporary trends of sustainable development and application of modern technical and technological solutions in the production of materials, in order to maintain a connection to nature, environment and tradition. Wood is a natural - environmentally friendly material. Wood is subject to recycling and with the addition of certain chemical compounds is obtained by various wood-based products used in modern architectural buildings. The application of wood in contemporary architecture, like old - new material, affected the occurrence of the elements of national creativity as an attempt of a change which has the aesthetic, constructive and stimulating effect on the overall perception and understanding of architecture.*
It is possible to achieve an original work of authorship by building in spirit of regionalism with the use of indigenous materials, building technology and traditional methods of designing for a specific situation - on the spot. The tendency to preserve the regional characteristics of architecture is an important, almost strategically important element of national expression from the viewpoint of the correct and rational use of land, preservation of the identity and particularity, the formation of high-quality environment in the natural or already built scenery, energy saving and conservation of natural resources and improvement of life conditions.

Key words: wood, wood-based products, composite materials, modern facade coatings, integration and impact of the architectural object on the environment.

1. INTRODUCTION

1.1. A tree - a symbolic meaning

The term "wood" has an exceptionally great symbolism and a "cult of the tree" is present in the tradition of many nations in the world, from ancient times until today. Wood is a symbol of the universal substance - materia prima, and the life of a tree symbolizes a life cycle from inception, through growth and development to death. A tree symbolizes life in general.

1.2. Wood as a renewable material

Renewable materials are those materials which will in due course once again be available and are all of completely natural origin or are bred in a controlled way. Wood and other agricultural crops belong to the group of the so-called renewable materials, unlike non-renewable materials such as: petrochemical products (plastics), minerals and metals derived from ore. From the point of view of ecology there is an increasing interest in the use of renewable materials in construction and materials that can be recycled, re-processed, and thus get a new product. Wood represents the best known renewable building material. In terms of appearance wood is cheap, because the growth of wood is necessary of the sun, soil, and water.

2. APPLICATION OF WOOD IN THE ARCHITECTURAL HISTORY OF SERBIA

Traditional, folk, architecture depended on the terrain, environment, natural resources, climate, as well as habits of people, religious beliefs and customs. The architecture of that era used the local materials in a way that is suitable for bioclimatic conditions of the area. The main materials that have been applied in folk architecture as wood, stone and soil in various ways of processing.

Stone in the traditional folk architecture was used for the building of foundation walls, retaining walls, fences and cellar walls. By the way of processing the most commonly used was roughly cut or semi-cut stone easy to handle. The stone was in some cases used as in-filling in the wall post and pan construction. Thin stone slabs were used as roofing material in some cases.

The use of wood is as old as the material culture of mankind, and hence the claim of its application in the first shelters built by the man and the oldest architectural structures. Wood has always been used as the most common building material. People have used wood for making shelters and refuges, which were emerging and disappearing, and construction techniques and use of wood have been perfected giving better and more ideal elements and forms.

Civil engineering used to apply wood to a large extent, evidence on that are still present buildings in which the entire structure was carried out in wood (wooden poles and wooden beams), and in - filling is wooden or of other materials (adobe, brick, mud). There are also facilities that are entirely made of wood - chalets. Such buildings are still kept in the less developed regions of Serbia. The wood was used for all the constructive - primary elements of the house (pillars, post and pan wall construction, mezzanine and construction of the roof structure) and secondary structure (doors, windows and trim elements: floor, wall, ceiling, roof). Wood was visible or hidden - covered. The texture of wood and colours were natural. The development of material and spiritual culture led to a replacement of wood with other materials.

Clay, compared to stone and wood, late began to be used in the construction of houses, first as the rammed earth construction and the lining, and later as cod - adobe, and finally as burnt bricks and various types of S-tile and tile.

All the factors that influenced the course, development and architecture design can be divided into: the natural and social factors.

Nature acts in two ways:

- direct influence on the choice of building materials located in the immediate environment,

- climatic conditions affecting the formation of certain areas and construction forms of architectural structures.

The study of folk architecture in addition to the analysis of form, structure, and materials used in the architectural building involves far more complex cultural study of the traditional relationship to nature - environment, in relation to customary and religious beliefs.

3. ATTITUDE TOWARDS WOOD IN CONTEMPORARY ARCHITECTURE

The application of wood is present in modern architecture. Wood as a material is used in the architecture that relies on tradition as well as the architecture that follows current trends. Factors affecting the use of timber in the architectural building are: the role of elements within a set as well as its location, type of wood, the possibility of final processing of the elements, the possibility of the realization of the designer‘s ideas related to an element designed and constructed in wood, and the possibility of combining wood with other materials [1].

Based on research on wood and its applications in the architectural object we can say that an element made of wood can have a constructive or decorative role or it can be used as coverings in the exterior or interior, but it can, and it is not unusual, include a number of functions, or even all.

Attitude towards wood in architecture can be:

- technicistic,
- organic.

Technicism has an objective to find formally new visual manifestation of architecture and a town. Basic characteristics of technicism in modern architecture represent abandoning the principles of spatial unity, elementary symbolism that linked one building to the ground as well as dynamic balance achieved by applying strict rules of technology.

Observing architecture throughout entire history two different tendencies may be determined. One is focused on a rational and geometrical approach, the other on irrational and organic [2]. These two fundamental principles have existed since the earliest period of human culture, in all the civilizations and cultures. The difference between geometric and organic maintained present until today, in modern architecture, and an individual, the architect, the designer is to decide which concept to apply. The viewpoint of organic architecture is that architecture should, in its appearance, have characteristics similar to those of a natural organism and gives the impression of being united with nature and with its environment. The development of organic architecture was based on the constructive means and new visual perception, although it is primarily aimed to determine the atmosphere of space with a pure functionalism. The application of natural wood without previous protection as the facade siding represents an organic approach to architecture. Wood without final treatment, used as the outer siding, gradually changes its appearance and begins to age in its own, dignified, way, which represents an organic approach to architecture. This process of aging has become a trademark of wood and it first begins to go grey due to the effects of ultraviolet radiation and time, with the development of fine cracks and the gradual development of roughness on the surface of wood.

Changes in colour, patina, which occur as a consequence of aging, ranges from light silver-grey to brown-black. Changes in raw wood resulting from the decay under the influence of environmental factors, have never been uniform. They are dependent on climatic conditions,

orientation, protection by roof overhang , eaves, obstructions of the treetop shadows and foliage and they may vary and be present even on only one facade.
Old artisans, on the basis of experience and knowledge of traditional craftsmanship, knew that it was the best to use: larch, conifers, red cedar and acacia, for outdoor use of wood without finishing.

4. IMPACT OF TRADITIONAL ARCHITECTURE ON CONTEMPORARY ARCHITECTURAL WORKS

Influences and interpretations of elements of traditional architecture in the contemporary architectural works in Serbia can be grouped into several categories. Various possibilities of interpretation of the motives used in contemporary architecture are developing based on the experiences of traditional folk architecture. These impacts can be classified into two main categories:

- creative procedure,
- creative analytical procedure [3].

Creative influence of tradition on contemporary architectural work is reflected in the direct visual recognition of the creative approach, which can be characterized as: formalism, imitation, citation, stylization.

Analytical creative process relies on the subjective experience of the interpretation of tradition by accepting the past as a criterion. This procedure excludes the past as a cult which should be cherished. The past experiences transformation in the modern architectural work. The methods applied in this procedure can be characterized as a partial influence of tradition and transposition (Figure 1. a). The transposition in architecture, in the most abstract form, becomes the best artistic result that takes the past as a criterion, shows a sense of belonging and attachment, as well as the ability to re-interpret the sensibility of traditional local architecture in spirit of modern sensibility in new architectural work [4].
As a reflection of the formalism in architectural structures in Serbia today, we can see the simplicity of form - great hipped roofs with emphasized eaves and elements of the wooden structure, flat facades with wood elements as decoration. The examples of family houses built in spirit of traditional architecture by application of forms and proportions of old buildings, as well as traditional materials have an impact on the creation of new environments associated with the tradition and the preservation of existing environmental units in which the spirit of tradition is intertwined with the modern spirit.

The connection to the traditional architecture is sometimes expressed by a quotation in the architecture, by introducing only a detail or element which represents a connection with the architecture of the past. The application of the symbols of folk architecture - porch, emphasized wooden roof structure, wooden shingle as a roof covering, post and petrail construction on the facade, or wood as a facade lining in the contemporary architectural structures -represents the partial impact of tradition on contemporary architecture.

By using stone, wood, brick and S-tile as roofing i.e. original materials typical for the architecture of Serbia as a region, it is possible to emulate a certain style simplifying the form and shape. There are examples of successful stylization in a large number of vacation homes and public buildings built as original work by excellent architects in Šumadija and the Morava

River basin. Porches, hipped roofs, deep eaves, wood as an element of the facade cladding, stone as an element of connection with the ground, are recognizable elements of structures built by emulating a certain style or architectural work, created from the designer's desire to preserve the original values of folk architecture (Figure 1. b).

Today in modern architectural structures wood and wood products are used in combination with other materials: stone, brick, concrete, steel, glass and other modern materials. The combination of these materials, not only in the function of a primary supporting structure, is also reflected in the combination of these materials as an element of siding in exterior and interior.

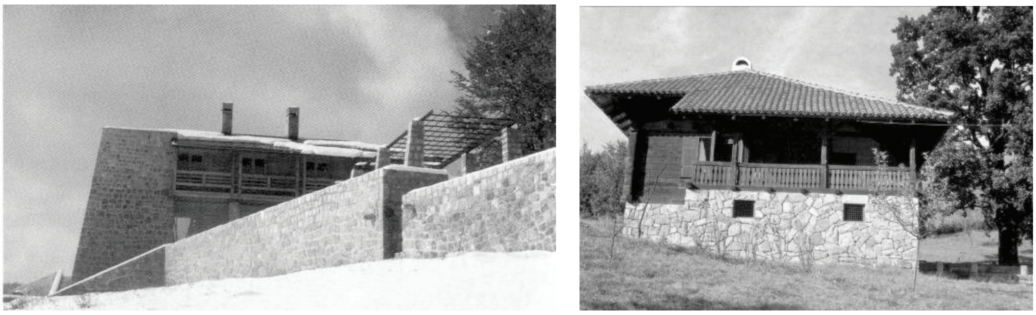

Figure 1. An example of partial impact of the tradition and transposition to the modern architectural work: a) House Pejovic, Povlen, architect B. Pesic, 2004. , b) Holiday home Petrovic, the village Dići, Ljig, architect B. Petrovic

The combination of wood and stone is a combination of two materials that was often present in past, as well as today, in the buildings made in spirit of traditionalism. In stone buildings in the past stone dominated the basement part of the house and maybe ground floor, while wood was applied to build the walls and roof. Today, wood and wood-based products, applied as a facade covering of contemporary architectural structures, represent a good quality, visually appealing and modern selection of materials in regard to the pedestal of the house lined with stone.

5. APPLICATION OF WOOD AND WOOD PRODUCTS IN MODERN ARCHITECTURE IN SERBIA

There is a tendency for the affirmation and realization of the continuity of the national heritage in one part of Serbian contemporary architecture. This is reflected in the protection of architectural heritage, the study of folk architecture and the tendency to transfer the principles and spirit of traditional architecture into the contemporary architectural works. The application of wood in contemporary architecture, like old - new material, affected the occurrence of the elements of national creativity as an attempt of a change which has the aesthetic, constructive and stimulating effect on the overall perception and understanding of architecture. It is possible to achieve an original work of authorship by building in spirit of regionalism with the use of indigenous materials, building technology and traditional methods of designing for a specific situation - on the spot. Our architectural tradition, whenever possible, should serve as inspiration to come up with modern construction methods and to design houses that would best fit in the environment.

5.1. Possibilities and limits of use of wood in our contemporary architecture

Wood can be applied only in certain parts of the architectural structure, using appropriate measures of protection and completion of the building in its entirety. The advantage of wood as a material is its lightness and the possibility of construction without the use of complex machinery. Wood products have a big advantage over wood in a modern building. Their exceptional properties can compensate for all the flaws of wood as a material.

Conifers are softwood and are used as building material for interior and exterior cladding. With soft wood work is easy, it is available in large quantities and is suitable for various building purposes. Types of softwood that can be used as a facade cladding are: juniper, larch, pine. Softwood in the form of veneer, wood wool, sawdust, wood chips and fibers, with the addition of glue or other adhesives is most commonly used for production of new composite products. Laminated constructions and wooden roof structures are made of softwood.

Deciduous trees are hard wood whose largest number of species (oak, hornbeam, etc.) is more lasting compared to the coniferous, soft wood. Raw hard wood has more universal application than raw softwood. The texture and colour of hard wood, visible on the surface, are aesthetically more valuable than the texture and color of soft wood, so the hard wood is more often used in visible places; in the interiors and for covering the furniture.

Hardwood, as well as softwood, is widely used in civil engineering for windows, door frames and facade cladding with boards in different ways, with and without overlap (on touch). This coating can be placed in different ways, depending on the desired effect, as follows: horizontally, vertically or diagonally.

5.2. Use of products of thermo-wood in modern architecture in Serbia

Ash and hornbeam are exposed to the procedure of thermal treatment in Serbia. The term thermo-wood refers to wood that is thermally treated at temperatures in the range of 160 to 260 °C. During the thermal treatment the most important thing is to achieve increased dimensional stability and resistance which significantly increases the durability of the wood. Under the influence of temperature the thermal insulating properties improve, but it is necessary to point out that the hardness of certain types of wood may be reduced by this process. Under the influence of high temperature warping, swelling and pulling in of the wood reduces by 50%, which allows the use of thermally treated wood in conditions of high humidity and direct exposure to atmospherilia, which is typical for our climate areas. Depending on the level of temperature to which the wood was exposed during the process its colour changes and can vary from light beige to dark brown. Treated in this way, domestic species of wood are similar in colour to tropical species. In addition to all the reasons above, the thermal treatment of wood is of particular importance for our country, rich in wood species whose quality is improved by thermal treatment. Thermally treated wood is a completely ecological product which does not contain substances that may be harmful to the environment. The use of this new technology enabled the use of thermally treated wood not only for the interiors but also for external use, as facade cladding (Figure 3.). Thermo-wood is used for the outer coating of porch floors, yards and pool decks.

5.3. Application of wood and wood products as facade coverings in contemporary architecture in Serbia

In contemporary Serbian architecture wood is hardly used as material for the outer coating. Mountain winter tourist centers: Kopaonik, Zlatibor , where wood is present as facade cladding, are exceptions. Combination of wood and stone can be found in the mountain buildings. Ground floor walls are covered with stone and facade walls on the first floor and big inclined planes of the roof are covered with wood cladding. Deep eaves lined with wood are typical architectural features in these mountainous regions (Figure 2.a). Wood applied for the cladding and as a roofing on the buildings represents an organic approach to architecture of Serbia (Figure 2.b).


Figure 2. Wood in combination with a full wall carcass as a facade cladding and roofing: a) Hotel „Klub A", Kopaonik mountain, Serbia, b) Mountain House "Rtanj", architect M. Djordjevic, Kopaonik mountain, Serbia

In Belgrade, the capitals of Serbia, there are few examples of setting a wood as façade cladding. Wood as facade cladding is exposed to all external negative influences in our weather conditions, which cause its natural aging. The application of modern technical and technological solutions in the design and implementation of individual architectural solutions are the result of following modern influences of the international architecture, with the aspiration for ecological design and the use of modern materials; integration into current trends in sustainable development and links with nature and tradition [5].

The application of wood as a façade cladding in the architecture of Serbia, excluding the mountainous area, it is very rare. The reason for this state is a peculiarity of our climate and the deterioration of wood trim under the influence of atmospherilia and solar radiation. Lonely are the examples of setting wood on the facades because of the need for permanent protection. A unique architectural work was obtained by combining wood with a painted wall surfaces and the parts of the facade covered with other composite materials (Figure 3.a).

Figure 3. The facade was performed in combination of wood, composite materials and painted wall surfaces: a) Multi-family residential building "Condominium 41-7, Velisava Vulovica Street, Dedinje, Belgrade, Serbia, architect M. Music, 2008., b) Residential building, Bulevar oslobodjenja Street, Belgrade, Serbia, 2011.

Modern technological solutions provide the possibility of installing thermally treated wood in places where the wooden cover is exposed to the influences of the environment. That significantly improves the properties of wood cladding and extends its life. Original appearance of wood, of course, changes gradually. However, the thermal treatment of wood delays its aging and its physical deterioration. In this way, by using this kind of products, we can keep all the aesthetic characteristics of natural wood that make it unique and unrepeatable. This modern solution affects the aesthetic experience of architectural structure [6].

Figure 4. The combination of wood and brick as a facade lining or facade of artificial stone: a) detail of the building, Milovana Marinkovića Street, Belgrade, Serbia, b) Residential building, Kumanovska Street, Belgrade, Serbia, 2000. architect B. Mitrovic

Façade cladding with composite material in form of plates is present on not very numerous facilities in Serbia. There are composites of high quality applied as facade coating with a face of the plate made of natural veneer, i.e. with a layer of real wood and with suitable protection. These products have excellent aesthetic properties and uniqueness of real wood (Figure 5.).

Figure 5. Composite material as a facade cladding in combination with glass and metal on the façade: a) Building in Jagićeva Street, Belgrade, Serbia, b) House on two corners, Mihaila Avramovica Street, Dedinje, Belgrade, Serbia, architects M. Bratusa, L. Bratusa, 2006.

7. CONCLUSION

Today, in a contemporary architectural work is necessary to aspire to establish the right balance between tradition and innovation, as well as between skill and industrial production. Natural wood as facade cladding in modern architectural buildings of Serbia, has very little use. Our climate - cold and long winters, with rain and strong wind, fervent summers, with large fluctuations in temperature, high humidity and great exposure of the material to the solar radiation, have an adverse effect on wood and therefore require constant maintenance and occasional replacement of facade coverings made of natural wood. Modern methods of coating with composites have found their modest application in modern architectural structures in Serbia and so, to some extent, allow the replacement of natural wood as a façade cladding.

In Europe and in the world, in addition to generally present aspiration for universal integration and globalization, in the arts, including architecture, regional cultural trends are being developed as a reaction to general tendencies. Considering the fact that the global trends in architecture are: diversity, variety, particularity and the pursuit of individual, in response to these aspirations in architecture in this region, there is interest in regionalism and the inspiration is sought in the folk architecture, using traditional natural materials, as integration of the architectural object in the environment.

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PRIMJENA DRVETA KAO EKOLOŠKOG MATERIJALA U SUVREMENIM ARHITEKTONSKIM DJELIMA I NJEGOV UTJECAJ NA OKOLIŠ

Sažetak: *Svjetski trend ponovne primjene drveta i proizvoda od drveta kao materijala za gradnju i oblaganje arhitektonskih objekata nije isključivo iz razloga zadovoljenja estetskih, likovnih i oblikovnih zahteva i traženja inspiracije u povratku tradiciji i prirodi, već i u njegovoj ekološkoj, ekonomskoj i energetskoj opravdanosti i uklapanju u savremene trendove održivog razvoja i primene savremenih tehničkih i tehnoloških rešenja pri proizvodnji materijala, a sve u cilju održanja veze sa prirodom, okruženjem i tradicijom. Drvo je prirodan – ekološki materijal. Drvo je podložno reciklaži i uz dodatak određenih hemijskih jedinjenja dobijaju se razni proizvodi na bazi drveta koji se koriste u savremenim arhitektonskim objektima. Primjena drveta u savremenoj arhitekturi, kao starog – novog materijala, delovala je na pojavu elemenata narodnog stvaralaštva kao pokušaj promene koji estetski, konstruktivno i podsticajno deluje na sveukupno shvatanje i poimanje arhitekture.*
Graditi u duhu regionalizma uz primenu autohtonih materijala, tradicionalne tehnologije građenja i metodom projektovanja za konkretnu situaciju - na licu mjesta, moguće je postići originalno autorsko delo. Težnja za očuvanjem regionalnih karakteristika arhitekture je bitan, gotovo strateški važan elemenat nacionalnog izraza sa stanovišta: pravilnog i racionalnog korišćenja zemljišta, čuvanja identiteta i posebnosti, formiranja kvalitetnih okruženja u okviru prirodnih ili već izgrađenih ambijenata, uštede energije i očuvanja prirodnih resursa i unapređenja uslova života.

Ključne riječi: drvo, proizvodi na bazi drveta, kompozitni materijali, savremene fasadne obloge, uklapanje i uticaj arhitektonskog objekta na okoliš.

AN ANALYSIS OF ENERGY CONSUMPTION MONITORING FOR ZERO ENERGY BUILDING IN SITE

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Abstract: *Increased energy prices and trying to decrease environmental loads have created many efforts to reduce the amount of energy consumed in buildings, and currently many nations are actively conducting research on passive houses, low-energy buildings and zero-energy buildings. On the other hand, the 2012 Expo will be held in Yeosu, South Korea from May to August 2012, so this study will monitor energy consumption, which is going to be used for the period, targeting the Korea Exhibition, built with the concept of low and renewable energy.*
The building is located on the south coast of South Korea that usually shows high temperatures and humidity over seasonal changes and summer during the exhibition. The heat transmission coefficient of the outer walls and windows is designed as 0.15W/m^{2}K and 1.8W/m^{2}K respectively to minimize energy consumption and a geothermal heat pump is introduced as a key heat source to improve the energy efficiency of air conditioning. In addition, the power generation facilities are using renewable energy, including two 50kW hydrogen fuel cells, a 200kW photovoltaic array and a 6kW wind power generator, in order to enhance the self-reliance level of the building site. A simulation-based calculation using DOE-2 will be conducted in order to estimate the energy consumption during the exhibition and although the energy consumption could be seen as different according to usage case, it is shown as 485 to 547MWh/year and the energy production as 501 to 548MWh/year, thus zero energy consumption in the building site is expected to be carried out during the operation phase.

Key words: Zero Energy Building, Fuel Cell, Photo Voltaic, Energy Monitoring, Simulation

1. INTRODUCTION

It was not until after the two oil shocks in the 1970s that energy efficiency began to be emphasized in the field of architecture. While, in the past, it was only a part of traditional concept of architecture, gradually, it has become a major factor that changes the actual paradigm in architectural design. In addition, with increasing demands for energy efficiency, research on zero-energy buildings is recently accelerating. Along with this trend, houses have already appeared of which the yearly use of energy is zero, but office buildings or commercial buildings are diverse in form and have high energy consumption, and thus it seems that different approaches are required from that of houses. 'The concept of zero energy' differs from country to country, or institution to institution due to different points of view, and a general agreement yet to be reached. Japan's research committee on realization and development of 'ZEB (net Zero Energy Building) defined zero energy building as "a building for which the annual primary energy consumption becomes net zero after aggregating the amount of energy used and of renewable energy within the building", while IEA defines such as "a building that does not use fossil fuels and utilizes the concept of renewable energy such as sunlight, solar heat, and biofuels to emit no carbon dioxide. The U.S.A.'s ASHRAE, on the other hand, defines such as "a building whose yearly energy use is lower than the amount of renewable energy produced within the site." As such, there is a little difference in word usage, but whatever definitions they have, they all share the basic idea of reducing the building consumption energy to zero and of making the outside supply of energy unnecessary, as is shown in Figure 1.

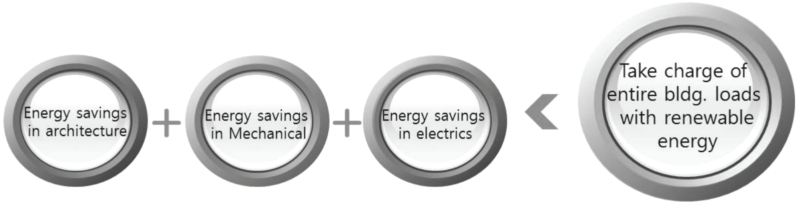

Figure 1. Concept of Zero Energy Buildings; ZEB(Zero Energy Buildings) uses passive and active method including architecture side and MEP. And it makes electric power using photo voltaic, wind power etc. The energy amount of renewable should be exceed building consumption to realize ZEB

2. STUDY OVERVIEW

The purpose of this paper is to introduce an exhibition building that uses sunlight and fuel cells, to predict and verify the annual energy generation within the site and the energy consumption of the building through simulations.

Table 1. Overview of the Korea Pavilion;
The site location, floor area, use are included in this table

Items	Details	Items	Schematic design	Working design
Site location	Yeousu, South Korea	Building area	3,395 m^2	3,399 m^2
Use	Convention facilities	Gross floor area	5,242 m^2	5,248 m^2
Site area	9,254 m^2	Building coverage	36.7%	36.8%
Scale	3 levels on ground	Floor area ratio	56.7%	56.8%

The International EXPO is being held in Yeosu city located on the southern coast of Korea through May to August, 2012, and the Korean Pavilion was designed as a zero-energy building model by the recent building related issues and the social needs. Large fuel cells and sunlight panels were installed on the exhibition building. Table 1 and Table 2 show the details of the facility, and Figure 2 show the site and floor plan respectively.

Table 2 The Facilities Area of the Korean Pavilion; Korea Pavilion consist of exhibition facilities on 2nd floor, office area, protocol center, public space on 1st floor , and multi-purpose space on the ground floor

Facilities		Guideline	Schematic design	Working design
Exhibition facilities	Exhibition hall	1,000 m^2	902 m^2	922 m^2
	Video hall	1,000 m^2	901 m^2	910 m^2
	Sub-total	2,000 m^2	1,803 m^2	1,832 m^2
Office work/ administration	Staff office, Operating room etc	100 m^2	96 m^2	90 m^2
	Sub-total	100 m^2	96 m^2	90 m^2
Multi-purpose hall	Multi-purpose hall	1,000 m^2	904 m^2	908 m^2
	Rooms in Multi-purpose hall	100 m^2	96 m^2	94 m^2
	Sub-total	1,100 m^2	1,000 m^2	1,002 m^2
Protocol center	R.VIP meeting room	120 m^2	108 m^2	106 m^2
	Director room	140 m^2	128 m^2	124 m^2
	VIP meeting room	50 m^2	45 m^2	45 m^2
	VIP entourage room	30 m^2	27 m^2	26 m^2
	Sub-total	340 m^2	308 m^2	302 m^2
Public Space	Waiting room	500 m^2	872 m^2	761 m^2
	Elevator	50 m^2	55 m^2	50 m^2
	Machine/electric room	300 m^2	813 m^2	918 m^2
	MDF/Equipment storage etc.	250 m^2	22 m^2	25 m^2
	Restroom	200 m^2	184 m^2	173 m^2
	Carbon zero facility	160 m^2	89 m^2	96 m^2
	Sub-total	1,460 m^2	2,035 m^2	2,022 m^2
	Total	5,000 m^2	5,242 m^2	5,248 m^2

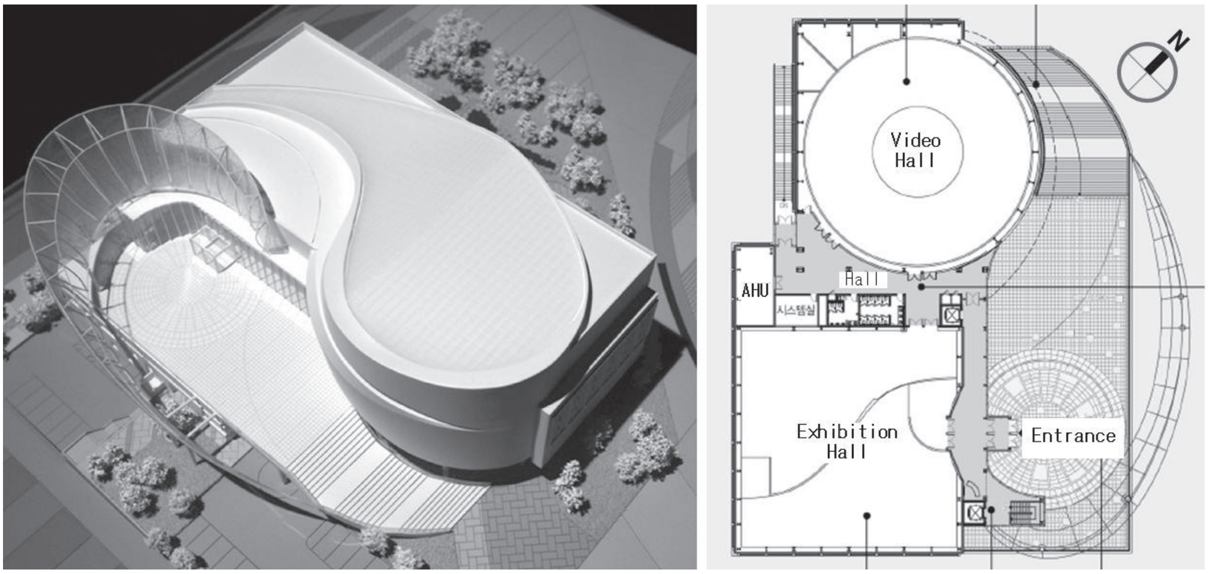

Figure 2. Bird Eye and Floor Plan; The left one is the bird of the Korea Pavilion and the right one is the 2nd floor plan which consist of video hall and exhibition hall

3 AN ANALYSIS WITH SIMULATION

3.1 Simulation with DOE-2 Tool

A simulation was conducted by using the DOE-2 tool to predict the annual energy generation and consumption of the Korean Pavilion. The DOE-2 tool which is continuously improved by the Lawrence Berkeley Laboratory in USA is a tool that is being used widely in evaluating energy performance of buildings all over the world.

It consists of five modules, which are BDL input data processor, LOADS energy calculator, SYSTEM, PLANT and ECONOMIC. Figure 3 shows the program diagram.

The BDL module converts the input file into data to read, the LOADS module computes loads and the result is sent to the HVAC to calculate the energy consumption of the equipment. Lastly, the ECONOMIC module analyzes the economic feasibility.

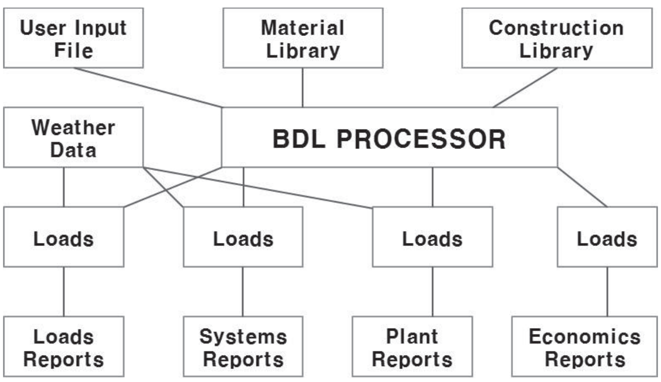

Figure 3. Program Diagram of the DOE-2; Program diagram for this study consist BDL, LOADS, SYSTEM, PLANT, ECONOMICS module and each module makes its report except BDL module.

3.2 Boundary Conditions

The input data for the DOE-2 Tool are as follows.
1 year was set as the base period, first 2 months was set as the trial operation period and 8:30 to 18:00 was set as operating hours. Occupancy was set to 50 people, and lighting and outlet load were set to 10% of the event period. The event period was 100days from May to August, and occupancy was 1,700 people. The load related with the exhibition was set to 100%, and a separate schedule was made for lighting and outlet loads by room in consultation with the operating committee. On average, it is equivalent to 65~70% of the equipment capacity.
When the event ends, some of the exhibition facilities are planned to be dismantled, and a 1 year full operation schedule was made including the dismantlement period. Lighting and outlet loads were predicted to be approximately 50% during the exhibition period.
Table 3 shows the skin performance of the building and its desired temperature for air conditioning and heating. The annual simulation was conducted based on it. Also, the building will be continuously in operation after the event ends. Taking this fact into consideration, an annual evaluation simulation including the event period as well as an annual evaluation simulation without any event were conducted as shown in Case 1 and Case 2 below.

Table 3 Skin Performances and Air Conditioning Set Point; The thermal performance of the structure including outer wall, roof, floor and the windows has been input for the simulation, and the indoor temperature set point as like below

Categories		Inputs
Thermal Performance	Structure	Outer wall: 0.15W/㎡·K, Roof: 0.15W/㎡·K, Floor: 0.18W/㎡·K,
	Windows	Window:1.8W/㎡·K, Shading coefficient: 0.57
Air conditioning set point		Cooling: 26℃, Heating: 20℃

3.3 Simulation Results

Figure 4 and Table 4 indicates the results of the annual energy consumption simulations based on the inputs as above. Also, the energy consumption by the use of Case 1 and that of Case 2 and the monthly energy consumption are shown in Figure 5. First, Case 1 shows that the energy consumption during the exhibition period from early May to the middle of August is relatively high and the energy consumption of other non-event period is very low. The electric load consumed in the exhibition during the exhibition period includes 540kW/h. It is because occupancy is 4 times higher than non-exhibition period, and thereby increases internal heat generation.

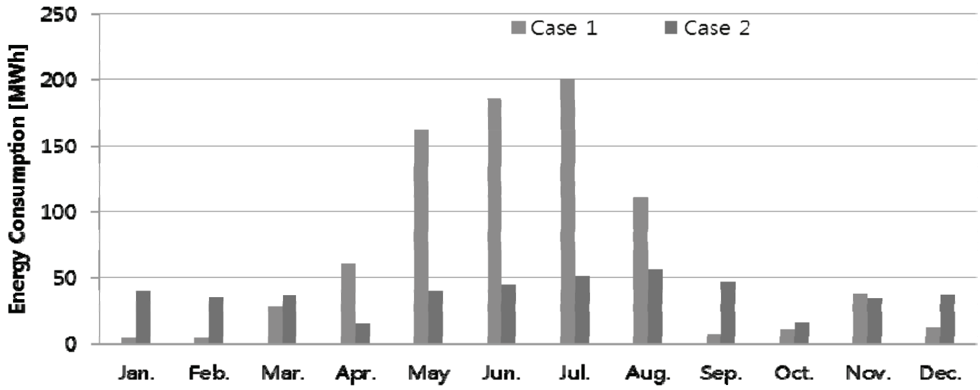

Figure 4 Cases based Annual Energy Consumption; The energy consumption amount of Case 1, including EXPO exhibition is about two times case 2 and the consumption is concentrated from May to Aug, exhibition period

Table 4 Factors based Energy Consumption [MWh/year]; The amount of energy consumption is very similar except exhibition energy between Case 1 and Case 2

	Case 1(including EXPO)	**Case 2(Non-exhibition)**
Area Lights	75.9	66.8
MISC Equipment	94.1	120.7
Space Heat	4.3	20.5
Space Cool	150.2	73.8
Pumps & MISC	38.8	50.6
Vent Fans	85.4	115.5
Hot Water	3.1	5.8
Exhibition	375.2	-
Total	826.9	453.6

The annual energy consumption of Case 1 is 826.9MWh. On the other hand, Case 2 which is the simulation of a general operation condition without any event shows an even energy consumption throughout the year. It can be known that energy consumption decreases during the intermediate season April and October, but increases in June and August the summer season and in December and January the winter season. The annual energy consumption of Case 2 is 547.5MWh.

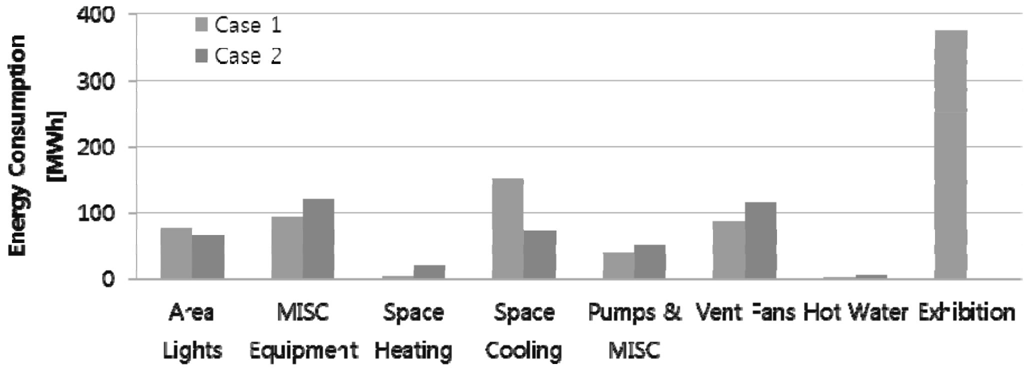

Figure 5 Energy Amount of Use by Category; Space heating energy is very small because the building site has moderate winter climate and the amounts of case 2's area lights, MISC equipment, space heating, pumps, vent fans energy are larger than case 1

4. REVIEW ON RENEWABLE ENEGY

This building is used for exhibition of a certain event, so it features high internal heat generation in the exhibition facilities along with the loads by the external climate factor unlike general office buildings. Accordingly, as mentioned earlier, energy production using fuel cells and sunlight panels was taken into consideration.

4.1 Fuel Cells

The capacity of a fuel cell installed on the building is 50kW and two fuel cells are able to generate 100kW in total. Presently this fuel cell is a test product and is still being developed by H Company in Korea. For this reason, the detailed specification of this fuel cell is still undisclosed. Its rated generation is 50kW, and it can output up to maximum 180%, but it is being operated with approximately 45kW/h output based on the actual data measured in May. With 70~74m^3/h of hydrogen consumption, its energy generation efficiency is estimated to be 50~55%. There is an oil-refining facility in the vicinity of the building, and hydrogen generated and collected during the refinement process is used for the operation of these fuel cells. Hydrogen is supplied by tank truck for now, but there is a plan to connect the oil refining facility and the building with a hydrogen pipe in near future.

4.2 Reviews on the Annual Generation by the Renewable Energy System

The fuel cells are operated 24 hours 365 days, and the simulation result shows that the fuel cells and the sunlight panel on the building can generate approximately 886.7MWh annually. Table 5 indicates the annual energy production by the fuel cells and PV. It is predicted that the zero energy goal can be attained by annual operation because the annual energy consumption of the simulations of Case 1 and Case 2 are 826.9MWh and 453.6MWh respectively and it is lower than the annual generation within the site.

Table 5 Annual Energy Generation by Renewable System

Fuel Cell	700.8MWh
PV	185.9MWh
Total of Renewable Energy	886.7MWh

5. ANALYSIS OF OPERATION DATA

5.1 Operation

The exhibition started from May 12, 2012, but opening ceremony and irregular events happened on May 13 and 14 which were the first weekend since the opening. For this reason, data measurement was officially conducted from May 14. Electricity is supplied through the electric power system as energy is consumed more than the energy generated within the site due to the loads of events and the building. However, in the night time, if the energy generated by the fuel cells is more than the base-load of the building, surplus energy is sent back to the electric power system and it becomes a minus count.

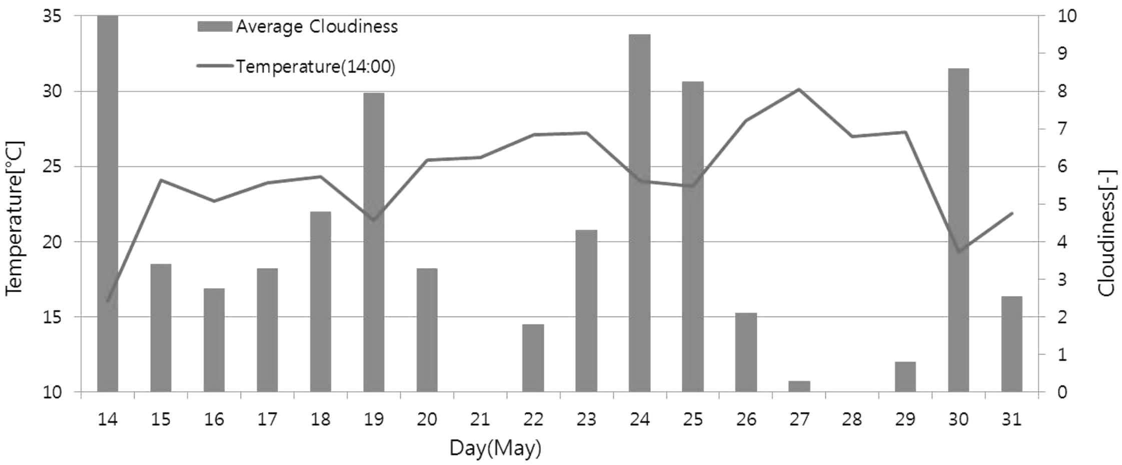

Figure 6. Outdoor Temperature and Cloudiness of the Building Site; Temperature is between 16 to 30 degree Celsius and the cloudiness is five. The range of cloudiness is zero to ten

Figure 6 shows temperature and average cloud data at 14:00 hour in the region where the building is located, and Table 5 indicates operation data from May 14 to 31.
Based on the operation data from May 14 to 31, Figure 7 shows the energy consumption by the renewable system within the site and Figure 8 shows the use of daily energy including system power.

Table 5. Actual Operation Date in May [kWh]

Day	Fuel Cell	PV	Energy supplied by Electric Company	Energy consumption	Electricity back	Net energy consumption
14th	1,755	22*1	2,137	3,915	92	3,823
15th	1,638	623	1,220	3,483	330	3,153
16th	2,197	518	2,370	5,086	76	5,010
17th	1,602	634	1,386	3,623	272	3,351
18th	2,242	714	2,988	5,945	13	5,932
19th	1,941	344	1,919	4,205	258	3,947
20th	1,912	637	2,210	4,760	159	4,601
21st	1,731	584	2,731	5,047	334	4,713
22nd	1,822	601	2,039	4,463	127	4,336
23rd	2,134	493	2,418	5,046	215	4,831
24th	2,133	280	2,305	4,719	206	4,513
25th	2,020	438	2,606	5,065	219	4,846
26th	1,976	242	2,359	4,578	207	4,371
27th	2,124	675	2,446	5,246	249	4,997
28th	2,118	621	2,051	4,791	238	4,553
29th	2,012	566	2,254	4,833	312	4,521
30th	1,919	154	2,714	4,788	117	4,671
31st	1,951	522	2,495	4,969	239	4,730
Total	38,986	9,721	51,437	84,559	3,987	96,175
Daily average	1,957	482	2,258	4,698	204	4,494

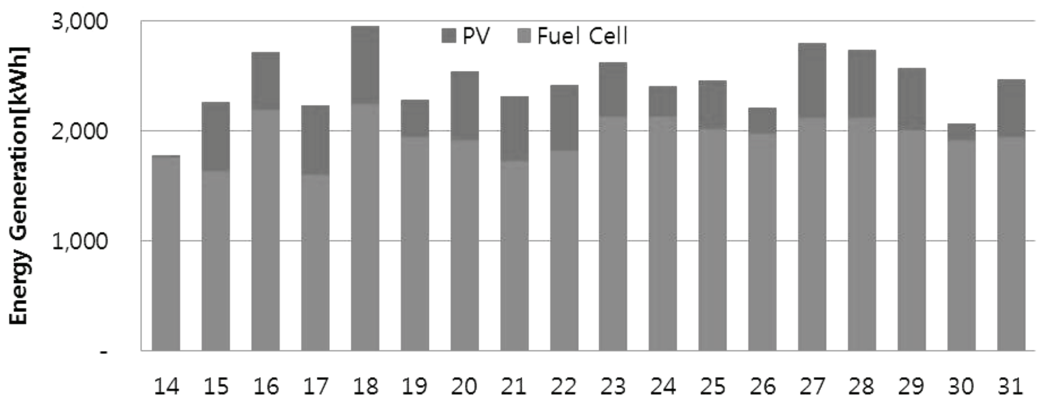

Figure 6. Electric Power Generation by PV, Fuel Cell; the amount of PV generation on 14th is almost zero because of the inverter system check. The fuel cell generation is stable, but PV generation has a large fluctuation

5.2 The Analysis of Energy

Daily energy consumption including the energy generated by the renewable system was about 2,532~ 5,932kWh and daily average was approximately 4,460kWh. Also, energy independence considering the energy generated of the daily energy consumption was approximately 54%. The exhibition period ends in the middle of August, therefore it is anticipated that air conditioning loads will increase after June, and the energy independence will be decreased by it as well. On the other hand, the solar photovoltaic (solar light power generation) showed relatively low energy generation compared to its system capacity due to some problems occurred in the inverter device and dust on the panel surface. Energy sent back into the electric power system is 204kWh on daily average and it is less than 5% of daily energy consumption. It is assumed that it is necessary to review on the operation method of increasing the amount of energy sent back into the electric power system by increasing the consumption of the fuel cells in the night time and decreasing the base load.

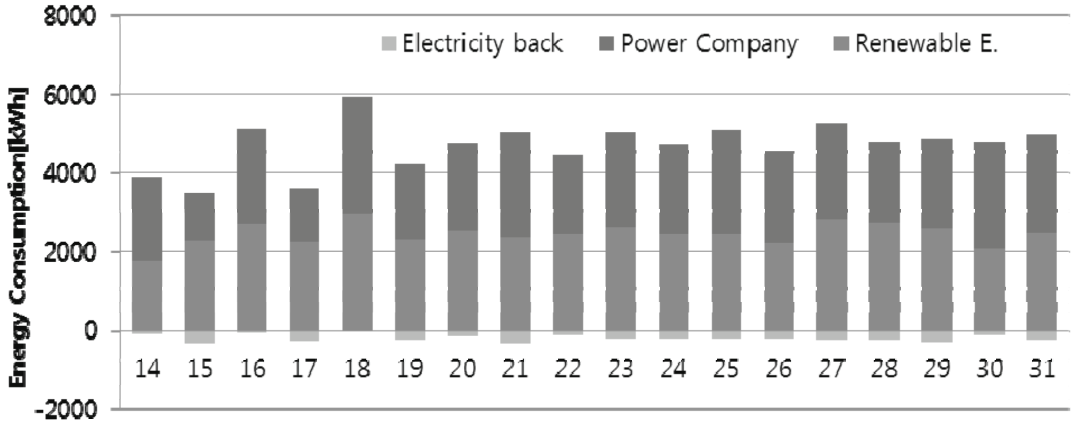

Figure 7. Daily Energy Consumption Data; The amount electricity back to power company is small compare to the whole energy consumption. The blue bar means energy independence and it may be assumed the bar size will be decreased by August, exhibition period

6 CONCLUSIONS AND PROSPECT

The annual energy generation and consumption of the exhibition facility with fuel cells and PV was reviewed through simulations, and the actual operation was analyzed based on the 3-week observed data. After examining the two cases of annual operations that are; the one includes the exhibition period and the other one without any event, it was found that it would be possible to operate zero-energy because energy generated within the site of the building exceeds the energy consumed.

However, the simulations were conducted at the point of time when the final schedule including the detailed exhibition plan and operation plan had not been confirmed yet. For this reason, the results of the simulations were slightly different from the actual energy generation and consumption. Accordingly, another study is planned to be conducted again reflecting the actual operation sooner or later.

According to the actual observation of the operation conducted in May after the grand opening of the exhibition, the fuel cells played the most important role in securing energy independence by being operated full time at 90% of rated level, whereas the PV operation didn’t satisfy expectations due to the troubles with the device and the pollution of the panel as mentioned above. In order to solve such problems, there are attempts to review on an operation method of improving energy independence by minimizing the base load and increasing the amount of energy sent back into the system in the night time.

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ANALIZA TERENSKOGA PRAĆENJA POTROŠNJE ENERGIJE U ZGRADI NULTE ENERGIJE

Sažetak: *Porast cijena energije i pokušaj smanjenja zagađenja okoliša rezultirali su mnogim naporima da se smanji potrošnja energije u zgradama. Trenutno mnoge zemlje aktivno istražuju pasivne kuć niskoenergetskzgradi zgrade s nultom energijom. U periodu od svibnja do kolovoza 2012. u Yeosu, Južna Koreja, održat će se Expo 2012 , a ovo će istraživanje pratiti potrošnju energije tijekom tog događaja .*
Zgrada se nalazi na južnoj obali Južne Koreje gdje se obično bilježe visoke temperature i vlažnosti tijekom prijelaznih razdoblja i i ljeti kada se održava izložba. Projektni koeficijenti prolaza topline vanjskih zidova i prozora iznose redom 0,15W/m2K i 1,8W/m2K, kako bi se smanjila potrošnja energije, a predviđena je uporabageotermalne dizalice topline kao ključna izvora topline radipoboljšanja energetske učinkovitosti klimatizacije. Osim toga, za proizvodnju električne energije se koriste obnovljivi izvori energije, uključujući dva sustava gorivnih članaka učina 50 kW, fotonaponski sustav od 200 kW i vjetroagregat snage 6 kW, kako bi se poboljšala samodostatnost zgrade. Proračun temeljen na simulacijama pomoću softvera DOE-2 provest će se kako bi se procijenila potrošnja energije tijekom izložbe, a iako se potrošnja energije može pokazati drukčijom u analiziranom slučaju, pokazuje se da iznosi 485 do 547MWh/god a proizvodnja energije 501 do 548MWh/god, tako da se očekuje nulta potrošnja energije u zgradi u promatranome periodu.

Ključne riječi: Zgrada nulte energije, gorive ćelije, fotonaponski sustav, monitoring energije, simulacija

UTJECAJ VERTIKALNIH RASPORA NA KOEFICIJENT PROLAZA TOPLINE RAVNOG KROVA KOD JEDNOSLOJNOG POLAGANJA KAMENE VUNE DVOSLOJNE GUSTOĆE

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Sažetak: S ciljem smanjivanja radova i troškova, jednoslojno polaganje kamene vune dvoslojne gustoće sve se češće koristi za izolaciju ravnih krovova. Eventualni zračni raspori između spojeva ploča mogu nastati zbog dozvoljenih dimenzijskih tolerancija ploča i/ili nesavršenog polaganja. U radu je numeričkim modeliranjem izračunata raspodjela temperatura unutar konstrukcije i koeficijente prolaza topline ovisno o širini zračnog raspora. Rezultati pokazuju da širina vertikalnog zračnog raspora do 7 mm ima zanemariv utjecaj na vrijednosti koeficijenta prolaza topline konstrukcije ravnog krova ukoliko je korištena kamena vuna dvoslojne gustoće u jednom sloju, i to bez obzira na njen položaj u odnosu na profilaciju čeličnog lima .

Ključne riječi: kamena vuna dvoslojne gustoće, jednoslojno polaganje, ravni krov

1. UVOD

Tvornički proizvedene izolacijske ploče kamene vune dvoslojne gustoće sastoje se od gornjeg sloja veće gustoće i donjeg sloja manje gustoće. Upravo zbog dva sloja različitih gustoća ploče je moguće postavljati jednoslojno, jer u presjeku predstavljaju pravilan raspored izolacije od kamene vune na ravnom krovu; iznad donjeg sloja manje gustoće koji osigurava bolja toplinsko izolacijska svojstva nalazi se gornji sloj veće gustoće koji osigurava veću otpornost na mehaničko opterećenje. Upotrebom navedenih ploča jednoslojnim polaganjem moguće je ostvariti uštede u vremenu, cijeni i opsegu radova prilikom izolacije ravnih krovova. Uočeno je da zbog dozvoljenih tolerancija dimenzija ploča i/ili nesavršenog načina polaganja može doći do pojave zračnih raspora između ploča kamene vune. S ciljem utvrđivanja utjecaja navedenih zračnih raspora i maksimalne dozvoljene širine raspora koji neće imati negativni utjecaj na toplinsko izolacijske karakteristike krovne konstrukcije, izvršili smo računalno modeliranje krovne konstrukcije i koeficijenta prolaska topline *k* ravnog krova sastavljenog od sljedećih elemenata (odozgo prema dolje):

- sintetska krovna folija debljine 1,5 mm;
- kamena vuna Monrock MAX E dvoslojne gustoće, proizvođača Rockwool Adriatic d.o.o., debljine 150 mm;
- parna brana debljine 0,15 mm;
- visoko-profilirani (trapezni) nosivi čelični lim debljine 1,2 mm.

U proračunu je uzet u obzir zračni raspor od 0 do 15 mm između ploča kamene vune.

2. ULAZNI PODACI

Koeficijent prolaza topline se računa prema izrazu (1). Podaci koje smo koristili kod proračuna *k* vrijednosti ravnog krova dani su u tablici 1.

$$\boldsymbol{k} = \frac{1}{\frac{1}{\alpha_1}+\sum\frac{\delta_i}{\lambda_i}+\frac{1}{\alpha_1}} \left[\frac{W}{m^2K}\right] \quad (1)$$

Gdje su:
α_1 i α_2 - koeficijent konvektivnog prijelaza topline u W/m^2K
δ_i - debljina sloja u *m*
λ_i - koeficijent toplinske vodljivosti u *W/mK*
k – koeficijent prolaza topline W/m^2K

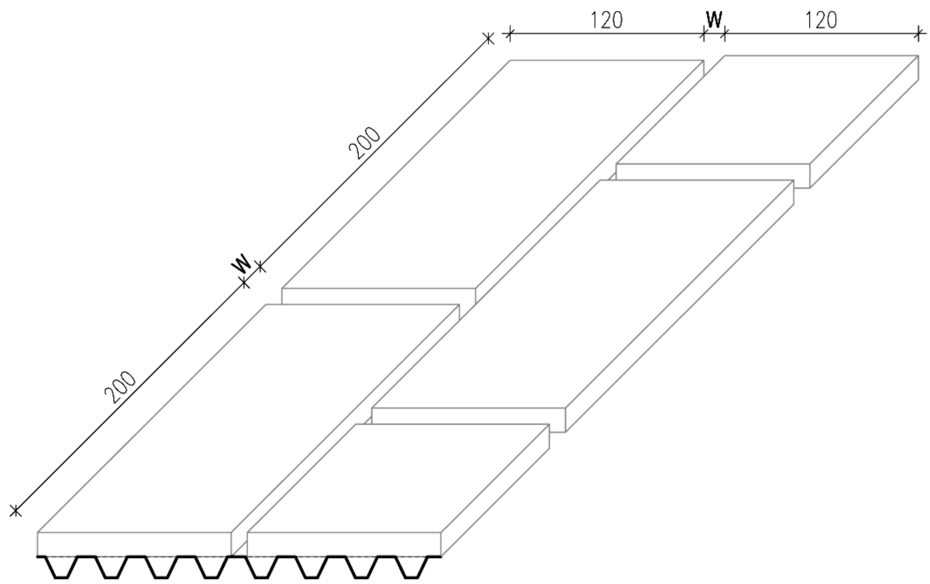
Tablica 1: podaci o debljinama i koeficijentima toplinske provodljivosti sastavnih dijelova ravnog krova.

Slojevi (odozgo prema dolje)	Debljina δ	Toplinska provodljivost λ, W/(mK)
krovna folija	1,5 mm	0,25
kamena vuna Monrock MAX E	150 mm	0,038
parna brana	0,15 mm	0,25
visoko-profilirani čelični lim	1,2 mm	50

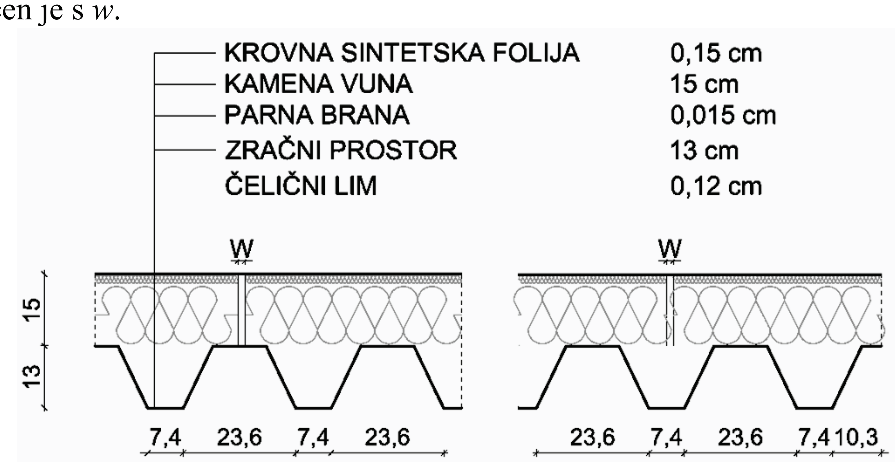
Kao toplinski izolator koristi se kamena vuna dvoslojne gustoće Monrock MAX E ukupne debljine 150 mm, duljine 2000 mm i širine 1200 mm, proizvedene prema zahtjevima norme proizvoda HRN EN 13162[1]. Dodatno, iako norma proizvoda dozvoljava tolerancije u duljini ± 2% i u širini ± 1,5% (što bi na konkretnim dimenzijama ploča iznosilo 40 i 18 mm), proizvođač u procesu proizvodnje dozvoljava tolerancije u duljini i širini od ± 2 mm. Kamena vuna Monrock MAX E je dvoslojne gustoće, postavljena na način da je sloj veće gustoće (210 kg/m^3) okrenut prema gore, a sloj manje gustoće (120 kg/m^3) prema dolje[2]. Toplinska provodljivost vune deklarirana je na 0,038 W/(mK) na punoj debljini vune od 150 mm. Vuna se na trapezni lim polaže s pomakom od pola duljine ploče (1000 mm), što je prikazano na Slici 1.
Čelični trapezni lim je visoko-profiliran, visine vala 130 mm, širine gornjeg vala (brijega) 112 mm i donjeg vala (dola) 74 mm, presvučen PE slojem debljine 15 μm. Vertikalni presjek kroz sustav ravnog krova prikazan je na slici 2 za dva slučaja: a) kada je zračni raspor širine *w* na sredini gornjeg vala trapeznog lima i b) kada je zračni raspor na sredini donjeg vala trapeznog lima.

3. PRORAČUN

Proračun k vrijednosti ravnog krova sproveden je računalnim programom BISCO proizvođača Physibel korištenjem podataka navedenih u Tablici 1 za način polaganja ploča dimenzija 2000 mm x 1200 mm prikazan na slici 1 (dulja stranica ploča paralelna s uzdužnom profilacijom trapeznog lima), i to za širinu zračnog raspora od w = 0, 3, 5, 7, 10, 12 i 15 mm. Kako kod polaganja ploča kamene vune točan položaj duljinskog spoja ploča (a time i zračnog raspora), koji je paralelan s duljom stranicom ploče, može doći na različite položaje profilacije trapeznog lima, za proračun su odabrana dva granična položaja duljinskog spoja: sredina zračnog raspora na sredini brijega trapeznog lima (slučaj a) i i sredina zračnog raspora na sredini dola trapeznog lima (slučaj b). Sam proračun je izvršen na način da se, uz danu geometriju duljinskog spoja i profila trapeznog lima, za širinu zone u kojoj je vršen proračun uzeto po pola širine ploče kamene vune sa svake strane zračnog raspora tj. po 600 mm od svake strane raspora. Tako dobiveni rezultati energijskog toka korišteni su da se dobiju normalizirane vrijednosti energijskog toka po jedinici ploštine, koji odgovara *k* vrijednosti cijelog sustava kada se on podijeli s razlikom temperatura korištenom u proračunu. Za model korišten u proračunu uzete su temperature vanjskog zraka od Θe = 0°C, unutarnjeg zraka Θi = 20°C, korištene vrijednosti koeficijenta emisivnosti od ε = 0,85, a vrijednosti 3 prijelaznih plošnih otpora bile su Rse = 0,04 m^2K/W (vanjski) i Rsi = 0,10 m^2K/W (unutarnji).



Slika 1: Način polaganja ploča kamene vune Monrock MAX E (mjere u cm). Razmak između ploča označen je s *w*.



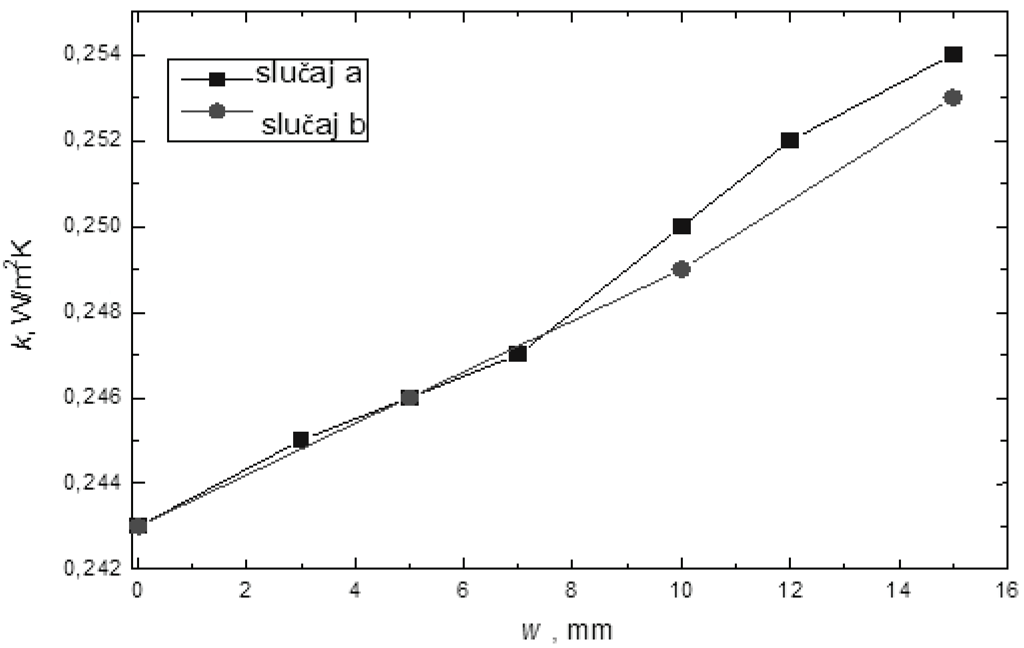
Slika 2: Vertikalni presjek kroz sustav ravnog krova s opisom sastavnih djelova (mjere u cm), za dva slučaja položaja zračnog raspora između ploča kamene vune u odnosu na gornji val trapeznog lima: a) zračni raspor na sredini gornjeg vala (lijevo) i b) zračni raspor na sredini donjeg vala. S *w* je označena širina zračnog raspora.

4. REZULTATI PRORAČUNA

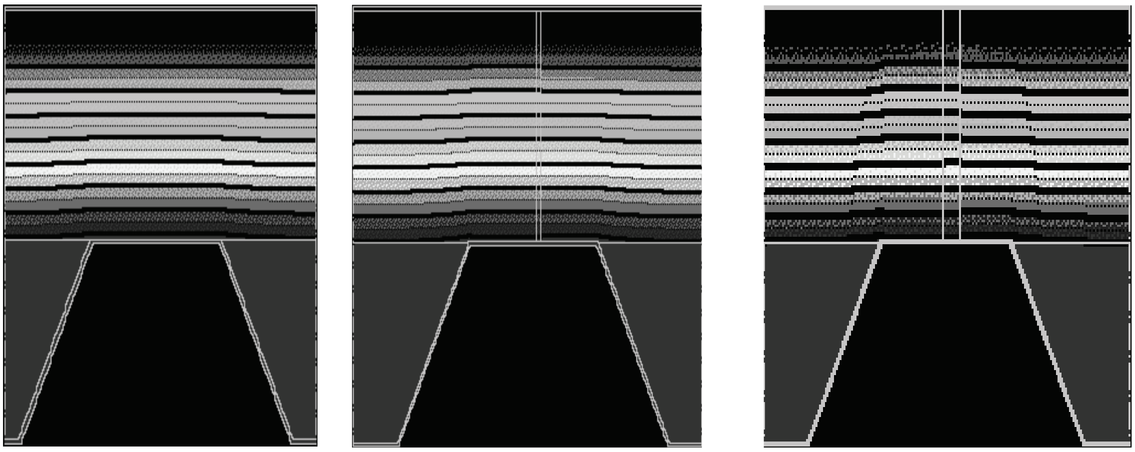
Rezultati proračuna vrijednosti koeficijenta prolaza topline k za oba ispitana slučaja u ovisnosti o širini zračnog raspora w dani su u Tablici 2.
Rezultati proračuna dani u Tablici 2 prikazani su i grafički na Slici 3, dok su na Slikama 4 - 9 rezultati proračuna prikazani pomoću izotermi, a područja između izotermi obojana su različitim bojama.

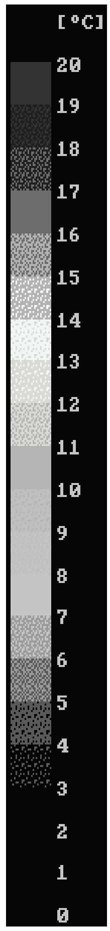
Tablica 2: Rezultati proračuna vrijednosti k za slučajeve a (zračni raspor na sredini brijega trapeznog lima) i b (zračni raspor na sredini dola trapeznog lima) u ovisnosti o širini zračnog raspora w. Δk je povećanje k vrijednosti u odnosu na k vrijednost za raspor w = 0 iznosi $\Delta k = (k_w - k_{w=0})/k_{w=0}$

w, mm	slučaj a		slučaj b	
	k, W/(m^{2}K)	Δk, %	k, W/(m^{2}K)	Δk, %
0	0,243	0	0,243	0
3	0,245	0,82		
5	0,246	1,23	0,246	1,23
7	0,247	1,65		
10	0,250	2,88	0,249	2,47
12	0,252	3,70		
15	0,254	4,53	0,253	4,12

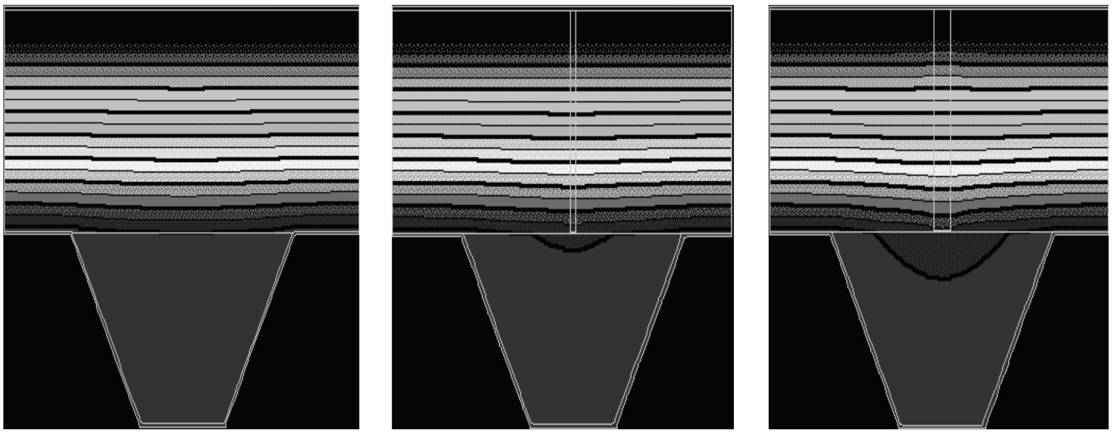


Slika 3: Grafički prikaz proračuna k vrijednosti za slučajeve a (zračni raspor na sredini brijega trapeznog lima) i b (zračni raspor na sredini dola trapeznog lima) u ovisnosti o širini zračnog raspora w.





Slike 4 (lijevo), 5 (sredina) i 6 (desno): prikaz izotermi za slučaj proračuna a) (zračni raspor na sredini brijega trapeznog lima) za širinu zračnog raspora w = 0 (lijevo), 5 (sredina) i 15 mm (desno). Izoterme su crne crte i dane su za raspon od po 2°C (deblje crte) i međuvrijednosti od po 1°C (tanje crte), s time da je najviša gornja izoterma 1°C, a najniža donja 19°C. S desne strane dana je i legenda boja.



Slike 7 (lijevo), 8 (sredina) i 9 (desno): prikaz izotermi za slučaj proračuna b) (zračni raspor na sredini dola trapeznog lima) za širinu zračnog raspora w = 0 (lijevo), 5 (sredina) i 15 mm (desno). Izoterme su crne crte i dane su za raspon od po 2°C (deblje crte) i međuvrijednosti od po 1°C (tanje crte), s time da je najviša gornja izoterma 1°C, a najniža donja 19°C. S desne strane dana je i legenda boja.

5. ANALIZA REZULTATA

Iz dobivenih rezultata proračuna k vrijednost za oba ispitana slučaja a) i b) vidljivo je da do 7 mm širine raspora nema bitnije razlike u oba slučaja i da se k vrijednost za w = 7 mm povećala 1,65% u odnosu na k vrijednost kada nema raspora tj. ploče kamene vune su tijesno priljubljene. Značajnije odstupanje k vrijednosti za slučaj a) u odnosu na slučaj b) nastupa od raspora većih od 7 mm. U tom slučaju konvekcijski doprinos prolasku topline postaje izraženiji u odnosu na ostala dva načina vođenja topline (kondukcijski i radijacijski), s obzirom da se proširenjem raspora stvaraju pogodniji uvjeti za brže strujanje zraka u prostoru raspora omeđenog bočnim stranicama kamene vune i krovne folije s gornje strane, a parne brane s donje strane.

6. ZAKLJUČAK

Temeljem dobivenih rezultata, zaključuje se da se *k* vrijednost modeliranog ravnog krova linearno povećava s 0,243 W/(m^{2}K) za širine zračnog raspora od 0 mm na 0,247 W/(m^{2}K) za raspor od 7 mm, što je povećanje od 1,65% i ne ovisi o položaju zračnog raspora između ploča kamene vune u odnosu na profilaciju čeličnog lima. S obzirom da su proračuni sprovedeni za dva granična slučaja, *k* vrijednosti u svim mogućim načinima polaganja kamene vune do širine raspora od 7 mm ne ovise o načinu polaganja ploča kamene vune i stoga kod izračuna *k* vrijednosti konkretnog ravnog krova ne treba voditi računa o njihovom položaju. S obzirom na proizvođačevu dozvoljenu toleranciju u duljini i širini ploče od ± 2 mm i uz uvjet da su ploče kamene vune pravokutne, uz savjesno polaganje ploča najveći zračni raspor između uzdužno složenih redova ploča može biti najviše 4 mm. To bi korištenjem linearne ovisnosti *k* vrijednosti o širini raspora u području širine raspora od 0 do 7 mm (Slika 3) značilo maksimalnu gornju granicu povećanja *k* vrijednosti za 1,03 % u odnosu na *k* vrijednost ploča postavljanih bez zračnog raspora, i to bez obzira na položaj zračnog raspora u odnosu na profilaciju modelnog trapeznog lima. Dodatno, norma HRN EN ISO 6946[2] propisuje da se u slučaju korekcija manjih od 3% korekcije *k* vrijednosti ne moraju primijeniti u proračunu, a utjecaj zračnih raspora se može zanemariti, što u našem slučaju pokriva zračne raspore do čak 10 mm u oba granična slučaja.

Način polaganja tj. položaj zračnog raspora u odnosu na profilaciju modelnog trapeznog lima počinje bitnije utjecati na *k* vrijednost ravnog krova pri širinama raspora većim od 7 mm i manjim od 15 mm. No, i u slučaju raspora od 15 mm *k* vrijednost kod nepovoljnijeg slučaja a) je samo za oko 0,4% veća od one za povoljniji slučaj b).

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[3] HRN EN ISO 6946:2008: Građevni dijelovi i građevni dijelovi zgrade - Toplinski otpor i koeficijent prolaska topline - Metoda proračuna (ISO 6946:2007; EN ISO 6946:2007)

IMPACT OF VERTICAL GAPS ON FLAT ROOF HEAT TRANSFER COEFFICIENT IN SINGLE-PLY INSULATION WITH DUAL DENSITY STONE WOOL

Abstract: In order to reduce amount of work and costs, single-ply insulation with dual density stone wool has been increasingly used for insulation of flat roofs. Possible air gaps between slabs might occur due to allowable dimensional tolerances of slabs and/or imperfect installation. The computer modeling is used to calculate the temperature distribution inside the structure and heat transfer coefficient *k* depending on the width of the air gaps. The results show that the width of the vertical air gap up to 7 mm has a insignificant impact on the *k* value of the construction of flat roof if dual density stone wool is installed in a single layer, regardless of its position in relation to the molding steel.

Key words: dual density stone wool, single-ply insulation, flat roof

ENERGY EFFICIENT HVAC SYSTEM FOR THE REGISTERED ARCHITECTURAL CULTURAL HERITAGE BUILDING

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Abstract: *The Rijeka's national theatre Ivan pl. Zajc, built in 1885 in the neo-renaissance and partially in the late baroque style, is registered as a cultural heritage monument. During the renovation period in 1970/82 the new HVAC system was not completed. During that period it was provisionally connected to the boiler-station of the nearby factory. The complete HVAC system design was started in 2003 and the construction of the new cooling station was placed in the ex-factory next to the boiler station. The design includes the cooling system powered by natural gas. Absorption cooling units function all year round, connected by the existing pipeline. The applied system of gas absorption devices represents a simple, modern, energy-efficient technical solution, financially supported by the national Environmental Protection and Energy Efficiency Fund. The newly constructed cube, with cooling tower built in place of the old oil reservoir, is a simple architectonic solution, appropriate for the future new urban area.*

Key words: theatre building, architectural cultural heritage, energy efficiency, HVAC system, air-conditioning, absorption cooling unit

1. INTRODUCTION

The building of the Croatian national theatre *Ivan p. Zajc* in Rijeka was built in 1885 as the first of the three European theatres designed by the renowned team of two Austrian architects, F. Fellner and H. G. Helmer. The second building was the Zagreb theatre and the third one was the Vienna theatre. The Rijeka building was built in the neo-renaissance style and the interiors in the late baroque style were decorated by G. Klimt and others and can accommodate about 677 visitors. The system for heating and ventilation had been solved at the time with the most innovative solutions for the period. It is worth mentioning that at the opening ceremony, the building had an autonomous system of electrical lighting, which, unfortunately, due to a short circuit, spoiled the ceremony of this event. The system of the electrical supply was powered by water. It is well known that the right bank of Rječina River has many underground water sources so that even in that period this natural resource of renewable energy was used. Today, after 125 years, we can say that the theatre building belongs to the Rijeka's rich history along with a great number of excellent performances where world-renowned musicians, composers and artists performed: Sarah Bernhardt, Giacomo Puccini, Enrico Caruso, Pietro Mascagni, Beniamino Gigli, Arturo Toscanini, Eleonora Duse and many others. In the theatre, a few politicians and presidents were seen and liked to deliver their speeches there: Gabriele D'Annunzio, Mussolini, Tito and Tuđman [1].

Figure 1: Photography of the theatre building in Rijeka/Croatia [2]

During the seventies the theatre building was closed for 12 years due to renovation and restoration of the interiors, facade and art pieces. In that period several structural details were solved [3]; the building lies on the embanked part of the town – at less than one meter deep are underground waters (sea water). The project solution of the engineering thermo-technical system included the system of insuring higher microclimatic conditions for the pleasant stay of visitors as well as actors and technical staff. Special care was given to the auditorium and to the stage. The previous solutions of heating and ventilation system with the new project were raised to a different comfort level with HVAC. Unfortunately, due to restricted financial resources for the renovation and reconstruction of the building, at that period the system of air-conditioning was not completed with the cooling of the building. Originally, the boiler room, see Figure 2, in the theatre building was on the ground level and it was not suitable for the location of heating and cooling devices. This space does not meet the minimal conditions for the location of a built-in chimney.

2. PRECONDITIONS FOR APPLICATION OF ACU ON THE THEATRE BUILDING

The project solution of the new heating, ventilating and air-conditioning (HVAC) system was reduced by minimal intervention or, better said, nonexistent building interventions on a building which is a registered cultural heritage monument. These new solutions, after the first projects which were advanced for the period, were not adequate from today's technical point of view. Primarily, it refers to the adequate space for the building of the main energy equipment and to the openings on the building to intake and to expel the air for ventilation. Today we have an additional condition: the system must also be energy efficient and it is clear that it is very difficult to obtain this stipulation in such architectonically complex buildings. It is very good

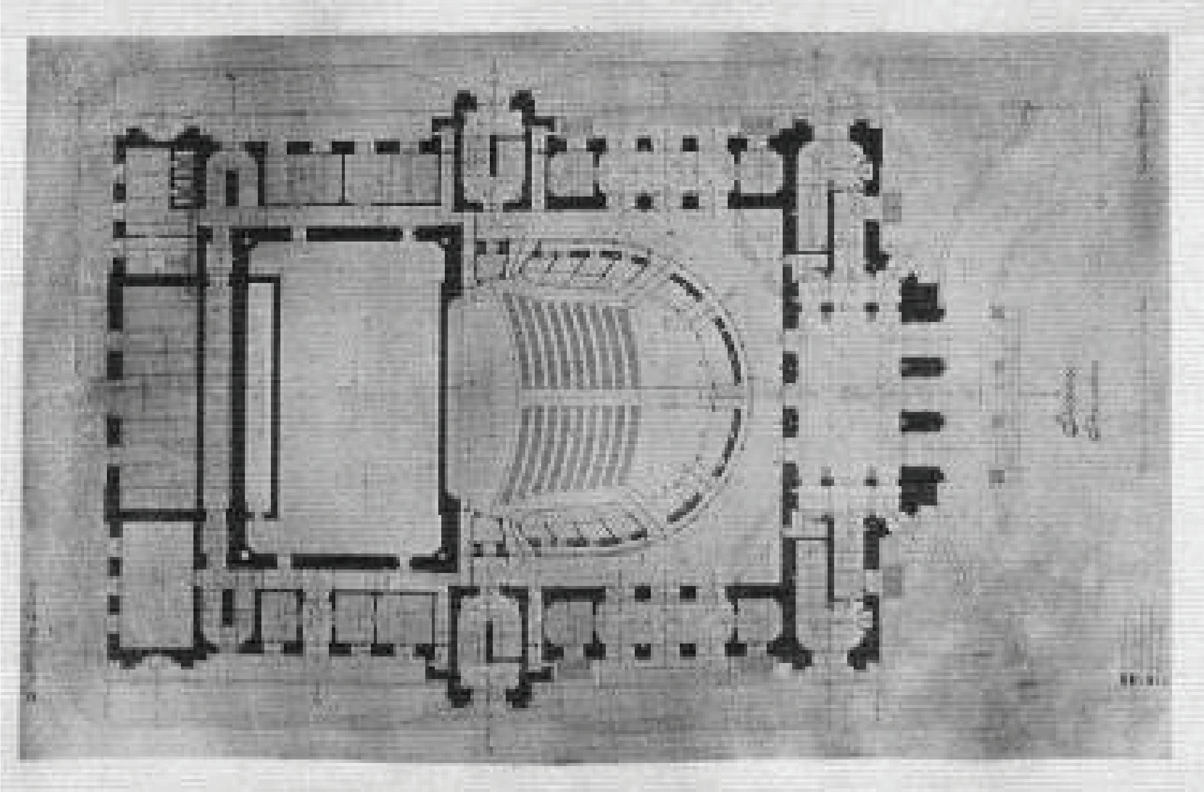

Figure 2: Lay out of the theatre building in Rijeka/Croatia [1]

that the project, done by professor Milan Viličić from the Faculty of Mechanical Engineering and Naval Architecture of the University of Zagreb during the seventies of the last century, has foreseen a very contemporary technical solution which at the time was only partially constructed. It included all the necessities for the performance of the HVAC system of the building. Even in that period it was clear that the heating and cooling supply must be done outside the building and the provisional solution was to connect the building to the boiler station of the nearby factory *Istravino*. The heat pipeline is 250 m long and it crosses the river's canal *Mrtvi kanal.*

After the introduction of natural gas in 2007, several projects have been completed in the Rijeka area with absorption cooling units (ACU) for the HVAC of public buildings: the Cultural centre, the building of Faculty of Civil Engineering and the Science Park, all at the new campus of the University of Rijeka. Similar systems have been adopted for buildings owned by the Municipality of Rijeka: the Croatian Cultural Centre in Sušak, the Museum of Modern and Contemporary Art and the HVAC system of the building of the Croatian national theatre, *Ivan pl. Zajc,* in Rijeka. These systems are supplied with two-step absorption cooling units. The working element in the unit is the mixture of lithium bromide ana water (LiBr-H_20). Such compounds during cooling reject waste heat through the cooling tower into the open space [4/11].

The design of the complete HVAC system of the theatre building was started in 2003. Four possibilities to house the water chiller-room were considered: next to the existing energy room in the theatre, in two possible locations in the block of houses south of the theatre, in the underground cooling station in the park in front of the theatre, and the one in the area of the *Delta* on the east side of the river canal where the previous connection to the heat pipeline already existed. After analysing the potential locations, it was decided that it should be in the area of the *Delta* and that it should be the permanent solution for the energy supply of the theatre building. Because of the complexity of the *status quo* and real dynamic of the design execution, the design was divided into four phases: reconstruction of the natural gas supply system in the *Delta* area, reconstruction of the boiler-station of the old *Istravino* factory, adjustments and reconstruction of the existing thermo technical - HVAC system in the theatre building and construction of the new cooling station next to the boiler station.

Figure 3: Rijeka City plan – The estuary and Delta area

3. SURVEY OF ADOPTED HVAC SYSTEM

There are three necessary conditions for the heating and cooling of the theatre building: Heating capacity is 1050 kW, taking into consideration that the morning charges of the building (rehearsals, regular staff) compared to the maximal charge during the evening performances, and heating of the auditorium and the stage is 40 to 60%. Cooling capacity is 700 kW. According to thermal needs, the two-step absorption cooling unit with LiBr-H_2O (product York, model YMPC-F 10EX) has been chosen.

Table 1: Capacity of absorption cooling unites

	Cooling capacity kW	Heating capacity kW	Rejected heat kW	Fuel
ACU	2×352	2×286	2×637	Natural gas

Table 2: Technical characteristics of two-step absorption cooling unit with LiBr-H_2O (York YMPC-F 10EX)

Model	YMPC-F 10EX	
Working regime	Cooling	Heating
Capacity, kW	352	286
Heat rejection, kW	638	/
Temperature outlet/inlet, °C	7/12,5	60/55
Max inlet temperature, °C	12	60
Max outlet temperature, °C	18	/
Min inlet temperature, °C	7	/
Min outlet temperature, °C	10	40
Cooling water temperature, °C	29-32/35-38	/
Power supply 400 V, 50 Hz, kW	4,03	1,78
Fuel	Natural gas (H_d = 34,43 MJ/m^3)	
Nominal heating capacity, kW	310	318
COP	1,134	0,897
Range of capacity	30-100%	
Annual working hours	1500-2000	

The absorption cooling devices with continuous power perform with a binary mixture of lithium bromide and water (LiBr-H_2O). In this unit, water is the cooling medium and

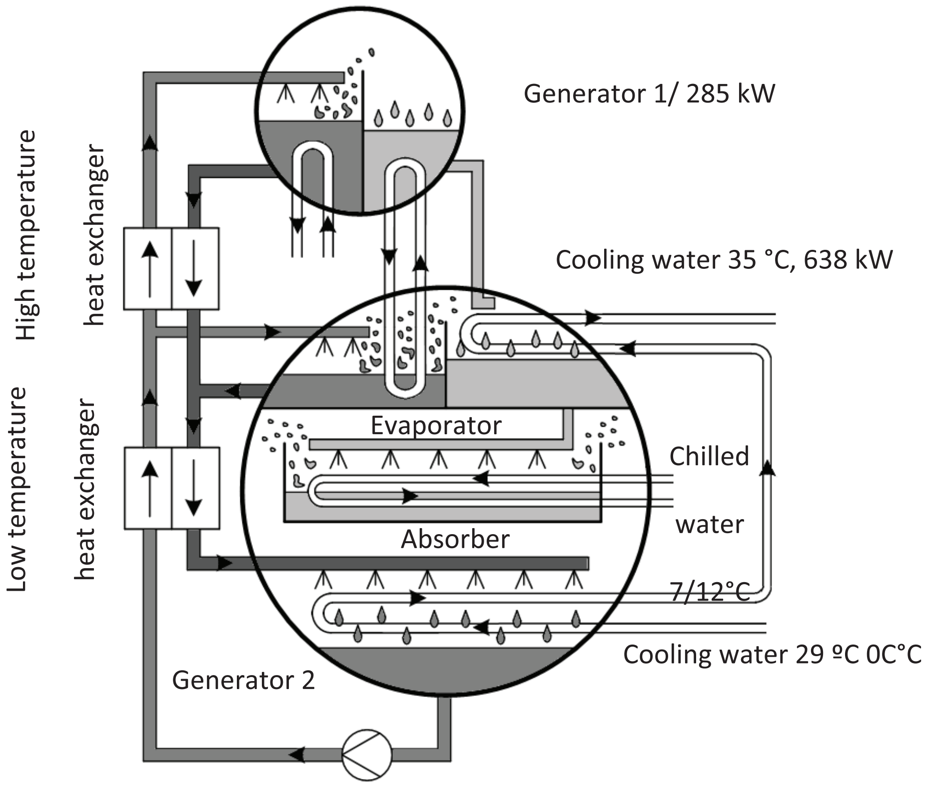

Figure 4: Two-step absorption cooling unit with LiBr-H_2O (York YMPC-F 10EX)

lithium bromide is the absorbent. ACU with LiBr-H_2O is constructed as two-step absorption cooling unit. In the two-step ACU with LiBr-H_2O, heat of vapour condensation from the first stage is used for additional evaporation of the water in the generator during the second stage.

High and low temperature heat exchangers use the temperature of rich (saturated) solutions, which are exhausted from the generators towards the absorber for the preheating of weak (low saturated) solutions which are oriented towards the generators. In such a way, the two-step ACU is almost 70% more efficient compared to the one-step ACU. The efficiency of the working conditions of the two-step ACU is about COP_h = 1,0 to 1,20, where the specific heat consumption in the generator is about 0,83 to 1,0 kWh/kWh. In the absorber and in the cold water condensator some 1,83 to 2,0kWh/kWh is carried away. The necessary flow of cooling water from the cooling tower is 180 to 270 kg/h/kW_0. The absorbed electrical energy in the one-step ACU is 0,002 to 0,008 kWe/kW. The two-step ACU-s are differentiated as parallel, serial and reverse, depending on the flow regime of solutions.

In the ACU with serial flow, the weak solution from the absorber passes through the LT and HT heat exchangers, after which it enters the generator of the 1st stage. At the ACU with parallel flow, the weak solution (from Figure 2) is divided and is directed into the HT heat exchanger of the 2nd stage after the LT heat exchanger. At the ACU with reverse flow the weak solution is preheated.

The ACU device, apart from being able to cool, can be designed to heat too. In the regime of heating, by opening of the valve between the generator of the 1st stage and the evaporator, the steam evades the condenser and goes directly into the evaporator where it heats water. Lithium bromide absorbs the water steam after which the wear solution is conducted into the generator and the cycle is repeated. The hot water in the ACU can be regulated for heating purposes up to 60 (80) °C. In the ACU device, while under the parallel regime of heating and cooling, the process is equivalent to the regime of cooling (Figure 2). In that case, the only exception is that one part of the steam from the 1st step generator is conducted before reaching the generator of the 2nd stage for heating necessities. In that case, the cooling capacity is diminished.

The ACU can be used as a heating device when it works as conventional boiler. It has primarily been used for cooling purposes and the recommended annual working hours are 2000. The waste heat of the ACU is conducted into the surrounding cooling towers. The temperature of the cooling water at the entrance of the cooling tower is 35 °C and at the exit it is 29 °C. One part of the waste heat of the CHW is possible to use rationally, i.e. for the preheating of the CHW. In that case, the condenser and the absorber of the ACU have to be connected to the container of the CHW and to the cooling tower. Depending on the needs of the building to be cooled, it can mostly be used for the preheating of the CHW. In the case of the complete cooling charge of a building of 700 kW, some 1 280 kW of waste water is produced and must be conducted to the ACU. In the future, this heat could be used to heat the existing building of the ex-factory when a new purpose would be found for it. The technical solution to use waste heat is rather easy to perform.

Figure 5: The cooling station

Figure 6: Smart architectonic solution of cooling tower next to the ex-factory [12]

Figure 7: The cooling tower in front of theatre

The absorption cooling devices, which are built into the cooling station, represent a simple technical solution [13, 14]. The primary energy is natural gas. The conventional hot water boiler station is exchanged for an adequate system and the conventional cooling station for a water chiller. It is a rather simple technical solution! The precondition of the realisation of this project was the reconstruction of the gas emergent of the existing boiler room of the ex-factory building. The result of this technical exercise is the realisation of the energy efficient HVAC system and reduction of the emission of toxic gases.

4. CONCLUSION

The design includes the cooling system by use of natural gas. An ACU and natural gas absorption plant have been built which in the summer period functions as cooling devices. In the wintertime these devices are used as a heating boiler station. The thermo-energetic connection with the theatre building is the existing pipeline system which is now a reversible energy connection in function all year around. The solution accepted has considered all the parameters of the protection of cultural heritage and the system of absorption cooling devices in the *Delta* area represents a simple, modern, and efficient technical solution. The newly built cube, in which the cooling tower is placed in place of the old oil reservoir, is a simple architectonic solution which is well adapted to the future of the new urban area. The applied system of gas absorption devices represents a simple, modern, energy efficient technical solution. The project has been financially supported by the *Croatian Environmental Protection and Energy Efficiency Fund.*

NOMENCLATURE

ACU	absorption cooling unit
COP	coefficient of performance
HT	high temperature
HVAC	heating, ventilating and air/conditioning system
LT	low temperature
CHW	consumption hot water

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ENERGETSKI UČINKOVIT TERMOTEHNIČKI SUSTAV ZA ZGRADU REGISTRIRANOG ARHITEKTONSKOG KULTURNOG NASLJEĐA

Sažetak: *Hrvatsko narodno kazalište Ivana pl. Zajca izgrađeno je 1885. u neorenesansnom i djelimično u baroknom stilu, registrirani je spomenik arhitektonske kulturne baštine. Tijekom obnove kazališta 1970./82. termotehnički sustav za klimatizaciju zgrade nije zaokružen, već je riješen na razini grijanja i ventilacije. Sustav grijanja bio je priključen na za tu namjenu izgrađenu kotlovnicu u tvornici u susjedstvu kazališta. Kompletiranje termotehničkog sustava započelo je 2003. izradom projekta hlađenja s rashladnom stanicom. Rashladni sustav koristi prirodni plin kao energent. Ugrađen je apsorpijski rashladni uređaj koji u zimskom razdoblju može raditi kao toplovodni kotao. Rashladni sustav predstavlja jednostavno i moderno rješenje kojim se učinkovito koristi energija, a realiziran je bez ijednog građevinsko-arhitektonskog zahvata na zgradi kazališta. Rashladna stanica je izgrađena u izdvojenom prostoru uz kotlovnicu, a arhitektonsko oblikovanje u prostoru slobodnostojećeg zaštitnog plašta rashladnog tornja predstavlja jednostavno arhitektonsko rješenje, prilagođeno urbanističkim planovima ovog gradskog područja. Projekt je sufinancirao Fond za zaštitu okoliša i učinkovito korištenje energije.*

Ključne riječi: zgrada kazališta, zaštićeno arhitektonsko kulturno nasljeđe, energetska učinkovitost, termotehnički sustav, klimatizacija, absorpcijski rashladni uređaj

Index of Authors