University of Zagreb

FACULTY OF ELECTRICAL ENGINEERING AND COMPUTING

ROBERT PAŠIČKO

OPTIMIZATION OF POWER SYSTEM OPERATION AND DEVELOPMENT UNDER EMISSION TRADING SCHEME

DOCTORAL THESIS

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Supervisors:
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Professor Ivar Wangensteen, PhD

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Sveučilište u Zagrebu

FAKULTET ELEKTROTEHNIKE I RAČUNARSTVA

ROBERT PAŠIČKO

OPTIMIZACIJA RADA I RAZVOJA ELEKTROENERGETSKOG SUSTAVA U UVJETIMA TRGOVANJA EMISIJAMA

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About the supervisor – Željko Tomšić

Željko Tomšić was born in Vrbovec in 1957. He received B.Sc., M.Sc. and Ph.D. degrees in electrical engineering from the University of Zagreb, Faculty of Electrical Engineering and Computing (FER), Zagreb, Croatia, in 1981, 1990 and 2001, respectively. From 1991 he is working at the Department of Energy and Power Systems at FER. In January 2010 he was promoted to associate Professor. From 2004 to 2008 he had the position of Assistant Minister for Energy and Mining in the Ministry of Economy, Labor and Entrepreneurship. From 2008 to 2009 he was Member of HEP d.d. (Croatian Power Utility) Management Board for strategy, corporate development, international relations and gas business development. He was head of Government Working Group for preparation of Accession Negotiations with EU on the chapter 15 – Energy.

He participated in six scientific projects financed by the Ministry of Science, Education and Sports of the Republic of Croatia and leader of two EU FP projects. He had many invited lectures on international and national scientific and expert conferences. Assoc. Prof. Tomšić is a member of the Croatian Academy of Engineering (HATZ), a senior member of IEEE, HK CIGRE, Croatian Nuclear Energy Society, KOREMA, European Nuclear Society.

O mentoru - Željko Tomšić

Željko Tomšić rođen je u Vrbovcu 1957. godine. Diplomirao je, magistrirao i doktorirao u polju elektrotehnike na Sveučilištu u Zagrebu Fakultetu elektrotehnike i računarstva (FER), 1981., 1990. odnosno 2001. godine.

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Sudjelovao je na šest znanstvenih projekata Ministarstva znanosti, obrazovanja i sporta RH i sudjelovao je na dva FP EU projekta. Koautor Sveučilišnog udžbenika „Elektrane i okoliš“. Objavio je preko 100 radova u međunarodnim i domaćim časopisima i zbornicima radova međunarodnih konferencija, te je koautor na preko pedeset znanstvenih i stručnih studija.

Bio je voditelj Radne skupine za poglavlje 15 Energetika pristupnih pregovora za EU.

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About the supervisor – Ivar Wangensteen

Ivar Wangensteen was born in Valdres, Norway in 1946. He received a MSc in 1971and a PhD in 1974 in Electrical Engineering from the Norwegian Institute of Technology. He received a M.Sc. in Economics from the University of Oslo in 1984. He has worked for Statkraft, The Norwegian Water Resources and Electricity Board (NVE) and the Norwegian Research Council. Since 1986 he has been with SINTEF Energy Research. Since 2002 he has been a Professor at the Norwegian University of Science and Technology (NTNU).
He is teaching in NTNU's master program on Energy and Environment. The main subject is Power Markets, Resources and Environment. He has been lecturing at the Indian Institute of Technology, Mumbai. He has been engaged in several research projects and has 65 international publications.
Prof. Wangensteen has been engaged in consulting for international clients (EPDC, Japan; EDF, France; The World Bank).

O mentoru – Ivar Wangensteen

Ivar Wangensteen rođen je u mjestu Valdres u Norveškoj 1946. godine. Magistrirao je na polju elektrotehnike 1971. godine, a doktorirao 1974. godine. Također je magistrirao ekonomiju na Sveučilištu u Oslu 1984. godine. Radio je za Statkraft, Norvešku upravu za vodne resurse i električnu energiju (NVE) i Norveško istraživačko vijeće. Od 2002. godine profesor je na Norveškom sveučilištu znanosti i tehnologije (NTNU).
Predavač je na diplomskom (Master) programu Energija i okoliš na NTNU. Glavni predmet je Tržište električne energije, izvori i okoliš. Također je i predavač na Indijskom institutu tehnologije u Mumbaiu. Uključen je u više istraživačkih projekata i ima 65 međunarodnih publikacija.
Prof. Wangensteen radio je kao konzultant za brojne međunarodne klijente (EPDC, Japan; EDF, Francuska; Svjetska banka).

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Today, in the world of raising complexities, an individual cannot do much alone, and true endeavors all take teamwork and cooperation. I would like to acknowledge contribution to this research from the FP7 project CLIMRUN (Climate Local Information in the Mediterranean region Responding to User Needs), funded by European Commission.

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Finally, and above all, I would like to thank my special team – Zoa, Zagor and Ivana – for their patience and support.

You never change things by fighting the existing reality.
To change something, build a new model that makes the existing model irrelevant.

Buckminster Fuller

Summary

Power system planning and development face new pressing challenges from climate change including the need to reduce its GHG emissions (climate change mitigation through different mechanisms such as emission trading, transition to low emission power system); and the need to adapt to climate change (climate change adaptation and vulnerability). Also, the development of energy sector should take the responsibility for the sustainable development – delivering positive and measurable impact on society, economy and environment.

The main objective of the research was to develop and verify methodology and models for the assessment of emission trading and climate change impacts on sustainable power system development. Two models were designed to fit the proposed methodology. The first model is for the assessment of emission trading and fuel price impacts on long term marginal costs for different power plants. The second designed model enables measuring sustainable development indicators from generation capacity expansion. This developed algorithm enables the power system model to include emission price in power system operation and planning. Data from Croatian power system are used for the verification of proposed methodology, designed models and algorithm,. Verification steps are included: power system modeling, modeling sustainable development indicators and assessment of climate change impacts on power system planning. Finally, the integrative model based on proposed methodology, developed models and algorithm performed a wide set of modeled scenarios. This holistic approach of modeling emission trading and climate change impacts on long-term power system planning is verified by using data for Croatian power system until 2030. Results from verification of the proposed modeling are presented and discussed. Based on these results, a summary of main findings, recommendations for policy makers and energy planners, and area for further research in this field are proposed.

Key words: emission trading, renewable energy sources, power system planning, climate change, power system modeling, low emission development.

Sažetak

OPTIMIZACIJA RADA I RAZVOJA ELEKTROENERGETSKOG SUSTAVA U UVJETIMA TRGOVANJA EMISIJAMA

Planiranje elektroenergetskog sustava suočeno je s novim izazovima koji dolaze od istodobne potrebe smanjenja klimatskih promjena i prilagodbe na njih. Paralelno je potrebno smanjivati emisije stakleničkih plinova i predvoditi tranziciju u niskougljičnu ekonomiju; kao i prilagoditi se na postojeće i buduće utjecaje klimatskih promjena. Pritom, potrebno je mjeriti uspoređivati i pozitivne i negativne učinke na održivi razvoj – društvo, ekonomiju i okoliš. Da bi se mogli analizirati ovi izazovi prilikom planiranja elektroenergetskog sustava, potrebni su novi modeli, nove metodologije i novi algoritmi koji omogućuju planeru da procjeni utjecaj klimatskih promjena i trgovanja emisijama na održivi razvoj kroz povećanje konkurentnosti niskougljičnih tehnologija.

U uvodnom poglavlju, predstavljeni su izazovi trgovanja emisijama i klimatskih promjena na planiranje i razvoj elektroenergetskog sustava. Definira se istraživački problem, hipoteze na kojima se temelji istraživanje i sveukupni cilj istraživanja. Diskutira se originalnost rada, očekivani znanstveni doprinosi, ciljana skupina kojoj su rezultati istraživanja namijenjeni te se navode glavna ograničenja rada.

U drugom poglavlju („Niskougljični razvoj i klimatske promjene“) fokus je stavljen na važnost utjecaja klimatskih promjena, klimatskih pregovora i niskougljičnog razvoja na elektroenergetski sustav.

Treće poglavlje („Trgovanje emisijama – teoretska i praktična pozadina“) analizira se utjecaj trgovanja emisijama na konkurentnost niskougljičnih tehnologija. Dan je pregled tržišta emisija stakleničkih plinova u svijetu, te teoretska pozadina trgovanja emisijama.

U četvrtom poglavlju („Dugoročno planiranje elektroenergetskog sustava s trgovanjem emisijama“) analiziraju se utjecaji trgovanja emisijama na dugoročno planiranje elektroenergetskog sustava promatranjem marginalnih troškova proizvodnje električne energije i marginalnih krivulja smanjenja emisija stakleničkih plinova.

U petom poglavlju („Modeliranje elektroenergetskog sustava i njegovog utjecaja na održivi razvoj“) istražena je klasifikacija modela za energetsko i elektroenergetsko planiranje, te su propitane njihove značajke važne za mjerenje utjecaja na održivi razvoj.

Uvodna poglavlja daju osnove za predstavljanje glavnog predmeta istraživanja - razvoj i verifikacija razvijene metodologije i modela za procjenu utjecaja trgovanja emisijama i klimatskih promjena na održivi razvoj kroz porast konkurentnosti niskougljičnih tehnologija. Metodologija za procjenu utjecaja klimatskih promjena i trgovanja emisijama na planiranje elektroenergetskog sustava prikazana je u šestom poglavlju („Predložena metodologija i modeli"). Opisana je metodologija koja je razvijena u doktorskom radu, a koja će biti iskorištena za provjeru postavljene hipoteze putem shematski opisanih koraka planiranje elektroenergetskog sustava. U ovom poglavlju, opisana su i dva modela koja su predložena i dizajnirana, te razvijeni algoritam. Prvi od tih modela je nazvan „Model za procjenu pokazatelja održivog razvoja" i omogućuje planeru usporedbu različitih scenarija novih proizvodnih kapaciteta, mjerenjem njihovog utjecaja na održivi razvoj. Drugi model je nazvan „Model za procjenu utjecaja trgovanja emisijama na granične troškove elektrana" i on procjenjuje utjecaj cijene energenata i emisija na konkurentnost obnovljivih izvora energije. Razvijeni algoritam omogućava da se prilikom modeliranja elektroenergetskog sustava uključi i utjecaj trgovanja emisijama u planiranje i rad samog elektroenergetskog sustava. Sedmo poglavlje („Verifikacija predložene metodologije, modela i algoritma s upotrebom podataka iz Hrvatske") koristi podatke iz Hrvatske da verificira predloženu metodologiju, modele i algoritam. Verifikacija je napravljena u nekoliko koraka, počevši od planiranja godine unaprijed do dugoročnog modeliranja elektroenergetskog sustava, modeliranja indikatora održivog razvoja i procjene utjecaja klimatskih promjena na elektroenergetski sustav. Cjelovit pristup modeliranju utjecaja klimatskih promjena i trgovanja emisijama na planiranje elektroenergetskog sustava verificiran je koristeći podatke iz Hrvatske za 2030. godinu, a rezultati modeliranja su opisani i prodiskutirani.

Zaključak sadrži sažetak glavnih rezultata istraživanja, kritički osvrt na postignute rezultate s obzirom na postavljene hipoteze, daje preporuke donosiocima politika te utvrđuje temeljne smjerove nastavka istraživačkog rada.

Glavni predmet istraživanja je razvoj i verifikacija razvijene metodologije i modela za procjenu utjecaja trgovanja emisijama i klimatskih promjena na održivi razvoj kroz porast konkurentnosti niskougljičnih tehnologija. Prilikom istraživanja, ostvaren je sljedeći izvorni znanstveni doprinos:

- Predložena je metodologija za procjenu utjecaja trgovanja emisijama i klimatskih promjena na održivi razvoj. Metodologija uključuje holističku procjenu utjecaja klimatskih promjena na elektroenergetski sustav i procjenu utjecaja trgovanja emisijama na porast konkurentnosti obnovljivih izvora energije;

- Dva modela su razvijena tijekom rada na disertaciji –Model za procjenu pokazatelja održivog razvoja koji omogućuje planeru usporedbu različitih scenarija novih izgrađenih elektrana u sustavu mjerenjem njihovog utjecaja na održivi razvoj; i Model za procjenu utjecaja trgovanja emisijama na granične troškove elektrana koji procjenjuje utjecaj cijene trgovanja emisijama i energenata na konkurentnost obnovljivih izvora energije. Primjena oba modela osnažuje proces dugoročno planiranja razvoja elektroenergetskog sustava, donošenje novih politika i strategija te pomaže prilikom donošenja odluka prilikom adresiranja izazova utjecaja klimatskih promjena;
- Predložen je i razvijen algoritam za modeliranje utjecaja trgovanja emisijama na elektroenergetski sustav, koji je na kraju i implementiran u model PLEXOS. Time je model PLEXOS osposobljen prilikom simuliranja rada i planiranja elektroenergetskog sustava uzeti u obzir i utjecaj cijene emisija, te pratiti njen utjecaj na profitabilnost pojedinih elektrana, visinu cijene električne energije i promjenu u voznom redu elektrana;
- Predložena metodologija i razvijeni modeli i algoritam su verificirani podacima iz hrvatskog elektroenergetskog sustava – to predstavlja prvi pokušaj procjene i modeliranja utjecaja klimatskih promjena na planiranje elektroenergetskog sustava; ali također i omogućuje razvoj i sagledavanje širokog raspona opcija i scenarija prilikom adresiranja trgovanja emisijama i procjene konkurentnosti niskougljičnih tehnologija.

Ključne riječi: trgovanje emisijama, obnovljivi izvori energije, planiranje elektroenergetskog sustava, klimatske promjene, modeliranje elektroenergetskog sustava, niskougljični razvoj.

TABLE OF CONTENTS

1. INTRODUCTION

This chapter presents the background, objective and framework of the research. It includes problem definition, and explains the hypothesis and the main objective of research. It explains scientific contribution of the thesis, importance and applicability of research conclusions in practical long term power system planning. Also, scope and limitations of the research are presented. Thesis outline is presented at the end.

1.1. Background and problem definition

Energy use is the most important anthropogenic contributor to climate change (with transportation and energy spent in buildings – 66% of worlds GHG emissions [1]). Therefore, energy sector planning and development faces new challenges coming from climate change:

- Need to reduce GHG emissions in power system (transition to low emission development of power system with support of mechanisms such as emission trading);
- Need to adapt to climate change that might occur during the lifetime of power system elements (climate change vulnerability and adaptation, including impacts in planning);
- Impacts on sustainable development through addressing climate change challenges.

These relationships are graphically represented in the Figure 1-1. Energy sector planning should take responsibility of its sustainability – delivering positive and measurable impact on society, economy and environment. These burdens got much more attention since economic and energy crisis in 2008 [2], and since then a number of studies and research have been appearing (for more information and a list of some of the relevant studies and documents, please see ANNEX 1).

Being an integral part of energy sector, this is also relevant for power system operation and development. In order to understand these interactions, new ways of thinking are necessary that would help a power system planner to comprehend a wide set of new impacts on power system development and operation such as:

- Demands for inclusion of low emission technologies in the system;
- Emission trading;
- Bigger concerns for energy security with more and more energy import at the same time;
- Demand to create local jobs;
- Demand to reduce other emissions which are more intensively monitored;

- Challenges with introduction of large shares of renewable energy sources in a power system and concerns about reserve margin;
- Public opposition to exclude some existing power plants which are technically in fully mature shape (most notably nuclear power plants in post-Fukushima era);
- Lack of long term support from policy makers (some power plants supported by one government might lose support from the next one), etc.

Mentioned challenges are intensively happening for the last 10-15 years. To address these challenges, new approaches, and new tools are needed. There is a growing amount of research happening in this field and new methodologies, methods and algorithms are being proposed, developed, tested and implemented in order to better face these challenges.

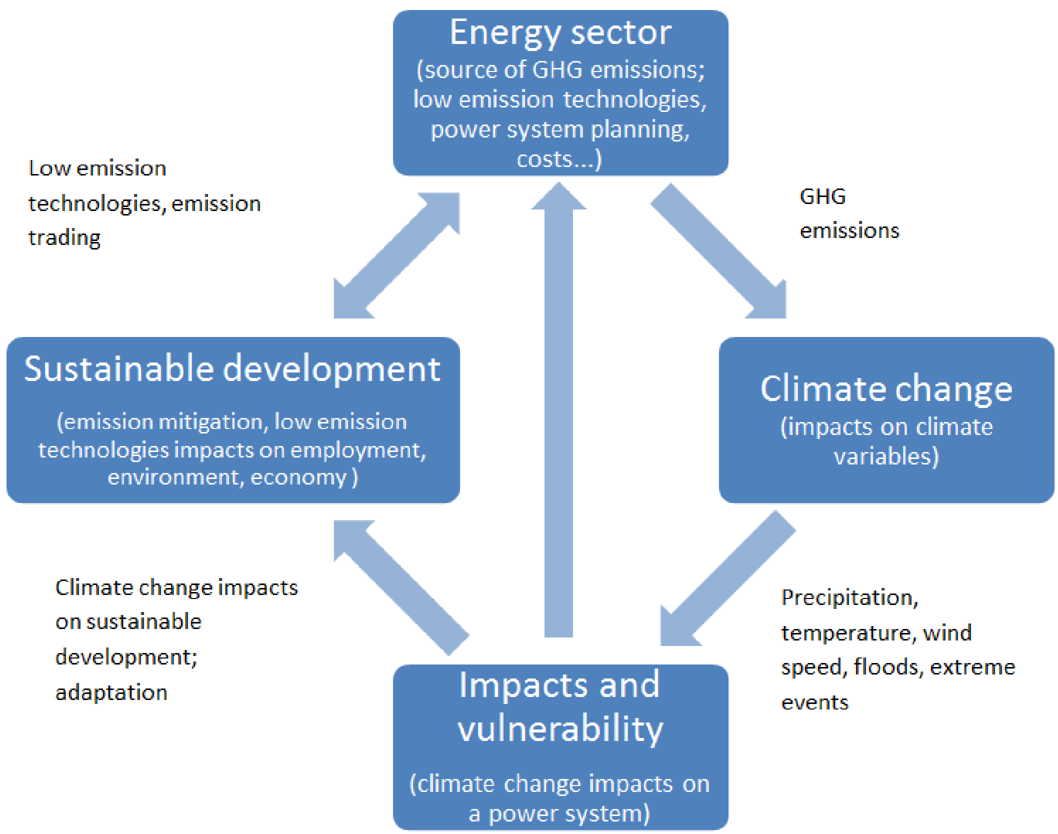


Figure 1-1: Relationships between power system, climate change (impacts, mitigation and adaptation), low emission technologies and sustainable development (author`s representation)

1.2. Hypotheses and objective of research

In research background and problem definition, it was highlighted that there is currently a need for new methodologies, models and algorithms that would enable to understand the relationships between climate change, power system planning and sustainable development. This is especially true when it comes to low emission technologies: their role is reducing emissions in energy mix. But they are also a subject to climate change, which has impacts on renewable energy sources, energy demand and energy efficiency measures.

Therefore, following hypotheses have been established as a basis for research:

- Climate change has an important impact on energy sector in terms of both mitigation and adaptation, resulting in complex relationships between them;
- Emission trading impacts on power system operation and development are increasing competitiveness of low emission technologies;
- Transition from fossil fuels to renewable energy sources brings positive measurable effects to sustainable development – economic, social and environmental;
- Interpretation of climate change modeling data is necessary to be included in power system planning in order to address vulnerability and adaptation issues;
- Existing methodologies, methods and algorithms need additional improvements to be able to address new challenges for power system planning coming from climate change adaptation and mitigation.

Derived from these hypotheses, the main objective of the research could be formulated as follows:

Overall objective of the thesis is to develop and verify developed models and methodology for assessment of emission trading and climate change impacts on sustainable power system development through increase of competitiveness of low emission technologies.

1.3. Scientific contribution from the thesis

This thesis was prepared as a result of scientific research and practical work in the field of low emission development, emission trading and power system planning in Croatia, South East Europe, Thailand and some other countries. It relies on existing research discussed and presented within thesis, but it upgrades it with the author`s own contribution. The novelty and originality is found in the following:

1. Proposed methodology for assessment of emission trading and climate change impacts on sustainable power system development - through increase of competitiveness of low emission technologies in a power system.

The proposed methodology is described in chapter 6. There is a schematic representation of a proposed methodology and a throughout description of its elements. Both climate change mitigation and adaptation have impact on power system planning and sustainable development. Climate change mitigation in methodology is represented through emission trading and increase in price for GHG emission-emitting technologies, and resulting competitiveness increase for low emission technologies. Further, climate change adaptation in methodology is represented through climate change impacts on renewable energy generation. The objective of the thesis derived from set of hypotheses is that it is necessary and possible to model in an integrative approach both climate change mitigation and adaptation impacts on a power system, and measure it against sustainable development. This will be done by measuring and by comparing the competitiveness change of low emission technologies and sustainable development indicators.

2. Two models designed and verified within work on thesis - Model for assessment of sustainable development indicators, and "LRMC model"

Both models were proposed and designed in order to enable the functioning of the proposed methodology (to fulfill its missing parts). Model for assessment of sustainable development indicators has a purpose of holistically assessing how low emission technologies influence sustainable power system development (through calculation of a set of economical, society and environmental indicators). Outputs from this model are connected with the two other existing small models that serve to compare and visualize the modeling results. It is described in chapter "6.3. Model for estimation of sustainable development impacts". The second model is proposed and designed to help and enable easy modeling of competitiveness increase for low emission technologies through CO2 impacts on Long Run Marginal Costs (LRMC) and Short Run Marginal Costs (SRMC) of different power plants, depending on economic variables such as discount rate, but also taking in account economic life time of a plant and all fixed and variable costs. This is described in chapter "6.2. LRMC model".

3. Algorithm for modeling emission trading impacts on a power system (electricity price profits of power plants, emission amounts, merit order) in a liberalized market

In order to enable the power system model PLEXOS to include emission trading impacts on modeling power system operation and planning (which it was incapable to do), an algorithm is developed and included in the model that enables modeling emission trading on a liberalized power system market (algorithm described in "6.4. Algorithm for emission trading developed for power system model”). Like this, this algorithm has become an integrative part of model PLEXOS.

4. Verification of proposed methodology and developed algorithm and models with data from Croatian power system

Verification of the proposed methodology, algorithms and models, and its ability to test the set of hypotheses was performed by using data from the Croatian power system. Use of models that fit in the proposed methodology is presented in chapter 7, while modeling results are presented in chapter 8 and results are finally commented in chapter 9. This is the first attempt of modeling emission trading impacts on development of Croatian power system and the first attempt of assessment of climate change impacts on renewable energy sources in Croatia.

Overview of the papers publish during the work on doctoral thesis

During the work on this doctoral thesis, 14 papers were written and published in journals and presented at the conferences. Topic of these papers was directly connected to the doctoral thesis topic, and represents a scientific contribution in the period 2006-2014 (4 papers published in CC and SCI cited journals):

1) Pašičko, Robert; Branković, Čedo; Šimić, Zdenko: Assessment of climate change impacts on energy generation from renewable sources in Croatia. Renewable Energy, Vol. 46, pp. 224-231, 2012
2) Pašičko, Robert; Robić, Slavica; Tomšić, Željko: Modeling CO2 Emissions Impacts on Croatian Power System. Thermal Science, Vol. 14, No. 3, pp. 657-673, 2010
3) Pašičko, Robert; Stanić, Zoran; Debrecin, Nenad: Modeling Sustainable Development Scenarios of Croatian Power System. The Journal of Electrical Engineering, Vol. 61, no. 3, pp.157–163, 2010
4) Pašičko, Robert; Kajba, Davorin; Domac, Julije: Impacts of Emission Trading Markets on Competitiveness of Forestry Biomass in Croatia: Forestry Journal, no. 7-8, 2009
5) Pašičko, Robert: Perception of Risk in Energy Sector. Social Ecology Journal, Vol.17; No. 2, April-June 2008, p. 117-132
6) Kordic, Zoran; Herencic, Lin; Pašičko, Robert; Carrington, Daniela: Renewable Energy Cooperation Potential between Member States and West Balkan Countries. 7th Dubrovnik Conference on Sustainable Development of Energy Water and Environment Systems" Dubrovnik, Croatia, 22-26. September 2013

7) Herencic, Lin; Kordic, Zoran; Pašičko, Robert; Carrington, Daniela: Modeling impacts of low-carbon technologies in the context of sustainable development in Croatia. 7th Dubrovnik Conference on Sustainable Development of Energy Water and Environment Systems" Dubrovnik, Croatia, 22-26. September 2013
8) Robert Pašičko, Čedo Branković, Ivan Rajšl. Use of Energy Models in Assessment of Climate Change Impact on Renewable Energy Generation, 2nd International Conference Energy and Meteorology, Toulouse, France, 25.-28. June 2013
9) Pašičko, Robert. Modeling impacts of emission trading on a power system. 2nd Regional Conference "Industrial Energy and Environmental Protection in Southeastern Europe", Zlatibor, Serbia, June 22-26, 2010
10) Pašičko, Robert; Šimić, Zdenko; Robić, Slavica: Climate Change Impacts on Renewable Energy Sources in Croatia. 10th International Probabilistic Safety Assessment & Management Conference, Seattle, USA, 2010
11) Pašičko, Robert, Tomšić, Željko. CO2 Price Impacts on Nuclear Power Plant Competitiveness in Croatia, 8th International Conference: Nuclear Option in Countries with Small and Medium Electricity Grids, Dubrovnik, Croatia, 16–20 May 2010
12) Pašičko, Robert; Andreas Tuerk; Željko Tomšić. Use of biomass in Croatia: options for CO2 mitigation // International Congress "World Renewable Energy Congress" Glasgow, Scotland, 19-25. July 2008.
13) Pašičko, Robert; Robić, Slavica; Tuerk Andreas. Impacts of CO2 emission trading on competitiveness of electricity production from biomass. International conference „Renewable energy sources in Croatia" Osijek, Croatia, May 2007
14) Pašičko, Robert; Debrecin, Nenad; Višković, Alfredo. Simulating the optimal generation capacity mix in Croatian power system; HRO HYDRO 2007 Conference; Šibenik, Croatia, May 2007

1.4. Target group and applicability

The results of this thesis are aimed (but not limited) to the following groups:

- Policy and decision makers in energy sector, environmental sector or labor;
- Experts on power system development and energy sector planners;
- Climate change experts with interest in energy field;

- Investors in fossil fuel based power plants and in low emission technologies.

Applicability of methodology or models is wide and already proven in real life projects and research papers:

- Both developed models ("Model for assessment of sustainable development indicators" and "LRMC model") could be used independently for any country (with inclusion of input data) – and were already used in development of Croatian Energy Strategy (2008-09), Framework for Low Emission Development Strategy for Republic of Croatia (2012-13), EU funded project BETTER (Bringing Europe and Third Countries Together through Renewable Energy) in 2014;
- Developed algorithm for model PLEXOS is an integrate part of the model and was used in numerous occasions worldwide in power system modeling with PLEXOS;
- Modeling climate change impacts on RES, or modeling impacts of power system development on sustainable development indicators can be easily used in other regions through here proposed methodological steps.

1.5. Scope and limitations of the thesis

The research in this thesis deals with a broad field of climate change impacts and policy; emission trading mechanism; modeling long term power system planning; and competitiveness low emission technologies. Therefore some limitations were used in order to make thesis focused.

When focusing on climate change impacts on a power system, only its impacts on generation side was used. More specifically, only its impacts on renewable energy sources were researched, namely: wind, hydro and solar energy. Impacts on other technologies or on demand side were not in the scope of this thesis.

Thesis is not technology oriented, so it does not address specificity of different technologies in more detail than it was necessary to test the set hypotheses in developed methodology and models.

Even though models, algorithm and methodologies are applicable for use in different timescales and on different power systems, their applicability was verified (and is in such a way presented in this thesis). First on one or more cases separately, and then on one case jointly by applying it to the data from Croatian power system until 2030 (integrative modeling – using all models according to the proposed methodology). Using methodology for integrative modeling to time period after the year 2030 brings too many uncertainties (regarding prices, markets, technologies) and also due to time and resource limitations it was therefore limited to case until 2030 – with development of several scenarios and sub-scenarios in planning.

One more thesis limitation is generalization. By modeling power system development some of the technical or economical characteristics not relevant for the research focus were generalized, in order to bring more simplicity and understanding of the relevant mechanisms. Also, when modeling low emission technologies, for simplicity of modeling only wind power plants are modeled as a variable that can be changed as an input to the model; while other technologies were already pre-defined and fixed.

The research was verified with data from Croatian power system – and it was taken from all publicly available sources, like strategies (or background documents used for them), official statistics, available climate change modeling results done during the EU funded FP7 research project CLIMRUN. Climate change impacts were concluded using modeling results which are all based on several presumptions (climate change models are fed with data on future consumption patterns, expected population, GHG emissions etc.)

Having all of these limitations in mind, the results of modeling presented in this thesis should be interpreted and it is application of proposed methodologies, designed models and algorithm with use of available data from Croatian power system.

1.6. Thesis outline

Chapter 2 gives introduction on climate change impacts and climate negotiations, and presents complex interactions between power system planning, climate change mitigation (through emission trading as chosen instrument to introduce low emission development in power system planning) and impacts of climate change on energy generation (and importance of adaptation in power system planning and vulnerability to climate variables). Further, it explains concept of low emission development and gives overview of long term climate strategies and low emission development strategies – what are their main characteristics and impacts on a power system.

In order to assess emission trading impacts on competitiveness of low emission technologies, goal of Chapter 3 is to give understanding of emission trading: which markets exist in the world today, where and how they are structured, which lessons were learned etc. Further it gives theoretical background of emission trading, presents existing research, conclusions and research on policy solutions.

This thesis consists of eight chapters and introduction– full outline of is schematically given in the Figure 1-2:

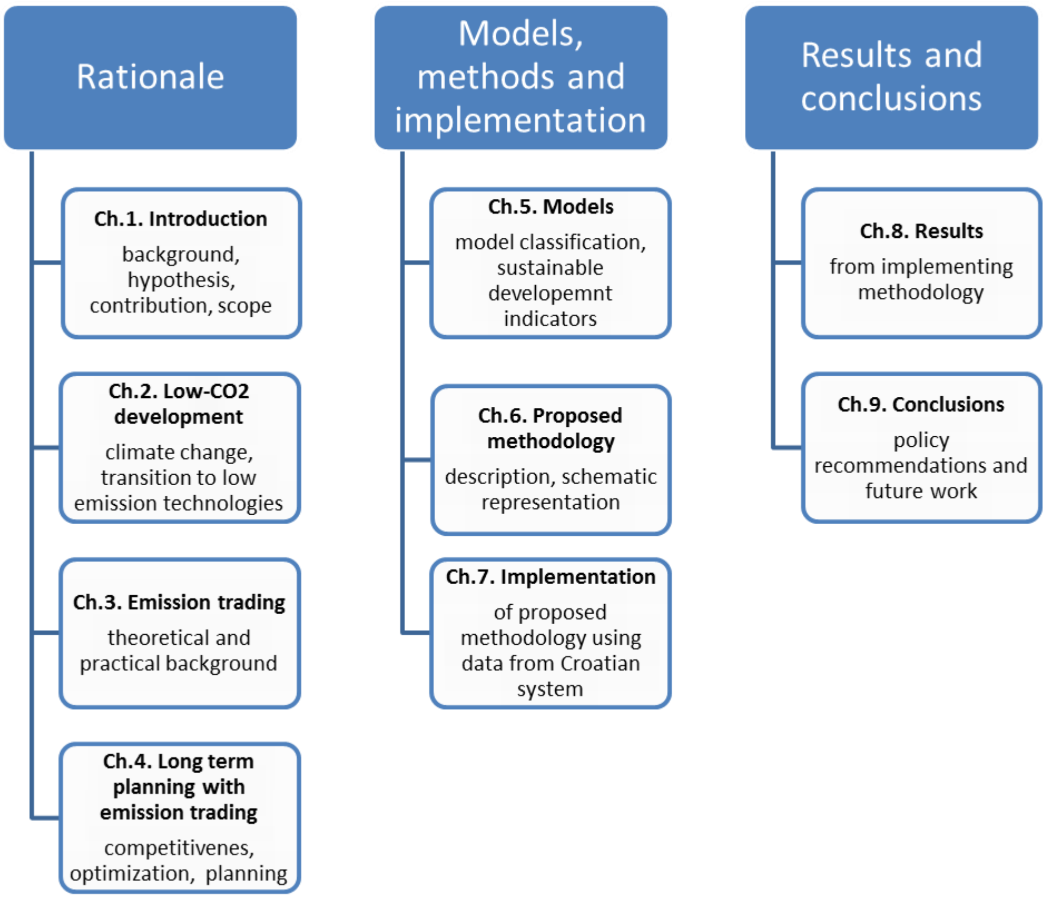


Figure 1-2: Thesis outline with description of chapters and keywords of contents

In Chapter 4, emission trading impacts on long term power system planning are presented. It starts by assessing emission trading impact on a power system through the definition and monitoring of short and long term marginal costs, and the introduction to elements of long term power system planning. Further, it analyses the concept of power system planning in a regulated market – difference between central and decentralized planning and other elements – depending on the chosen perspective. Finally, it finishes with an overview and characteristics of long term power system planning.

Chapter 5 gives extensive classification of energy and power system models – and focuses on main elements. Based on model PLEXOS (model chosen for chosen for the verification of the proposed methodology), to gives introduction to functions of power system model. It also gives introduction to modeling sustainable development indicators – which is an element in proposed methodology.

Chapter 6 is the main part of the thesis. It starts with the description of the proposed methodology in all its elements. Proposed methodology is presented in order to test the set of hypotheses, how climate change and emission trading would impact sustainable development in long term power system planning. In a schematic description of methodological steps, it presents a holistic and comprehensive path of power system planning. Specific steps of methodology and models that need to be developed so they could enable such assessment are further described, as well as the algorithm that needs to be implemented in a power system model.

Chapter 7 presents verification of proposed methodology, models and algorithm developed with data from the Croatian power system. It starts with inclusion of proposed and developed models in schematic representation of methodology. Further implementation steps are described – power system modeling, modeling sustainable development indicators and assessment of climate change impacts on power system planning. Finally, it presents integrative modeling – holistic approach of modeling emission trading and climate change impacts on power system planning by using data for Croatian power system until 2030 (starting year is 2013).

Chapter 8 presents results from verification of proposed modeling, in a way corresponding to previous chapters.

Chapter 9 concludes thesis with a summary of main findings. These are used to shape recommendations for policy makers. It also gives critical review of results and presents area for further research in this field.

Two Annexes are added after chapters, in order to lay down additional research materials for further work. Annex 1 is a list of publications reviewed during the thesis on topics of green growth, green economy and low emission growth strategies; and Annex 2 is a list of reviewed models used in power system modeling.

2. CONTEXT FOR LOW EMISSION DEVELOPMENT

While climate change is often understood as a threat (to people and eco system, to the way we live) [3], low emission development (as a form of development) is understood as an opportunity. It is not just the difference in approach, but focusing on proactive positive approach that low emission development brings, also presents a different way of thinking – and this is especially the reason why it becomes so increasingly important after economic crises in 2008.

This chapter focuses on giving short introduction to climate change as a threat that influences energy sector as the one which has the largest share of anthropogenic greenhouse gas emissions, but also being influenced by climate change on energy demand side (climate variables such as temperature) or on energy generation (climate variables such as rainfall, wind speed etc). It continues with presenting low emission economy concept and how does it impact power system. This chapter presents that different terms such as green economy, green growth and low emission development could point in the same direction. Low emission development of a power system does not only mean power system without emissions, but development on principles of pillars of sustainable development – bringing benefits also to people, environment and economy. Different approaches and strategies for achieving low emission development are presented, with main elements needed for planning.

2.1. Climate change as an imperative for society to change

2.1.1. Climate change as a threat

Threat from climate change was first recognized as a serious international environmental and political challenge at First World Climate Conference in Geneva in 1979 [4]. In addition to the main plenary sessions, the conference organized four working groups to look into climate data, the identification of climate topics, integrated impact studies, and research on climate variability and change. Conference led to the creation of the Intergovernmental Panel on Climate Change (IPCC) by WMO (World Meteorological Organization) and UNEP (United Nations Environmental Programme) in 1988.

IPCC has tasks of reviewing and assessing the most recent scientific, technical and socio-economic information produced worldwide relevant to the understanding of climate change. IPCC does not carry out its own original research, nor does it do the work of monitoring climate or related phenomena itself. A main activity of the IPCC is publishing special reports on topics relevant to the implementation of the United Nations Framework Convention on Climate Change (UNFCCC). The IPCC bases its assessment on peer reviewed and published scientific literature.

The IPCC has prepared and presented their First Assessment Report in 1990 while the Fifth Assessment Report (FAR) was presented in 2014 (outputs from Working Group 1 “The Physical Science Basis” have been published already in 2013 [5]).

The IPCC’s latest report, Fifth Assessment Report describes progress in understanding of the human and natural drivers of climate change, observed climate change, climate processes and attribution, and estimates of projected future climate change. It builds upon past IPCC assessments and incorporates new findings from the past six years of research, and one of its main messages is that continued emissions of greenhouse gases will cause further warming and changes in all components of the climate system, and that limiting climate change will require substantial and sustained reductions of greenhouse gas emissions. Since energy sector is one of the main contributors to the anthropogenic climate change, the reduction of CO2 production requires transition to low emission energy system.

IPCC research documents significant increase in concentrations of the key greenhouse gases over pre-industrial levels due to human activities. Carbon dioxide CO_2 concentrations increased due to fossil fuel burning and land use change, and methane (CH_4) and nitrous oxide (N_2O) due to agriculture. The global atmospheric concentration of these gasses and their source is presented on Figure 2-1.

Main conclusion from IPCC FAR is condensed in the following [5]:

Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased.

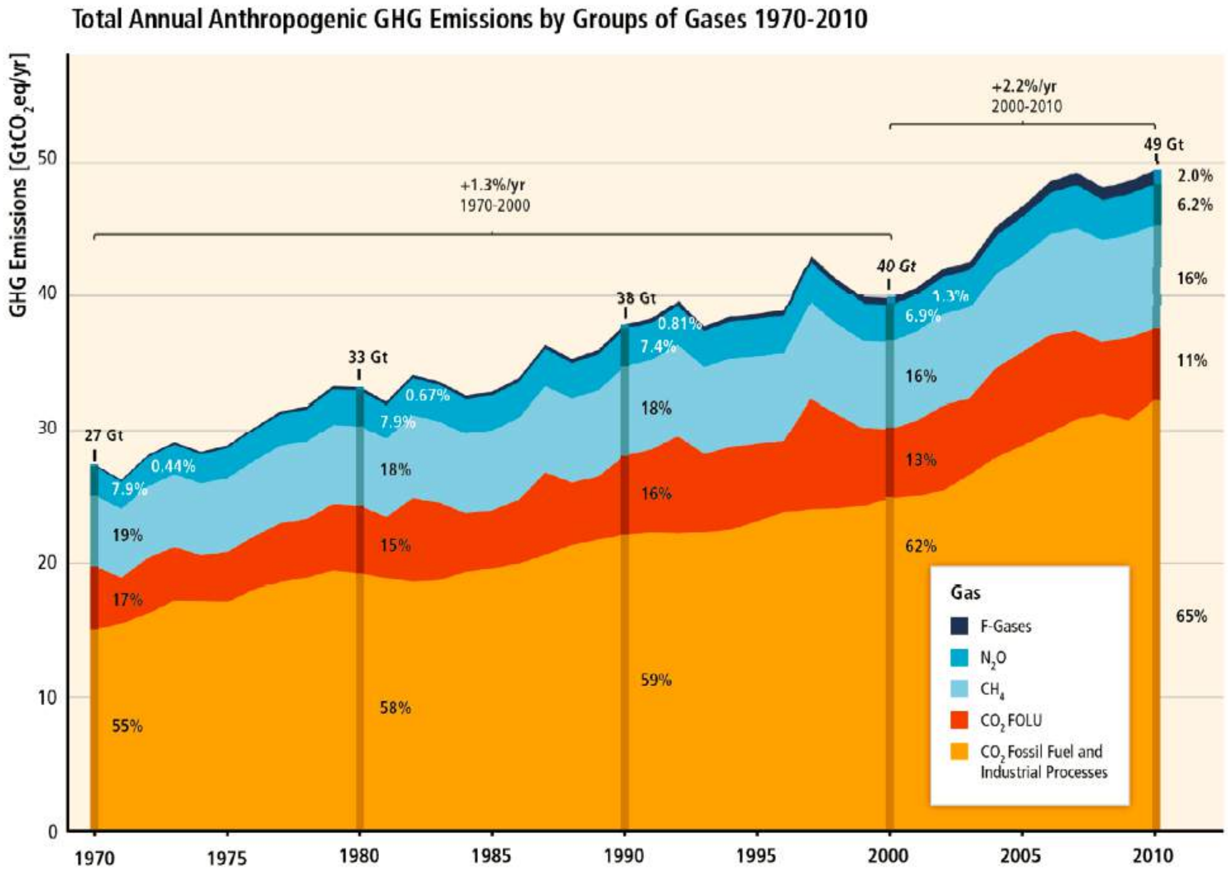


Figure 2-1: Concentration of Greenhouse Gases from 1970 to 2010. Total annual anthropogenic GHG emissions (GtCO2eq/yr) by groups of gases 1970-2010: CO2 from fossil fuel combustion and industrial processes; CO2 from Forestry and Other Land Use (FOLU); methane (CH4); nitrous oxide (N2O); fluorinated gases3 covered under the Kyoto Protocol (F-gases). Source: [5]

Map of the observed temperature change from 1901 to 2012 is given in Figure 2-2. Fifth Assessment Report from IPCC [5] predicts following climate change impacts:

- Most of the climate modeling simulations was performed with prescribed CO2 concentrations reaching 421 ppm (RCP2.6), 538 ppm (RCP4.5), 670 ppm (RCP6.0), and 936 ppm (RCP 8.5) by the year 2100. Including also the prescribed concentrations of CH4 and N2O, the combined CO2-equivalent concentrations are 475 ppm (RCP2.6), 630 ppm (RCP4.5), 800 ppm (RCP6.0), and 1313 ppm (RCP8.5);
- Regarding the future temperature change, global mean surface temperature change for the period 2016–2035 relative to 1986–2005 will likely be in the range of 0.3°C to 0.7°C (medium confidence);
- Increase of global mean surface temperatures for 2081–2100 relative to 1986–2005 is projected to likely be in the ranges 0.3°C to 1.7°C (RCP2.6), 1.1°C to 2.6°C (RCP4.5),

1.4°C to 3.1°C (RCP6.0), 2.6°C to 4.8°C (RCP8.5). The Arctic region will warm more rapidly than the global mean, and mean warming over land will be larger than over the ocean (very high confidence);

- Extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will very likely become more intense and more frequent by the end of this century, as global mean surface temperature increases;
- Year-round reductions in Arctic sea ice extent are projected by the end of the 21st century from multi-model averages. These reductions range from 43% for RCP2.6 to 94% for RCP8.5 in September and from 8% for RCP2.6 to 34% for RCP8.5 in February (medium confidence). A nearly ice-free Arctic Ocean in September before mid-century is likely for RCP8.5 (medium confidence);
- Global mean sea level rise for 2081–2100 relative to 1986–2005 will likely be in the ranges of 0.26 to 0.55 m for RCP2.6, 0.32 to 0.63 m for RCP4.5, 0.33 to 0.63 m for RCP6.0, and 0.45 to 0.82 m for RCP8.5 (medium confidence).

Table 2-1: Extreme weather and climate events: Global-scale assessment of recent observed changes, human contribution to the changes, and projected further changes for the early (2016–2035) and late (2081–2100) 21st century. Source: [5]

Phenomenon and direction of trend	Assessment that changes occurred (typically since 1950 unless otherwise indicated)	Assessment of a human contribution to observed changes	Likelihood of further changes	
			Early 21st century	Late 21st century
Warmer and/or fewer cold days and nights over most land areas	*Very likely* {2.6} *Very likely* *Very likely*	***Very likely*** {10.6} *Likely* *Likely*	*Likely* {11.3}	*Virtually certain* {12.4} *Virtually certain* *Virtually certain*
Warmer and/or more frequent hot days and nights over most land areas	*Very likely* {2.6} *Very likely* *Very likely*	***Very likely*** {10.6} *Likely* *Likely* (nights only)	*Likely* {11.3}	*Virtually certain* {12.4} *Virtually certain* *Virtually certain*
Warm spells/heat waves. Frequency and/or duration increases over most land areas	***Medium confidence*** on a global scale *Likely* in large parts of Europe, Asia and Australia {2.6} *Medium confidence* in many (but not all) regions *Likely*	***Likely***[a] {10.6} Not formally assessed *More likely than not*	Not formally assessed[b] {11.3}	*Very likely* {12.4} *Very likely* *Very likely*
Heavy precipitation events. Increase in the frequency, intensity, and/or amount of heavy precipitation	*Likely* more land areas with increases than decreases[c] {2.6} *Likely* more land areas with increases than decreases *Likely* over most land areas	***Medium confidence*** {7.6, 10.6} *Medium confidence* *More likely than not*	*Likely* over many land areas {11.3}	***Very likely*** over most of the mid-latitude land masses and over wet tropical regions {12.4} *Likely* over many areas *Very likely* over most land areas
Increases in intensity and/or duration of drought	***Low confidence*** on a global scale *Likely* changes in some regions[d] {2.6} *Medium confidence* in some regions *Likely* in many regions, since 1970[e]	***Low confidence*** {10.6} *Medium confidence*[f] *More likely than not*	*Low confidence*[g] {11.3}	***Likely*** *(medium confidence)* on a regional to global scale[h] {12.4} *Medium confidence* in some regions *Likely*[e]
Increases in intense tropical cyclone activity	***Low confidence*** in long term (centennial) changes *Virtually certain* in North Atlantic since 1970 {2.6} *Low confidence* *Likely* in some regions, since 1970	***Low confidence***[i] {10.6} *Low confidence* *More likely than not*	*Low confidence* {11.3}	***More likely than not*** in the Western North Pacific and North Atlantic[j] {14.6} *More likely than not* in some basins *Likely*
Increased incidence and/or magnitude of extreme high sea level	*Likely* (since 1970) {3.7} *Likely* (late 20th century) *Likely*	***Likely***[k] {3.7} *Likely*[k] *More likely than not*[k]	*Likely*[l] {13.7}	***Very likely***[l] {13.7} *Very likely*[m] *Likely*

The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%. Additional terms (extremely likely: 95–100%, more likely than not >50–100%, and extremely unlikely 0–5%) are also sometimes used.

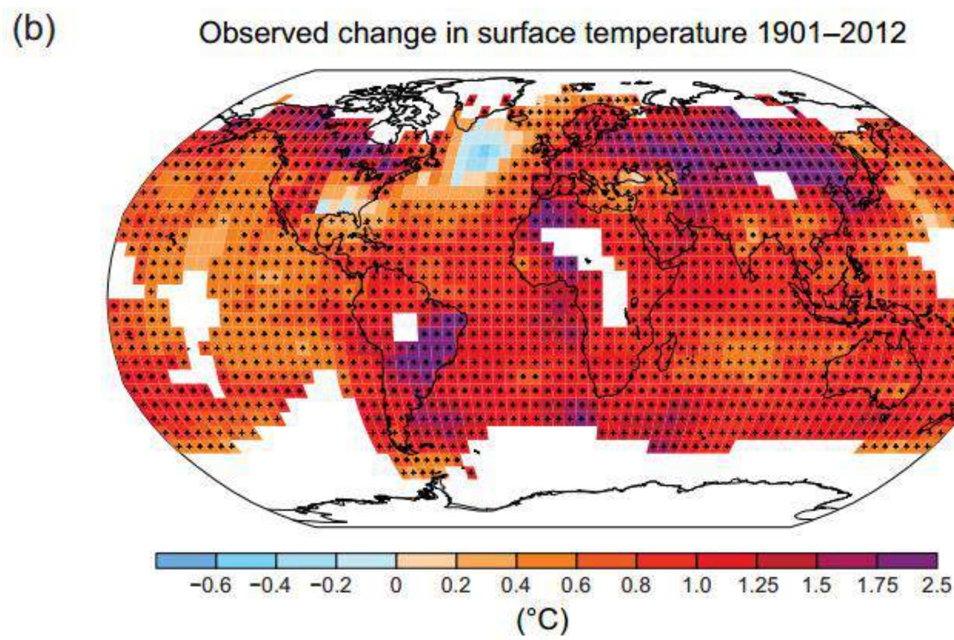


Figure 2-2: Map of the observed surface temperature change from 1901 to 2012 derived from temperature trends determined by linear regression from one dataset (orange line in panel a). Source: IPCC [5]

2.1.2. Global climate negotiations

Last IPCC Report [5] concludes that society will need to both mitigate and adapt to climate change if it is to effectively avoid harmful climate impacts. There are demonstrated examples of synergies between mitigation and adaptation in which the two strategies are complementary, and renewable energy sources are one of them. More generally, the two strategies are related because increasing levels of mitigation imply less future need for adaptation.

900 mitigation scenarios were used in [5] to point to a range of technological and behavioral measures that would allow the world's societies to follow emissions pathways compatible with atmospheric concentration levels between about 450 ppm CO2eq to more than 750 ppm CO2eq by 2100; this is comparable to CO2eq concentrations between RCP 2.6 and RCP 6.0 (high confidence). Report has an important message for climate change negotiations:

- Reaching atmospheric concentrations levels of 430 to 530 ppm CO2eq by 2100 will require cuts in GHG emissions and limits on cumulative CO2 emissions in both the medium and long term. The majority of scenarios reaching 430 to 480 ppm CO2eq by

2100 are associated with GHG emissions reductions of over 40% to 70% by 2050 compared to 2010;

- Limiting peak atmospheric concentrations over the course of the century—not only reaching long term concentration levels—is critical for limiting temperature change;
- In order to reach atmospheric concentration levels of 430 to 530 ppm CO2eq by 2100, the majority of mitigation relative to baseline emissions over the course of century will occur in the non-OECD countries;
- Scenarios reaching atmospheric concentrations levels between 430 ppm and 530 ppm CO2eq by 2100 are characterized by a tripling to nearly a quadrupling of the share of low-carbon energy supply from renewables, nuclear energy, and fossil energy with carbon dioxide capture and storage (CCS) by the year 2050 relative to 2010;
- The Cancún Pledges for year 2020 are broadly consistent with scenarios reaching 550 ppm CO2eq to 650 ppm CO2eq by 2100 without delays in mitigation;
- Infrastructure developments and long-lived products that lock societies into GHG intensive emissions pathways may be difficult or very costly to change;
- Integrated models identify three categories of energy system related mitigation measures: the decarbonization of the energy supply sector, final energy demand reductions, and the switch to low-carbon fuels, including electricity, in the energy end use sectors;
- Evidence from mitigation scenarios indicates that the decarbonization of energy supply is a key requirement for stabilizing atmospheric CO2eq concentrations below 580ppm. In most long-term mitigation scenarios not exceeding 580ppm CO2eq by 2100, global energy supply is fully decarbonized at the end of the twenty-first century with many scenarios relying on a net removal of CO2 from the atmosphere.

UNFCCC is an international environmental treaty adopted at the United Nations Conference on Environment and Development held in Rio de Janeiro in the year 1992. The overall objective of the UNFCCC is ″stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system″ [6]. Entering into force on March 21, 1994, to date 194 countries are parties to the UNFCCC.

The Kyoto Protocol on the UNFCCC was adopted on 11 December 1997, pursuant to Decision 1/CP.3 at the session of the Conference of Parties (COP 3) held in Kyoto and entered into force on 16 February 2005.

The 15th Conference of the Parties (COP 15) held in Copenhagen in December 2009, has taken note of the Copenhagen Accord (CA) - a political declaration which agrees to limit climate change to not more than +2°C above preindustrial levels in the context of equity and sustainable development and reaffirms the developmental aspects of climate change, including low-emission development strategies - even though the Copenhagen Accord does not have a legal binding targets.

The 16th Conference of the Parties (COP 16) held in Cancun in December 2010 adopted the Cancun Agreement, which encourages governments to prepare low-carbon development strategies in the context of sustainable development. The Cancun Agreement [7] "*encourages governments to prepare low-carbon development strategies in the context of sustainable development.*", and *"realizes that addressing climate change requires a paradigm shift towards building a low-carbon society that offers substantial opportunities and ensures continued high growth and sustainable development"*. Developed countries agreed to develop low-carbon development strategies or plans, which will ensure robust foundations for GHG emission mitigation are built in the context of sustainable development that will stand the test of time.

The conference agreed to a legally binding deal, which will be prepared by 2015, and which will take effect in 2020. This means there will be a break in the legally binding commitments of individual countries between 2012 and 2015 although most countries have voluntarily agreed to reduction targets under the Copenhagen accord.

The first commitment period of the Kyoto Protocol began on 1 January 2008 and ended on 31 December 2012. For a subsequent commitment period to begin on 1 January 2013, amendments to the Kyoto Protocol pursuant to its Article 3, paragraph 9, needed to enter into force.

In Doha, Qatar, on 8 December 2012, the "Doha Amendment to the Kyoto Protocol" was adopted. The amendment includes [8]:

- New commitments for Annex I Parties to the Kyoto Protocol who agreed to take on commitments in a second commitment period from 1 January 2013 to 31 December 2020;
- A revised list of greenhouse gases (GHG) to be reported on by Parties in the second commitment period; and
- Amendments to several articles of the Kyoto Protocol which specifically referenced issues pertaining to the first commitment period and which needed to be updated for the second commitment period.

During the first commitment period, 37 industrialized countries and the European Community committed to reduce GHG emissions to an average of five percent against 1990 levels. During the second commitment period, Parties committed to reduce GHG emissions by at least 18 percent below 1990 levels in the eight-year period from 2013 to 2020.

Some of the 37 parties with binding targets in the second commitment period are [9]: Australia, the European Union, Belarus, Iceland, Kazakhstan, Liechtenstein, Norway, Switzerland, and Ukraine. Some parties have participated in Kyoto's first-round but have not taken on new targets in the second commitment period (Japan, New Zealand, and Russia). Other developed countries without second-round targets are Canada (which withdrew from the Kyoto Protocol in 2012) and the United States (which has not ratified the Protocol).

At the conference Rio +20 Earth Summit, official discussion had two main themes: how to build a green economy to achieve sustainable development and lift people out of poverty, including support for developing countries that will allow them to find a green path for development; and how to improve international coordination for sustainable development [10].

2.1.3. EU Strategy to combat climate change

Despite the slow progress of the international negotiations to reach a global legally binding agreement post Kyoto, the EU's affirmative approach to mitigating climate change is aimed at strengthening the EU leadership in global negotiations, to promote green growth internally and for international competitiveness in low carbon technologies.

In order to keep climate change below 2ºC, the European Council reconfirmed in February 2011 the EU objective of reducing greenhouse gas emissions 80-95% below 1990 levels by 2050 in the context of necessary reductions by developed countries as a group [11]. In response to a request by the European Council the EC recently proposed the Europe 2020 Flagship Initiative for a Resource-Efficient Europe [12]. Within this framework the EC is now putting forward a series of long-term policy plans in areas such as transport, energy and climate change.

The "energy-climate" package of proposals of the European Commission also known as the "20-20-20 plan" outlines the EU's energy and climate targets for the year 2020: a 20% reduction in greenhouse gas emissions, a 20% improvement in energy efficiency, and a 20% share for renewable energy sources in the EU energy mix. This package ensures the strict implementation of the unconditional commitment to reduce greenhouse emissions by 20% by 2020 and reduce them by 30% by 2020 if other annex I countries make a comparable commitment and developing countries make verifiable, commitments.

The White Paper on Transport the Energy Efficiency Plan and Roadmap for moving to a competitive low carbon economy in 2050 comprise key deliverables under the Resource Efficiency Flagship. The EC has analyzed the implications of reducing GHG emissions in its "Roadmap for moving to a competitive low-carbon economy in 2050". In the "Energy roadmap 2050" the EC explores the challenges posed by delivering the EU's decarbonisation objective whilst ensuring security of energy supply and competitiveness.

Effort sharing decision

Member State reduction efforts are based on the principle of solidarity. Thus, Member States that currently have a relatively low per capita GDP and thus high GDP growth expectations may increase their greenhouse emissions compared to 2005, while taking measures to limit the growth of their emissions.

> The EU policy on climate change is to strengthen the legislation on GHG emission reductions. Despite of the slow progress of the international negotiations to reach a global legally binding agreement EU has embedded in the national legislation the target of 20% reduction by 2020 compared to base year 1990. The EU adopted the Climate and Energy package and the EU countries have already in place strategies and plan to implement it. Since the EU has made a commitment to deliver long-term low-carbon development strategies, some Member States have already made steps in this direction, or are in the process of doing so, including setting emission reduction objectives for 2050 (e.g. United Kingdom, France, Germany, Hungary, Czech Republic, Finland and Denmark).

Low-Carbon Competitive Economy 2050 Roadmap

This Roadmap will outline possible pathways to a low-carbon economy to reduce greenhouse gas emissions by 80 to 95% by 2050 while improving the EU's energy security and promoting sustainable growth and jobs, including milestones, sectorial contributions and policy implications for the next few years. Roadmap provides guidance on how this transition can be achieved in the most cost-effective way. The EC has also taken the initiative because leading the global transition to a low carbon and resource-efficient economy will have multiple benefits for the EU.

European Commission European Energy Efficiency Directive 2020

Current estimates show the EU may not be on track to achieve its target of reducing its estimated energy consumption for 2020 by 20% (or compulsory 17% target). As a result, new measures on energy efficiency such as the draft proposed Energy Efficiency Directive (EED) are now being proposed to bring the EU back on track to achieve its objective by 2020. Obligatory EU and recommended national legislation and action under the EED will achieve substantial savings in energy generation and distribution and reduced fuel expenditure and GHG emissions.

The current draft EED outlines a number of member states face a legal obligation to establish energy efficiency schemes for households, industries, and transport or bring in policies to drive efficiency improvements. The directive also compels large companies to undergo energy audits, while small businesses and households will be encouraged to do the same.

Governments will also have to improve efficiency in energy generation, transmission, and distribution, and ensure three per cent of the floor area of public sector controlled buildings is renovated to meet minimum energy performance standards, although buildings that have particular architectural merit can be exempted. Member states could face mandatory national targets should their progress be deemed insufficient by a review in 2014.

European Commission White Paper on Transport – “Roadmap to a Single European Transport Area”

This White Paper presents a vision for a low-carbon, resource efficient, secure and competitive transport system by 2050 that improves infrastructure, adopting new legislation to achieve removal of all obstacles to the internal market for transport, promotes new and clean technologies that will allow better management of traffic and vehicles and modernizes transport networks. It outlines benchmarks for achieving the 60% GHG emission reduction target (compared to 1990 levels) set in the EU for the transport sector.

EU ETS

The European Emission Trading System (EU ETS) set up by Directive 2003/87/EC [13] is a system of trading emissions allowances. The first - and still by far the biggest - international system for trading greenhouse gas emission allowances, the EU ETS covers more than 11,000 power stations and industrial plants in 31 countries, as well as airlines. More on ETS is in Chapter 2.1.

A policy framework for climate and energy in the period from 2020 up to 2030

The operational objectives for a 2030 climate and energy policy framework is to:

- Propose coherent targets for climate and energy at the EU level to develop climate and energy policy in a 2030 perspective;
- Propose key indicators for the competitiveness of the energy system and security of energy supply, to keep track of progress over time and get a clear basis for policy response;
- Propose the general direction of the appropriate design of future concrete policies needed to meet 2030 objectives.

Policy framework recognizes that measures to reduce GHG emissions can in principle incentivize both renewables development and energy savings, but e.g. higher levels of the ETS price than those experienced over the last few years would be needed to have considerable impact. Finally, energy savings help to ensure progress towards higher shares of renewables. A share of gross final energy consumption and higher shares of efficient renewables reduce primary energy consumption at any given level of final energy consumption through lower transformation losses.

2.2. Transition towards low emission development

2.2.1. Reasons for transition to low emission economy

The concepts of green economy, low emission development or achieving 100% renewable energy systems became increasingly important after 2008 – as shown by overview of relevant documents presented in ANNEX 1. Since 2008, its importance was visible both in number of published studies, analysis or papers, and also in attention it gained on an international level. There are several reasons mentioned in this literature why that is so; mostly as it became clear that existing model of economic development needs to change, and transition towards different foundations is needed:

- Economic crises that started in 2008, and which were connected with energy crises (record ever price of oil and gas) and which combined and/or resulted in other crises such as food crises (Figure 2-3), political crises; countries in EU that suffered most severe economic crises are the ones with highest share of oil in fuel mix (Figure 2-4).
- Increased warnings that society is in danger of transgressing a number of planetary and social boundaries or ecological limits [14]; contrary to economic philosophy that resources are coming from the market, it is more and more clear they are coming from

the nature. Incidents such as those with deep oil drilling are reminder that harm to society and to environment are becoming higher as less fossil fuels are available;

- Global warming becoming more evident, while on the other side there is a clear lack of political decision on the global level to do serious commitments for this issue;
- Avoid the trap of "growing first, cleaning up later" [15];
- Growing pressure from people excluded from economic growth (1.3 billion still do not have access to electricity, 2.6 billion do not have access to sanitation and 900 million lack access to clean drinking water);
- Given the fact that fossil fuels are still heavily subsidized by the governments in a much higher share than renewable energy or energy efficiency [16], present economic model represents a sort of lock-in against low emission development;
- Most of R&D budgets are directed to conventional energy generation, and since 1882 (Figure 2-5) renewable energy sources were subsidized against conventional by a ratio of more than 1:8 [17];
- Energy security issues – with higher and higher energy import dependences, renewable energy and energy efficiency are becoming more and more important.

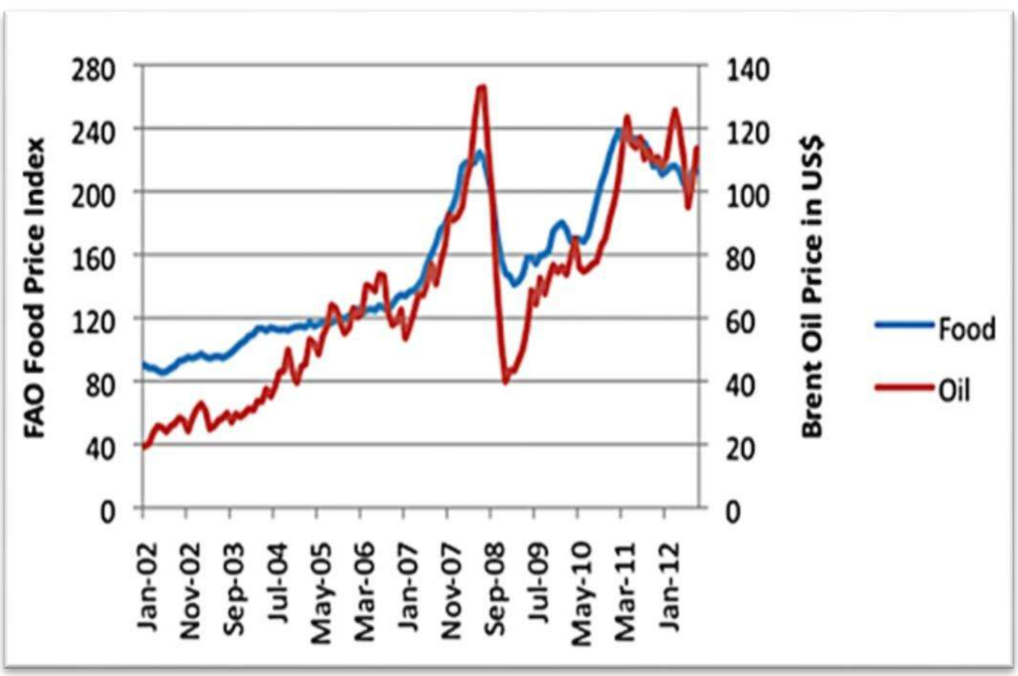


Figure 2-3: Comparation of food and oil prices. Source: [18]

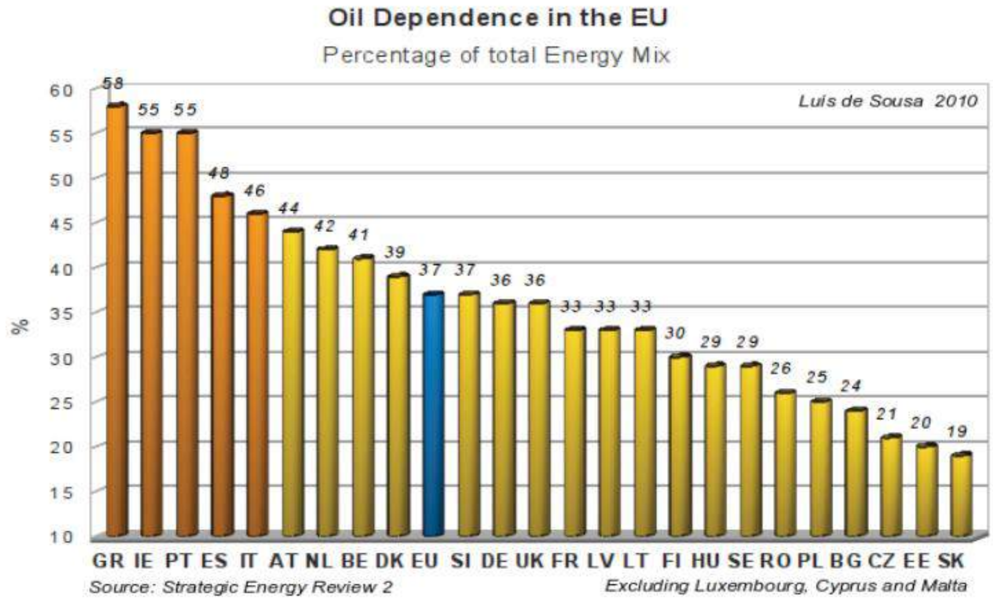


Figure 2-4: Oil dependence in the total energy mix is the highest in the countries where economic crisis was the strongest (so called PIIGS: GR, IE, PT, ES, IT). Source: [19]

In order to find appropriate definition for sustainable development, an international exercise was performed which catalogued, analyzed, and synthesized: written submissions and expert testimony from “senior government representatives, scientists and experts, research institutes, industrialists, representatives of non-governmental organizations, and the general public” held at public hearings throughout the world, in 1987, the United Nations released the Brundtland Report, which included what is now one of the most widely recognized definitions: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." [20]. Much before that, Thomas Jefferson concluded that “No generation can contract debts greater than may be paid during the course of its own existence” [21].

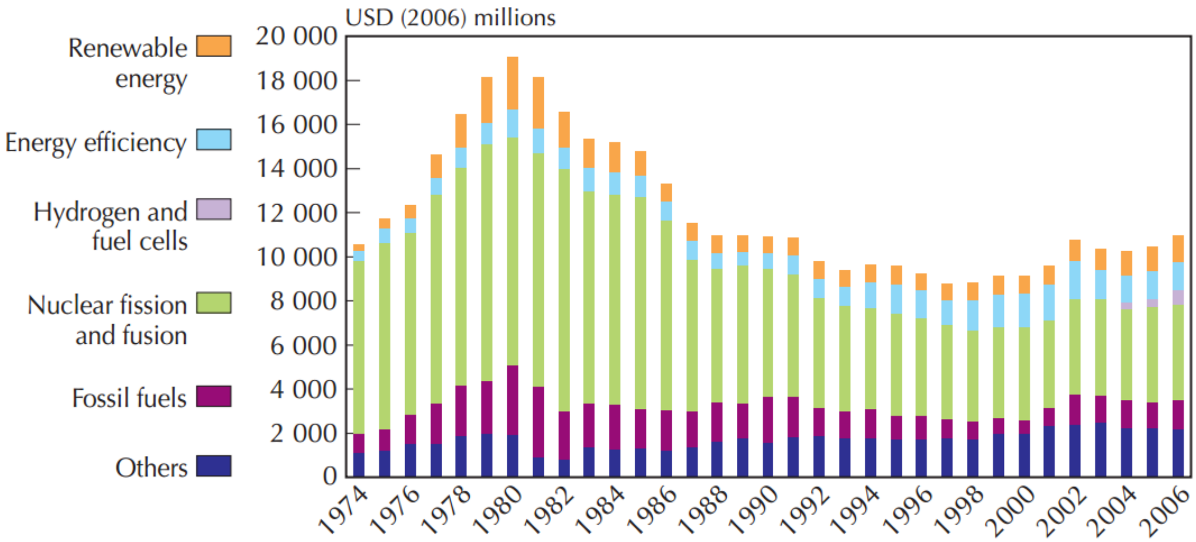


Figure 2-5: Energy Research and Development Budgets, IEA Members, 1974-2006. Source: [17]

According to Brundtland report, the above definition contains within it two key concepts [20]:

- The concept of 'needs', in particular the essential needs of the world's poor, to which overriding priority should be given; and
- The idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs.

Additional key contributions of the Brundtland report to the concept of sustainable development include the recognition that the many crises facing the planet are *interlocking crises* that are elements of a single crisis of the whole and of the vital need for the active participation of all sectors of society in consultation and decisions relating to sustainable development. This was proven additionally in events after 2008 (Figure 2-3, Figure 2-4).

The 1992 Rio de Janeiro Earth Summit ended with industrialized countries signing an agreement, Agenda 21. Sustainability can be defined in many ways and in relation to different issues such as economic and environmentally sound development, reduction of greenhouse gases, responsible use of natural resources, social equity, etc; but the key element is that efforts should not be done separately for environment, society or economy, but affecting all of them.

Amongst numerous commitments, Rio Conference in 1992 called upon governments to develop national strategies for sustainable development, incorporating policy measures outlined in the Rio Declaration and Agenda 21. The Rio Declaration included principles promoting the internalization of environmental costs and the use of economic instruments (Principle 16) as well as eliminating unsustainable consumption and production (Principle 8). Some of challenges concerning sustainability relevant for power system are satisfying minimal production fraction from renewable energy sources, constraints on emissions or minimal energy efficiency goals.

In “Rio + 20” Conference that was organized in 2012 on the 20 years anniversary of original Rio Conference, or so called “Earth Summit 2012”, official discussions had two main themes [22]:

- How to build a green economy to achieve sustainable development and lift people out of poverty, including support for developing countries that will allow them to find a green path for development;
- How to improve international coordination for sustainable development by building an institutional framework.

This 10 day mega-conference was the biggest UN event ever organized (more than 45,000 participants), and it showed global attention and need to achieve sustainable way of economic growth. The primary result of the conference was the nonbinding document, "The Future We Want," which largely reaffirms previous action plans like Agenda 21. In it, the heads of state of the 192 governments in attendance renewed their political commitment to sustainable development and declared their commitment to the promotion of a sustainable future. All nations reaffirmed commitments to phase out fossil fuel subsidies, and recognition was made that "fundamental changes in the way societies consume and produce are indispensable for achieving global sustainable development.”

2.2.2. Different approaches: green growth, green economy and low emission development

As mentioned before, there is clear evidence in a rapidly growing literature and analysis including new publications on topics such as green economy, green growth, low emission development, etc which appeared since 2008. This is appearing from a variety of international organizations (such as UN programs or agencies, World Bank, etc), national governments, think tanks, experts, nongovernment organizations, private sector and others. There is also a huge development of strategies for achieving it on a national level - green economy, green growth and low-carbon development strategies; which occurs in both developed and the developing countries.

There is a big variety of concepts which are appearing in the literature and national strategies – various concepts are mentioned such as low carbon economy, inclusive sustainable development, Green Growth, Green Economy, Low Emission Development, Green Jobs Development

Strategies, Genuine Savings, Genuine Progress, Sustainable Development, Gross National Happiness, De-Growth, Better Life Index, Green GDP etc.

In order to understand if all talk about the same thing or are there clear differences between different mentioned concepts, literature review was performed within this doctoral thesis (full list of reviewed studies/papers/strategies is given in ANNEX 1 of the thesis). For most used concepts, origins and definitions are investigated and described below.

Green Economy

Definition of green economy is similar to definition of sustainable development plus more emphasis on low-carbon development - the "*one that results in improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities. It is low carbon, resource efficient and socially inclusive*" [23].

The term *Green Economy* was first time used in the report *Blueprint for a Green Economy* [24], commissioned to advise the UK Government if there was a consensus definition to the term "sustainable development". This term was used recently by several governments to implement 'green stimulus' packages as part of their economic recovery efforts – "green economy".

Green Growth

As a response to a global financial crises, and as a strategy "lead by example approach" to present in Climate Change Conference in Copenhagen in 2009, the Republic of Korea adopted 'low carbon green growth' as the country's new development vision in 2008. Year later, their *National Strategy for Green Growth* and *Five-Year Plan for Green Growth* was released.

Several definitions of green growth are showing similar building elements to the definition of green economy:

- Growth that emphasizes environmentally sustainable economic progress to foster low-carbon, socially inclusive development (UNESCAP);
- Growth that is efficient in its use of natural resources, clean in that it minimizes pollution and environmental impacts, and resilient in that it accounts for natural hazards and the role of environmental management and natural capital in preventing physical disasters (World Bank);
- Green growth is the new revolutionary development paradigm that sustains economic growth while at the same time ensuring climatic and environmental sustainability. It focuses on addressing the root causes of these challenges while ensuring the creation of

the necessary channels for resource distribution and access to basic commodities for the impoverished. It is also the concept of decoupling economic growth from natural resource depletion (GGGI).

Low Emission Development Strategy (LEDS)

A Low Emissions Development Strategy (LEDS) represents an innovative strategy document which simultaneously decouples GHG emissions from development whilst providing the basis for informed investment and policy decisions to achieve green growth. LEDS form a number of national and sectorial visions and goals to guide policy decisions across development and climate change priorities to move societies towards long term sustainability over the long-run. Furthermore LEDS represent a bottom up participatory approach to seek holistic and appropriate solutions to climate change mitigation.

The initial proposal to introduce LEDS was put forward by the EU in 2008, highlighting how information on planned low-carbon pathways can help to inform the international community about funding needs and priorities and to help gauge the level of global climate change action. Though no formally agreed definition exists, LEDS are generally used to describe forward-looking national economic development plans or strategies that encompass low-emission and/or climate-resilient economic growth. Difference between two previously analyzed concepts (green growth and green economy) would be long-term approach, and encompassing importance of GHG mitigation in environmental aspects.

Review conclusions

Conclusion from paper research within this theses is in line with conclusions from a paper review of different publications [25] - that whilst the concepts of green economy, green growth and low-carbon development have emerged from different sources, through the work of different organizations and with different target audiences, the distinctions among them have become blurred and they are now being used almost interchangeably. A main driver behind the development of these concepts has been the move towards a more integrated and holistic approach to incorporating environment and development in economic decision making, policy and planning. More recent references to an ‘equitable green economy’ or ‘inclusive green growth’ are clearly attempting more holistically to integrate the three dimensions of sustainable development. Low emission development can be seen as a subset of both green growth and green economy.

At the OECD Ministerial Council Meeting in June 2009, 30 members and five prospective members (comprising approximately 80% of the global economy) approved a declaration acknowledging that green and growth can go hand-in-hand, and asked the OECD to develop a green growth strategy bringing together economic, environmental, technological, financial and development aspects into a comprehensive framework [26].

What is found is that the similar building elements in these strategies are found in all of them:

- Making pollution more costly by reforming environmentally harmful subsidies, taxes and charges, pricing negative environmental externalities;
- Innovation and green technology development and diffusion; reforms that improve the working of product markets; innovation policies;
- Skills development and labor – education for "green jobs";
- Market policies such as regulations and standards for leveraging long-term investments for green infrastructure technologies (sending clear signals for investors);
- Sustainable consumption - greening consumer behavior address information failures, measurement issues and behavioral biases;
- Creating an incentive road map that increasingly values long-term sustainable development in investment and financial transactions;
- Increasing financial resources and partnerships (private and public) for financing large-scale sustainable development; redirecting public investment and green public procurement;
- Rethinking measuring progress in sustainable development by creating a set of sustainable development indicators.

The message that is found in this literature is that:

- Greening growth is necessary, and with setting up proper scheme could be affordable;
- Obstacles to greening growth are political and behavioral inertia, and a lack of financing instruments;
- Green growth should look at what needs to be done in the next 5-10 years;
- We cannot assume that green growth will be inclusive and equitable;
- The way forward requires a blend of economics, political science, and social psychology;
- There is no single green growth model.

A comparation of the current “state of the alternatives” to Growth-as-Usual done by Atkisson [15] considers only concepts and indicators in active use by some government, somewhere in the world. His report concludes three things:

- That national government interest in shifting emphasis away from the GDP, and toward measuring happiness and well-being, emerged almost simultaneously with the financial crisis of 2008;
- The financial crisis may have helped opened the door for New Economic thinking, and especially for new measures of happiness and well-being; but the old economics is still very much in charge of national and international policy.
- The combined effect of all of geopolitical pushes and pulls on the world can be summarized as a strong tendency to continue pushing for growth — but with a good possibility for global consensus forming around the concept of Green Growth, which represents a compromise position: it may be seen as a weak step (or even a problematic development) from the perspective of serious growth critics, but it has the potential to unite many different and be transformative.

Atkisson put in graphic representation range (Figure 2-6) between De-Growth and Growth as Usual, and concludes that the financial crisis is causing most governments to act strongly to push for Growth as Usual; but some governments are using the crisis to invest in a shift to Green Growth - in order for Green Growth to emerge as the “new normal,” it may be enough to have a sizeable minority of nations and companies lead change in that direction. The private sector remains committed to Growth as Usual, but more of them are leading to Corporate Social Responsibility towards Green Growth.

Low emission development is irrelevant of GDP change so it is put in the middle of the spectrum, with democracy movements active in the world today that all begin from a position of neutrality on the Growth as Usual/De-Growth, or poverty reduction where it is also the case (but where push is towards Growth.

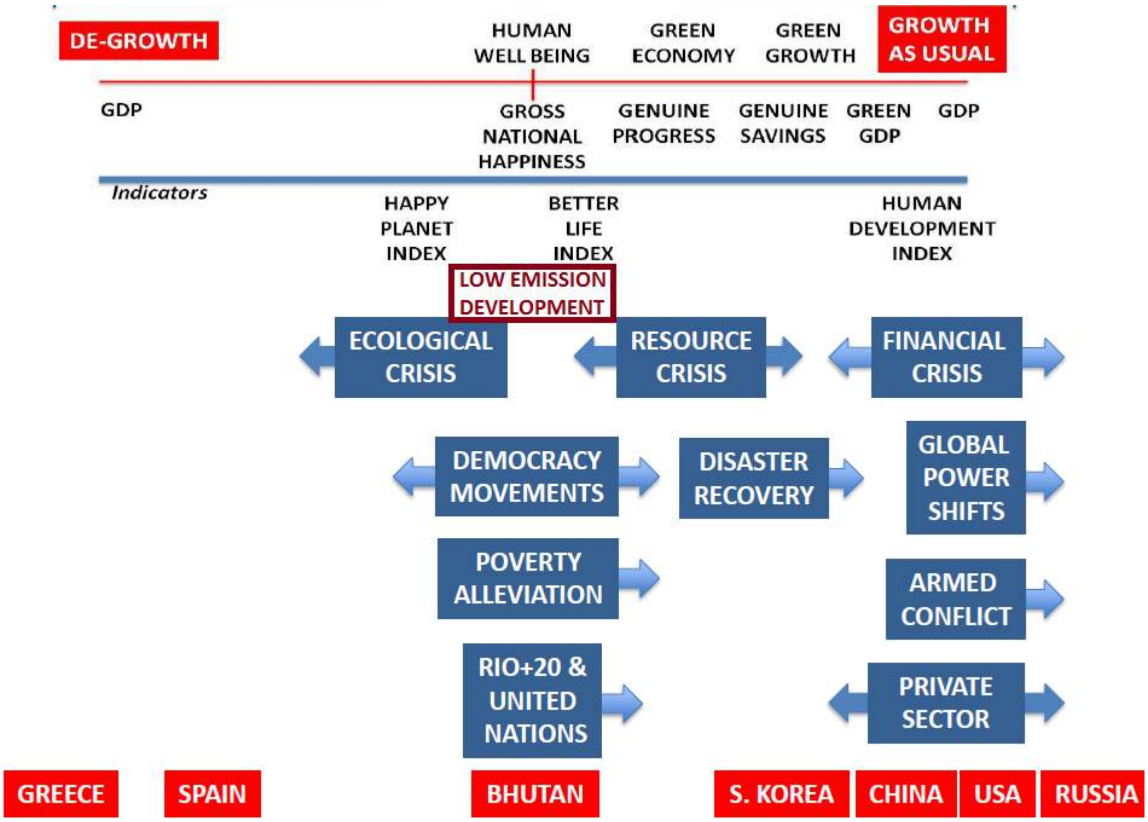


Figure 2-6: Graphic representation of geopolitical issues on the near-term development of New Economics ideas. Source: [15]

2.2.3. Low Emission Development Strategies experiences

Despite a range of LEDS development tools and the common elements of LEDS, there is no accepted international methodology on how they should be designed and what elements they should contain [27]. Typically LEDS vary widely in their content and development approach. One explanation is that LEDS are first of all country-driven and correlated to the development priorities of a country. The unique intention of a LEDS is to integrate country's economic, social and environmental development plans (together considered sustainable development) with climate change planning. As LEDS incorporate the development priorities of a number of sectors there is an imperative to develop an evidence base and narratives that build a political case for LEDS. This can consist of the positive practical implications of LEDS impacts on jobs, economic growth, global competitiveness, renewable energy sectors, energy access and security, health and mobility [28].

First moves towards low emission development were done by developed countries. Major Economies Forum in Italy in July 2009 where leaders declared that their countries would prepare low-carbon growth plans (the 17 major economies participating in the MEF are: Australia, Brazil, Canada, China, the European Union, France, Germany, India, Indonesia, Italy, Japan, Korea, Mexico, Russia, South Africa, the United Kingdom, and the United States). After that, LEDS have attracted interest in the climate negotiations as a soft alternative to voluntary or obligatory GHG emission reduction targets in developing countries [27].

The concept has been included in the negotiating texts under the UNFCCC since the run up to COP15 in Copenhagen in 2009 and is part of both the Copenhagen Accord and the Cancun Agreements, which recognize that a LEDS is indispensable to sustainable development and that incentives are required to support the development of such strategies in developing countries.

As low emission development strategies are the most developed documents that focus on how to put forward low emission technologies and which one to use, a review of components of existing LEDS in several countries was completed (Moldova, Japan, South Korea, Turkmenistan, United Kingdom, Slovenia, Mexico, Czech Republic and European Union). The results of this review were analyzed on the most important structure blocks:

Time frame: Outlining the timeframe of the strategy is important as it indicates the period within which proposed management measures are to take place and their associated emissions projections/scenarios. The timeframe for LEDS proposed by the EU is 2011-2050. A short term LEDS usually lasts until 2020 and longer term ranges for emissions reductions for key sectors until 2030 or 2050, up to 2068 for Japan. Short term strategies such as that of Moldova focused on prioritizing existing and proposed actions and measures to cut emissions until 2020. Whereas longer term strategies of UK, Korea, Japan, Slovenia focused on wider sectorial changes necessary to stimulate the green economy whilst reducing emissions overtime.

Vision/goal: An over-arching vision or goal can help guide policy decisions across development and climate change priorities over the long-run. The EU Roadmap for moving to competitive low carbon economy [11] is a key deliverable under the Resource Efficiency Flagship. It presents a Roadmap for possible country action up to 2050, and outlines milestones which would show whether EU countries are on course for reaching their energy targets, policy challenges, investment needs and opportunities in different sectors, bearing in mind that the 80 to 95% reduction objective in the EU will largely need to be met internally across countries. The LEDS form a number of national and sectorial visions and goals to guide policy decisions across development and climate change priorities over the long-run. Economic stimulation, green sector growth and implementation of emissions mitigation across all sectors of the economy are central to all LEDS. The focus is set on education, training and job creation aligned with green industry growth in order to achieve sustainable development and emissions reduction goals.

Table 2-2: Overview of existing National climate change strategies, and Low emission development strategies (Source: [27])

	Country	Name and timeframe
Annex I*	Australia	Australia's Action on Climate Change
	Austria	Austria Climate Strategy (2008-2012)
	Belarus	Belarus National Program for Climate Change Mitigation Measures in 2008-2012 (pending)
	Belgium	The Flemish Climate Policy Plan 2006-2012 Walloon Sustainable Development Plan to 2020 (PMDE) (2009-2020)
	Bulgaria	Bulgaria National Action Plan on Climate Change 2005-2008
	Croatia	Croatia National Climate Change Strategy and Action Plan
	Czech Republic	National Program to Abate the Climate Change Impacts in the Czech Republic (2004-2020)
	EU	EU Climate and Energy Package (2008-2020)
	Finland	Finland National Climate and Energy Strategy (2008-2020) Finland Foresight Report on Long-term Climate and Energy Policy (2009-2050)
	France	Le Plan Climat de la France (2005-2020)
	Germany	Germany Integrated Energy and Climate Program (2007-2020)
	Hungary	Hungary National Strategy on Climate Change (2008)
	Iceland	Iceland Climate Change Strategy (2007-2050)
	Ireland	Ireland National Climate Change Strategy 2007-2012
	Italy	Italy Climate Change Action Plan (pending)
	Japan	Japan Action Plan for Achieving A Low-Carbon Society (2008-2050) Japan Innovation for Green Economy and Society (2009) The New Growth Strategy (Basic Policies): Toward a Radiant Japan (2009)
	Latvia	Latvia Climate Change Mitigation Programme for 2005-2010
	Luxembourg	Luxembourg CO_2 Reduction Action Plan (2006)
	Netherlands	Netherlands Clean and Efficient: New Energy for Climate Policy (2007)
	New Zealand	New Zealand Climate Change Solutions: An Overview (2007)
	Norway	Norwegian Climate Policy (2008)
	Poland	Poland's National Climate Strategy (2003-2020)
	Portugal	Portugal National Climate Change Programme (2004)
	Romania	National Action Plan on Climate Change of Romania 2005-2007
	Russia	Russia Green Growth Plan of Action
	Slovenia	Slovenia Operational Programme for Limiting Greenhouse Gas Emissions (2006)
	Spain	Spanish Climate Change and Clean Energy Strategy (2007-2020)
	Sweden	Sweden: Towards a Low Carbon Society (2009-2011)
	Tanzania	Tanzania National Action Plan on Climate Change (1997)
	Turkey	Turkey National Climate Change Action Plan (pending)
	UK	UK Low Carbon Transition Plan (2009-2020)
Non-Annex I	Bangladesh	Bangladesh Climate Change Strategy and Action Plan (BCCSAP) (2008-2018)
	Brazil	Brazil National Plan on Climate Change (2008-2030)
	Chile	Chile National Climate Change Plan (2008-2012)
	Costa Rica	Costa Rica National Strategy on Climate Change
	China	China National Climate Change Program (2007-2010)
	Guyana	Transforming Guyana's Economy While Combating Climate Change (2010-2030)
	Honduras	Honduras National Climate Change Strategy
	India	India National Action Plan on Climate Change (2008-2017)
	Indonesia	Indonesia National Action Plan Addressing Climate Change (2007-2050) Climate Change Sectoral Roadmap (pending)
	Israel	Israel Climate Change Action Plan (pending)
	Korea	Korea Green Growth Strategy (2008-2068) Korea 1st National Basic Energy Plan (2008-2030) Korea Comprehensive Plan on Combating Climate Change

Priority programmes and policies: An indication of policy priorities for mitigation and adaptation integrated with an economic development strategy can identify synergies and trade-offs. The EU Roadmap takes a sectorial oriented approach: "Low carbon innovation: a sectorial perspective". With the exception of transport sector, all sectors of the EU economy; power, industry, transport, residential and services, agriculture and other non-CO_2 have the potential for reductions in the short term (until 2020), in the long term, until 2030 and 2050 all sectors are targeted to make reductions. Similarly the priority programs within the LEDS reviewed include reduction in emissions across major economic sectors, including industrial activities, energy generation and efficiency, transport, building, and land use sectors. Some countries provide more detailed measures, the UK and Japan for example outline quite specific industry measures to reduce emissions such as specific energy efficiency plans in the building sectors, nuclear power in energy and ultralow emissions vehicles' in transport (UK) and community based initiatives (Japan). In addition to sectorial measures outlined, Turkmenistan and the Czech Republic intend to implement additional regulatory and institutional frameworks and acts related to several sectors to facilitate emissions reductions. Priority programs should focus upon the specific areas of each country in line with their EU and UNFCCC requirements.

Assessment of current situation: Is present in all LEDS, both on international (understanding of global initiatives to curb climate change in relation to the UNFCCC and Kyoto Protocol) and national (a demonstrated understanding of national major GHG emitting sectors and socio-economic indicators is fundamental to determining a path forward).

Emission projections: Planned pathways for business-as usual and with mitigation measures emissions scenarios can help provide a sense of the national emission trajectory with and without mitigation measures.

Mitigation potential: Outlining the emissions reduction potential of different measures and the timeframes for implementation provides LEDS with output goals.

Costs of mitigation measures: Expected costs of mitigation measures and indication of the need for various finance options. With the exception of Turkmenistan and Japan all countries provided a minimal level of information on expected costs of mitigation measures. National strategies have provided this information in different ways. The UK provides cost estimations in an analytical annex to the LEDS. Moldova provides a thorough estimation of costs and a marginal abatement cost curve analysis. Slovenia designates the distribution of GDP and a climate change fund to assist in implementation of mitigation measures. Mexico explores the cost effectiveness ranges of potential mitigation actions derived from marginal abatement cost curve calculations contained in independent national studies. The Czech Republic estimates the total costs of emissions reductions for the period 2000-2020 using cost abatement curves. Korea provides costs associated with public and private investments to address the effects of climate change.

Finance: Alignment of priority policies with national budget and an indication of financing needs can be important information to communicate to domestic and international stakeholders.

Vulnerability assessment: Indications of how a country may be impacted by climate change can help engage stakeholders, including the general public, and can help identify adaptation needs and the range of possible adaptation outcomes.

Institutional arrangements: Assessment of responsible institutions for implementation provides clarity on responsibilities across government and contributes to effective policy implementation. Moldova, Slovenia and Mexico clearly indicated which institutions would be responsible for implementing actions and thus providing clarity on responsibilities across government which can contribute to effective policy implementation. These countries outlined that all government ministries, in particular the ministries of agriculture, energy, industry, economy, development and transport will be involved. Some countries have said a working group between these government bodies (committee) will be formed to implement the LEDS. Also, "champions" with convening power and agreement between sectors on the roles and responsibilities can all be achieved and outlined in LEDS negotiations with stakeholders.

Barriers to implementation: It is important to outline possible technical, institutional and policy challenges to the implementation of various mitigation measures early in order to avoid and address these issues if they should arise. The EU Roadmap identifies a number of financial barriers to successful implementation of any LEDS such as an absence of economic stimulus plans and investment frameworks. Other barriers included international barriers created when action taken by Europe is not taken by trade partners and competitors in other countries, thus threatening trade exposed industry. Some countries address such barriers to implementation exploring an array of financial, technological and institutional barriers which constrain the effective, large scale deployment of low GHG emissions technologies and various mitigation measures in key sectors.

Relation to other Economic/Development plans and strategies: Considering the unique intention of a LEDS to be the integration of economic, social and environmental development plans (long-term sustainable development plans) and climate change planning, the extent to which policy priorities are incorporated into other development plans, budgets or are aligned with other sources of financial support help assess the extent to which the national climate change strategies in these countries are integrated with development planning. The EU Roadmap outlines the intended framework and is now putting forward a series of long-term policy plans in areas such as transport, energy and climate change.

Sustainable Development characteristics: Consideration of the intended social, economic and environmental impacts associated with mitigation and adaption measures. In order to track to which extent low emission is happening, it is important to measure it with set of indicators. Review of LEDS shows that all strategies relate to sustainable development, some outline this in short statements whilst others integrate the idea of sustainable development throughout the strategy, and some are proposing measuring to ensure it is on track.

Generally, a review of existing LEDS reveals that developed countries generally have more ambitious LEDS. Under these LEDS the most ambitious and comprehensive approach is taken, a country first develops a general low emissions development concept and through workshops and consultation develops a full LEDS containing a set of concrete mitigation actions (NAMAS) ensuring quantifiable emissions reductions in various sectors [27].

Table 2-3: Review of elements in different LEDS [29]

	Time frame until 2020.	Time frame until 2050. (or Japan until 2068)	Vision/ goals	Proposed measures	Costs (minimal level of information)	Institutions included	Barriers	Connection with other strategies	Sustainable development indicators
Moldavia	•		•	•	•	•	•	•	•
United Kingdom		•	•	•	•		•	•	•
South Korea		•	•	•	•		•	•	•
Japan		•	•	•			•	•	•
Slovenia		•	•	•	•	•	•	•	•
Mexico	•		•	•	•	•	•	•	•
Turkmenistan	•		•	•			•	•	•

This process is most suitable for countries with more advanced national climate change processes with good information and analytical basis such as GHG projections. Alternatively it is suggested that a sectorial focused LEDS with a focus on appropriate mitigation actions or

NAMAs offer countries limited in their capacity to undertake more comprehensive LEDS an option to better ensure the coordination of the implementation of actions and MRV. There is also a dilemma whether LEDS should support mitigation and adaptation; although ideally LEDS should support both oftentimes they focus on mitigation alone where capacity may be limited to coordinate adaptation.

2.2.4. Existing strategies and roadmaps to achieve emission free energy or power system

Large number of scientific reports and publications appeared after 2008, all demonstrating that 100% emission free energy or power system, or 100% renewable energy or power system is technically and economically feasible (documents from ANNEX 1: ECF 2010, PwC 2010, PwC 2011, WWF and Ecofys 2011, EREC: Rethinking 2050, 2010). In most of them focus was solely on Europe. Conclusion in most of them was that decarbonized power system (in Europe) could be reached if one of the following is reached, or a modest combination of the following:

- Strong acceptance of public, governments and local authorities for inclusion of renewable energy sources, energy efficiency and sustainable consumption (using almost every available roof for photovoltaics, all available biomass for energy generation and using available wind spots for wind energy);
- Scaling up nuclear power on a considerable level;
- Using large scale commercially available carbon capture and storage technology (CCS) on nearly every thermal power plant;
- Importing solar and wind power from North Africa.

Overview of publications, reports and studies in ANNEX 1 recognizes that key components to introduce emission free or 100% renewable power system are:

- Regional power system based on SuperGrid (centralized long term planning to transform existing infrastructure);
- Need to build on existing EU directives for promotion of RES, EE and phasing out fossil fuel subsidizes – setting firm and binding targets for Member States for RES). Since Lisbon treaty signed by EU Member States (MS) in 2007, national energy policies are not only concern of MS, but jointly Union and MS;
- Scaling up all forms of RES;
- Unified European power market (first smaller one and then getting them together);

- RES electricity production at the most suitable sites by the most suitable technologies;
- Affordable energy, eradication of energy poverty;
- Importance of internalizing costs and social externalities;
- Importance of creation of new jobs – more than one million people employed in RES in EU in 2011, which according to various estimations might rise to 2,7 million by 2020 and 4,4 million in 2030;
- Prospects of nuclear power after Fukushima: what mix of fuel sources to replace reduced or delayed nuclear capacity?
- Over 50% of world population lives today in urban environments – need for smart cities that use energy more efficiently, generate heat, fuel and electricity from RES, with smart energy buildings, efficient public transport;
- After 2020, or 2030 significant increase in electricity consumption expected (heat pumps) and shift of transport (cars, trains) to electrical;
- Vision until 2050 is needed – longer term perspective and broader geographical coverage!

Even though technically and economically feasible, one of the key needs recognized for 100% renewable power system are “softer instruments” - political commitment, market regulations and public acceptance. The later one is becoming increasingly important, with growth of regionally focused protests against RES and not-in-my-backyard (NIMBY) syndrome, opposite than nuclear protests which are nationally organized. Good example for this is France, where not a single wind power plant was approved in 2010 due to local protests [30].

The climate and energy package accepted by EU in 2008 is a set of binding legislation which aims to ensure the European Union meets its ambitious climate and energy targets for 2020. National Renewable Energy Action Plans (NREAP) set by EC Directive 2009/28, which requires each EU MS to submit Action Plan on how they will meet their 20% renewable energy target in 2020. What can be seen in national NREAPS is mostly growth in wind energy, biomass and photovoltaics, while there is no important increase expected in electricity generation from hydro power plants. What can be seen from submitted first version of national NREAPs [31] is that the largest surpluses of generated electricity from renewables are expected from Germany (+2,7 Mtoe) and Spain (+1.4 Mtoe), while largest import from Italy (-1.2 Mtoe). With lowering feed in tariffs but also investment cost for PV and wind energy in some of these countries, one can expect that in further NREAP reviews some of these figures will be changed.

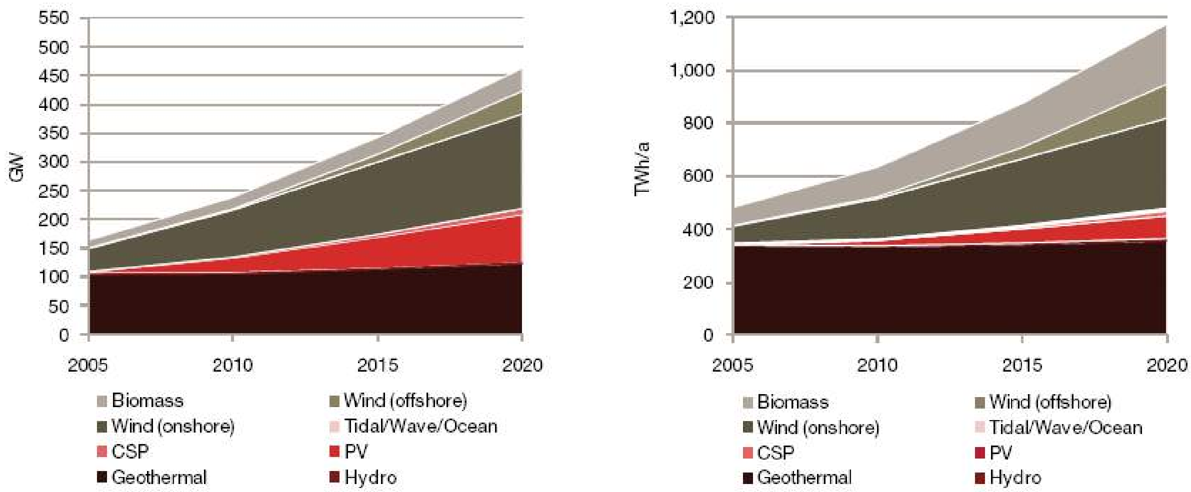


Figure 2-7: Renewable capacity (GW) and electricity generation (TWh/a) as given in the NREAPs of the EU member states. Source: [31]

ADAM project (*ADAM ADaptation And Mitigation Strategies: supporting European climate policy*), was estimating the costs of emission free energy by which the extent to which existing climate policies can achieve a socially and economically tolerable transition to a world with a global climate no warmer than 2°C above pre-industrial levels. Research took place among 26 research institutions across EU. Project is trying to anticipate the costs of decarbonizing electricity sector in Europe, and results are showing at most costs will be 1-2 GDP for coming decades [32].

3. EMISSION TRADING - THEORETICAL AND PRACTICAL BACKGROUND

In order to understand impact of emission trading on competitiveness increase of low emission technologies, impact of emission trading on a power system needs to be understood properly. This chapter deals with theoretical background of emission trading, done research and observed conclusions and research on policy solutions. It starts by introduction to existing emission trading schemes and concept, after which theoretical approach to emission trading impacts on a power system is analyzed, and checked against existing research.

3.1. Emission trading and emission markets

3.1.1. Emission trading

Emission trading could be understood as an instrument to minimize costs for achievement of ecological target, where local distribution is not important for environment but the total impact. This applies to climate change and greenhouse gases. Emission trading can therefor minimize costs for emission reduction because it enables that emissions are reduced there where marginal costs for emission reduction are cheapest.

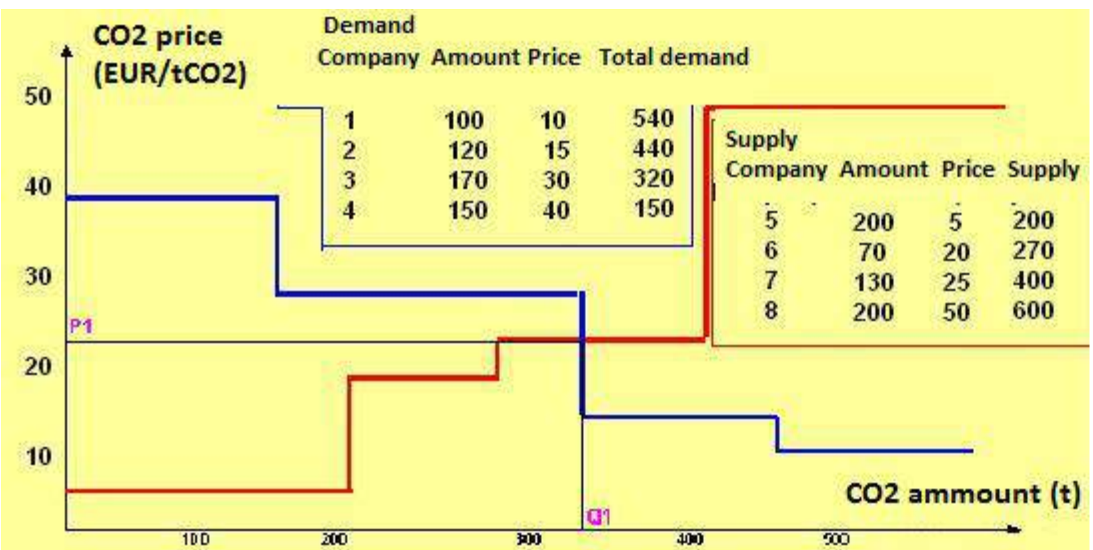


Figure 3-1: Representation of emission trading as a meeting point on demand and supply side for quantity of emissions and price reductions within different companies [33]

Emission trading could have very important impact on power system development. As large-scale energy conversion technologies have a life of several decades and hence a turnover of only

1–3% per year, the need for immediate action to make significant impact in the longer term is very high [1]. If emission trading manages to influence policy decisions taken today, it will affect the rate of deployment of carbon-emitting technologies for several decades.

Fourth Assessment Report that IPCC published in 2007 [1] analyses several policy instruments to reduce emissions over proposed criteria, with tradable permits being one of them (Table 3-1).

Table 3-1: National environmental policy instruments and evaluative criteria. Source: [34]

Instrument	Criteria			
	Environmental effectiveness	**Cost-effectiveness**	**Meets distributional considerations**	**Institutional feasibility**
Regulations and standards	Emission levels set directly, though subject to exceptions Depends on deferrals and compliance	Depends on design; uniform application often leads to higher overall compliance costs	Depends on level playing field; small/new actors may be disadvantaged	Depends on technical capacity; popular with regulators, in countries with weak functioning markets
Taxes and charges	Depends on ability to set tax at a level that induces behavioural change	Better with broad application; higher administrative costs where institutions are weak	Regressive; can be improved with revenue recycling	Often politically unpopular; may be difficult to enforce with underdeveloped institutions
Tradable permits	Depends on emissions cap, participation and compliance	Decreases with limited participation and fewer sectors	Depends on initial permit allocation, may pose difficulties for small emitters	Requires well-functioning markets and complementary institutions
Voluntary agreements	Depends on programme design, including clear targets, a baseline scenario, third-party involvement in design and review, and monitoring provisions	Depends on flexibility and extent of government incentives, rewards and penalties	Benefits accrue only to participants	Often politically popular; requires significant number of administrative staff
Subsidies and other incentives	Depends on programme design; less certain than regulations/ standards.	Depends on level and programme design; can be market-distorting	Benefits selected participants; possibly some that do not need it	Popular with recipients; potential resistance from vested interests. Can be difficult to phase out
Research and development	Depends on consistent funding, when technologies are developed, and polices for diffusion. May have high benefits in long-term	Depends on programme design and the degree of risk	Initially benefits selected participants, Potentially easy for funds to be misallocated	Requires many separate decisions; Depends on research capacity and long-term funding

Results of analysis of various options for emission reduction suggest the following:

- Regulatory measures and standards provide environmental certainty, but do not generally give polluters incentives to develop new technologies to reduce pollution;
- Taxes and charges (that could be applied to GHG emissions) are cost effective as they are in control of marginal cost of emission reduction; but they cannot guarantee a particular level of emissions;
- Tradable permits – emission trading gets popular for policy makers as volume of emissions allowed determines the carbon price and the environmental effectiveness of this instrument, but needs very careful design if it is to be effective. Uncertainty in the price of emission reductions under a trading system makes it difficult to estimate the total cost of meeting reduction;

- Voluntary agreements between industry and governments cannot guarantee delivering results beyond business-as-usual, but several existing platforms worldwide show accelerated use of best available technologies and emission reductions;
- Financial incentives (subsidies and tax credits) are best used to overcome barriers to the penetration of new technologies as their economic costs are often higher than other mentioned instruments;
- Research and development can be an important instrument to ensure that low GHG-emitting technologies will be available in the long-term, but are more focused on later-to-come technologies.

Three most commonly recognized types of emission trading systems are [33]:

a) Cap-and-trade

In this type of emission trading system, regulatory body (such as government) sets maximally allowed emission quota within defined period, and provides a definite quantity of emission allowances (tone of CO_2). Every participant in the market is granted specific amount of emission allowances, mostly based on their past emissions. For each emission tone emitted, one emission allowance is being retired (used), and at the end of reporting period all market participant need to have enough emission allowances to cover real amount of their emissions. Starting emission allowances are either granted for free, either traded on auction process or some combination of these two.

b) Rate-based

In this type of emission trading system, specific amount of emissions per unit of product is set (such as tCO_2/MWh for generated energy). Idea is to promote production efficiency without limiting economic growth. If higher efficiency than set standard is being achieved, surplus could be sold to other participants in this emission reduction scheme. Those that cannot meet the set emission targets need to purchase surplus from others.

c) Baseline-and-credit

This type of emission trading system usually includes subjects that are not obliged to limit their emissions. These are the projects that are lowering emissions below set baseline value (set in referent scenario). Such saved emission surplus (called emission credit) could be used to compensate emissions somewhere else, or sold on the market (Kyoto Mechanism Clean Development Mechanism is representative of this type). The main difference against Cap-and-trade system is generation of new emission rights (allowances, credits) in this case, instead of in cap-and-trade system amount of emission allowances remains the same.

3.1.2. Emission markets

In several countries and regions worldwide emission trading markets already exists or are in the phase of preparation or discussion. However, these markets are fragmented or partly connected and they function under different organizational criteria or legal types. All these markets together created very active secondary markets whose value according to the World Bank was 176 billion USD in year 2011 (value of emission allowances and volume of transactions), and forecasts are saying that by 2020 it would grow up between 2000-3000 billion USD [35].

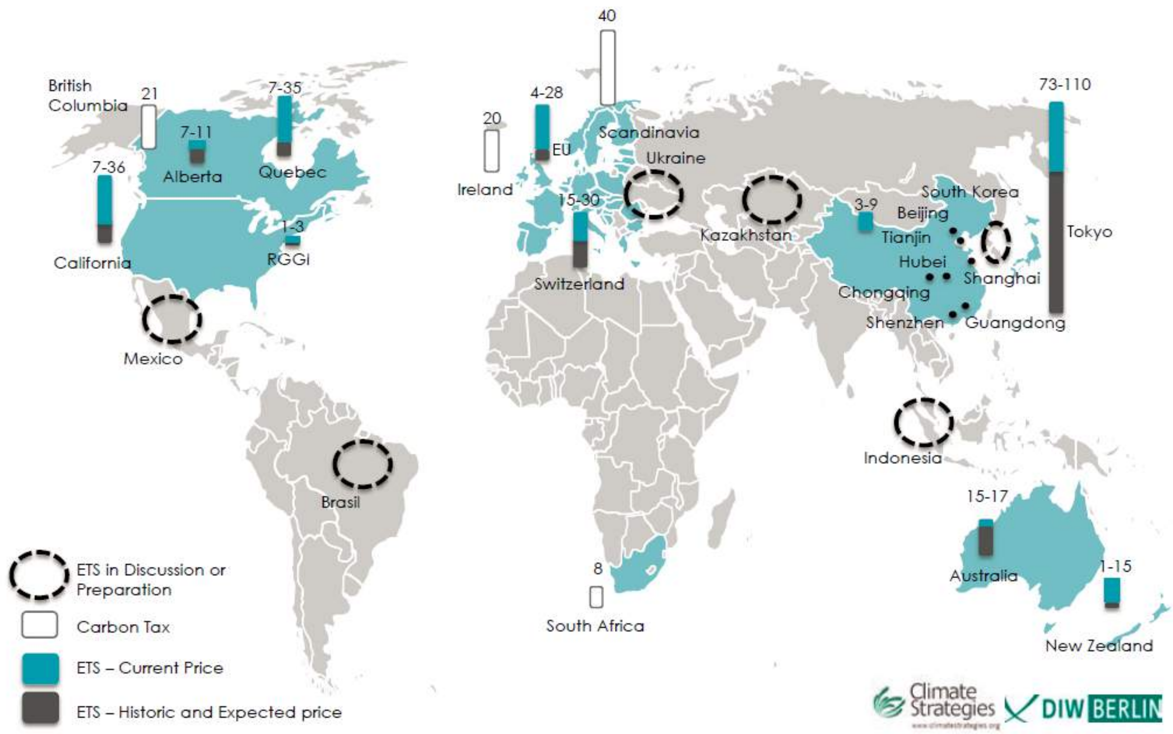


Figure 3-2: Global carbon price policies and expected carbon prices (EUR/tCO2) - several countries and regions have implemented or are preparing carbon pricing. Source: [36]

Representation of existing emission markets worldwide with traded volume and price is given on Figure 3-2, and starting time for emission trading schemes is given on Figure 3-3. With EU ETS being the largest market worldwide, several initiatives in USA (California as well as several East-Coast states, RGGI scheme) have implemented regional emissions trading schemes; a number of Canadian provinces have implemented a carbon tax or emissions trading scheme (Western Climate Initiative) and several countries in the Asia-Pacific region have also recently launched (or are preparing to launch) emissions trading schemes, for example New Zealand, South Korea and regional scheme in several Chinese provinces [36]. Australia's existing emissions trading scheme is currently under discussion while 16 countries, including Brazil, Indonesia, Mexico, South Africa and Ukraine are participating in the World Bank Partnership for Market Readiness program and are preparing themselves for the introduction of carbon pricing in the near future.

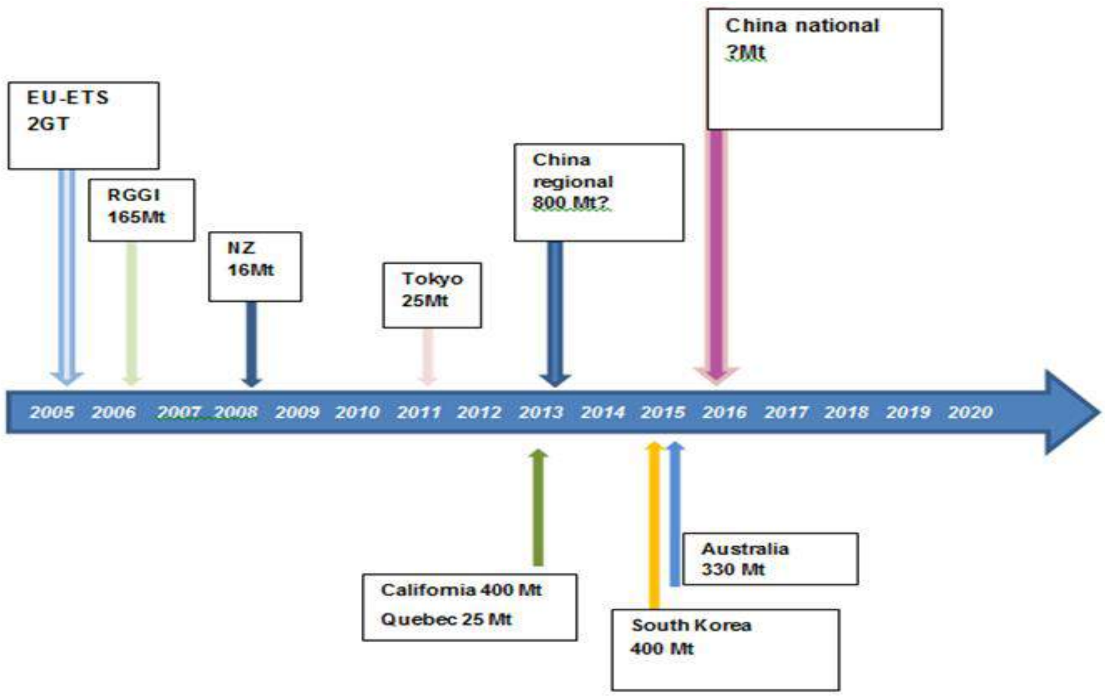


Figure 3-3: Emerging emissions trading schemes: implementation date and (possible) size [37]

There are also several different commodities that could be traded at emission markets – for example in Europe, there is a difference between voluntary markets and compliance markets (EU Emission Trading Scheme, but also Kyoto Protocol market for compliance with governmental Kyoto targets):

- CER – Certified Emission Reductions (CDM projects);
- ERU – Emission Reduction Units (JR projects);
- AAU – Assigned Amount Units (International emission trading within Kyoto market);
- EUA – European Allowances (from EU ETS);
- VER – Verified Emission Reduction (voluntary markets).

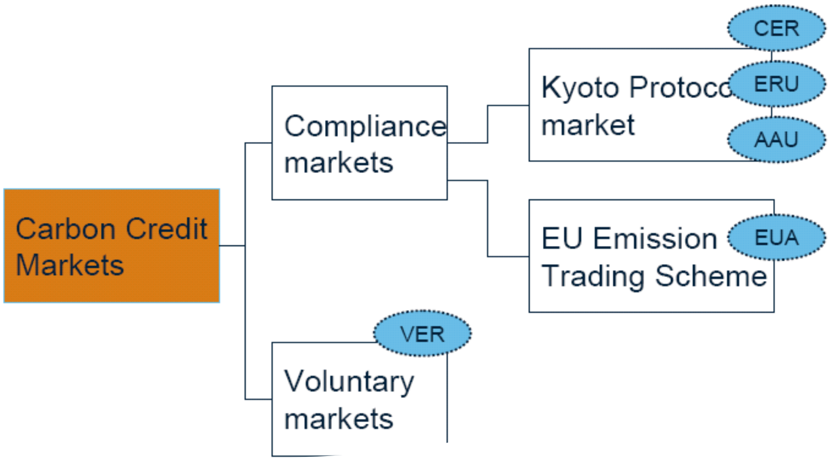


Figure 3-4: Representation of main emission markets and names of commodities on these markets

Existing emission markets differ in their structure. Rough representation of several main national and regional emission markets is given in table below.

Table 3-2: Structure of main emission markets worldwide. Source: [37]

	European Union	WCI	RGGI	Australia	New Zealand	Japanese regional (Tokyo)	South Korea	China regional (based on Beijing, Shanghai and Guangdong)
Coverage	Downstream coverage of energy and industry sectors	Downstream electricity generation and industry, upstream residential, commercial and industrial fuel, transportation	Downstream coverage of power generation	Electricity and industry. Also fugitive emissions and waste, and some transport fuels (rail, shipping)	Stepwise inclusion of all sectors of the economy	Commercial and institutional buildings and industrial facilities	Factories, buildings and livestock farms	Broad coverage (factories, buildings), including also indirect emissions reductions from energy savings
Trading units and offsets	CERs/ERUs - 20% 2020 target: leftover amount from period 2008-2012 or minimum 11% of allocation in 2008-2012 period -more stringent 2020 target: half of additional effort Possibility for EU offset projects	Domestic offset projects including forestry, international credits including from REDD	Allowances measured in short tons (907.18 kg); offset credits from RGGI states; limited EUAs, CERs, ERUs if price exceeds certain level. Sink credits allowed	During fixed price period no intl' permits, (ACCUs) by the Carbon Farming Initiative may be used to max 5%. During flexible price period intl' credits up to 50% (12,5% limit on Kyoto units) and unlimited ACCUs	Unlimited use of Kyoto credits (with the exception of certain credit types)	Emission reductions from small and midsize facilities within the Tokyo area Renewable Energy Certificates Emission reductions outside the Tokyo area	CERs allowed	Chinese Certificated Emission Reductions (CCERs) other domestic project-based credits subject to approvment of the schemes' authorities
Stringenc	At least 21%	15%	Stabilisation	At least 5%	in line with	-25%		unclear

y of targets	below 2005 levels by 2020, may be further strengthened	reduction from 2005 level by 2020	at 1990 level in 2009-2015	reduction up to 2020 compared to 2000	Kyoto target (meeting 1990 GHG levels)	between 2000-20201		
Temporal flexibility	1-year compliance periods Banking possible De facto borrowing possible within trading periods but phasing out	3-year compliance periods Banking possible In principle prohibited, but de facto borrowing possible within trading periods	1-year compliance periods Unlimited banking possible Borrowing prohibited	limited borrowing (up to 5% of compliance requirement and unlimited banking of permits	banking and borrowing	banking allowed, no borrowing	banking and borrowing	no banking, no borrowing
Allocation method	In the second phase auctioning with exemptions for energy intensive industries	At least 10% auctioning		Auctioning with exemptions for Energy intensive industries	Auctioning, free allocation on an intensity basis for industries with leakage risk	Historical emissions and compliance factor	100% free allowances at the begin (2015), 3% auctioning from 2018	Based on historical emissions, mostly free allocation
Penalties	EUR 100 per excess tonne plus surrendering of missing allowances in the next calendar year	3 allowances for each tonne not covered		thrice the market value per excess tonne of emissions	twice the annual average market price	1.3 times the shortfall, monetary fines	three times the market price for each tonne of CO2, with an upward limit of 100,000 Won ($86)	unclear
Price management	Possibility to move forward auctions to address excessive price volatility	Limited use of interventions mechanisms	Access to offsets is increased if price exceeds certain level	Climate Change Authority; price collar initially planned, price floor was dropped	Price cap originally until end of 2012, but in the meantime extended	increasing the use of credits outside Tokyo and enabling the use of Kyoto Credits	staging early auctions of allowances to increase the supply of credits when the price rises too high	unclear

3.1.3. EU ETS

The EU ETS was set as to be an important part of the European Climate Change Programme aimed at achieving the Kyoto and Post-Kyoto targets of the EU. Till date, it is the largest emissions trading scheme in the world, covering over 11,000 installations in the EU, and covers for around 2 Gt or 40% of EU greenhouse gas emissions, a figure that is set to expand further as additional sectors [36]. Currently, the EU ETS operates in 30 countries – all 27 EU Member States as well as Iceland, Liechtenstein and Norway.

The EU ETS is a cap-and-trade system, so there is a fixed amount of CO_2 emission allowances is allocated among a set of participating installations that can use or trade these allowances in order to cover their emissions. As stated in Annex III of the Directive 2003/87/CE, all combustion installations with a rated thermal input exceeding 20 MW (except hazardous or municipal waste installations) fall under the directive of the EU ETS. In other words, basically all major power and heat generators are covered by the scheme. In addition, the EU ETS covers all oil refineries, coke ovens and installations that meet a certain output threshold level in specific industries (cement clinkers, ferrous metals, pulp and paper, glass and ceramics). From 2012 on, air transportation is also included in ETS, and from 2013 on, utilities for production of ammonium, adipic acid and aqua fortis.

EU ETS was set in 2005, and it has been divided in three time periods. First one was from 2005-2007, second one 2008-2012 (which corresponded to Kyoto Protocol framework), and the third one form 2013-2020 (which corresponds to EU 20-20-20 targets). Total emission reduction in second phase was 6,5% lower than from the first one, while in third phase it is 21% emission reduction compared to 2005.

The interaction of the EU ETS with the Kyoto Mechanisms, notably JI and CDM, is laid down in the so-called *Linking Directive* (European Commission, 2004), allowing installations covered by the EU ETS to convert credits from JI and CDM projects into EU Allowances (EUAs) in order to fulfill their obligations under the EU ETS.

The process of allocating allowances in first two ETS phases to installations by each Member State has been one of political gaming between companies, national governments and the European Commission. For each country, there was a total CO_2 emission budget in the National Allocation Plans based mainly on a bottom-up analysis of emission projections for the covered installations and a top-down analysis regarding a country’s commitment to meet its Kyoto target.

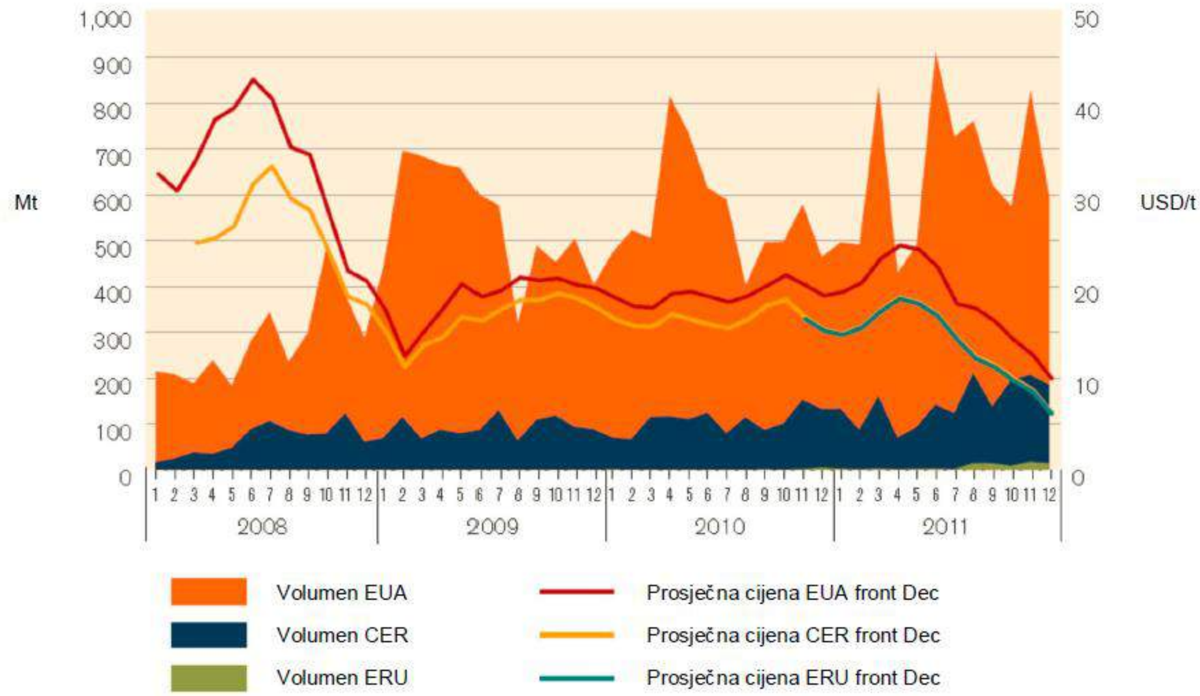


Figure 3-5: Trend of emission volume and price at ETS with volume ad average price for EUA, CER and ERU. Source: [35]

Auctioning in phase III of EU ETS

Based on the lessons learned from the first two phases of ETS (in more detail explained in Chapter 3.3.), policy makers included some crucial changes for the third trading period which started on 1 January 2013. Climate-energy legislative package was proposed by the Commission in January 2008, and was finally adopted as amending Directive 2003/87/EC to improve and extend the GHG emission allowance trading scheme of the Community on 26^{th} March 2009. New ETS provides that GHG emissions permits are auctioned by Member States from 2013 onwards. As power producers have the ability to fully pass the emission allowances price on consumers, they are obliged to acquire all of their emissions allowances at auctions. Other installations covered by ETS sectors must start by purchasing 20% of their emissions permits at auctions in 2013, which will rise gradually to 70% in 2020, and reach 100% in 2027.

The maximum quantity of JI and CDM credits authorized per Member State is set at 3% of verified 2005 emissions. CDM allowances, which are not used in the second phase of the ETS, can be banked and used as a part of reduction efforts in the post-2013 ETS.

Solidarity mechanism was also provided in order to help less affluent EU states with the transition to a low-carbon economy. They received 12% more emission allowances than their actual share in overall EU GHG emissions, which means additional revenues from selling these allowances. At least half of the proceeds were foreseen to be used to fight climate change and to alleviate the social consequences of moving towards a low-carbon economy. Out of these 12% of overall emission allowances, 10% will be added to amount of allowances that will be auctioned between countries with lower economic development – Greece, Portugal and 12 new member states. Remaining 88% emissions from total of 100% will be allocated in shares that are identical to the share of verified emissions under the Community scheme for 2005 or the average of the period from 2005 to 2007.

Other 2% of allowances will be allocated between Member States that managed to do emission reduction higher than 20% from amount based on base year's limits within Kyoto Protocol.

But as some countries don't have good connection to European electricity network, and as some countries are highly dependent on fossil fuels, it is agreed that ten member states can apply for reduced auctioning rates in power generation: at least 30% in 2013, gradually rising to 100% in 2020. Their obligation anyway is to invest in clean technology to the market value of the permits, in order to prevent market distortions. These countries are as follows: Bulgaria, Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland and Rumania. This 70% of allocations received from free allocation can be seen as a financial support for switching towards low carbon power plants.

Criteria that need to be met in order to receive this partly free allocation (one of the following):

- Power system not connected to UCTE network in 2007;
- Power system is connected to UCTE network, but transmission line limit is less than 400 MW;
- In year 2006 more than 30% of electricity was generated from one fossil fuel, and GDP per capita was less than 50% of EU average.

Croatia doesn't satisfy any of these criteria, so it was not possible to get partly free allocation like other new Member States. Energy security issues are concerned when it comes to possibility of carbon leakage to other countries. Good example is situation on West Balkans – after Croatia joins ETS, new investments in power plants that use fossil fuels would have serious competitiveness from surrounding countries – especially Bosnia and Herzegovina, Serbia or Kosovo which have large quantities of coal reserves. New energy climate package says that "the Commission may take appropriate measures regarding impact of carbon leakage on Member

States' energy security, in particular where the electricity connections with the rest of the European Union are insufficient and where electricity connections exist with third countries.

Plans for phase IV of EU ETS

On 22nd January 2014, the European Commission proposed two structural reform amendments to the ETS directive:

a) The linear reduction factor, at which the overall emissions cap is reduced, from 1.74% (2013-2020) to 2.2% each year from 2021 to 2030 thus reducing 43% of EU CO_2 emissions in the ETS sector as compared to 2005 [38];

b) The creation of a 12% "automatic set-aside" reserve mechanism of verified annual emissions (at least a 100 million CO_2 permit reserve) in the fourth ETS period from 2021 to 2030, thus creating a quasi-carbon tax or carbon price floor with a price range set each year by the European Commission's DG for Climate Change [39].

Several EU Member States that heavily invested in it, are advocating for a higher CO_2 permit price which would be beneficial to gas power plants that are currently not competitive. Most power plants which run on gas have been closed, as with low CO_2 price gas-based electricity generation is unprofitable [40], and utilities across the continent have repeatedly warned that these shutdowns could jeopardize the long-term security of the continent's energy supply. In order to change it, large companies like E.ON, Royal Dutch Shell, Standard Oil Companies and GDF Suez are lobbying to change CO_2 legislation which would make gas-fired power stations profitable again [41].

Impact of EU ETS on decision making

Findings from the most recent questionnaire performed in 2014 by Thomson Reuters Point Carbon (around 180 correspondents from emission trading business) are proving that emission price has an impact on their decision making – only 6% of respondents have said there is no importance on their decisions [42].

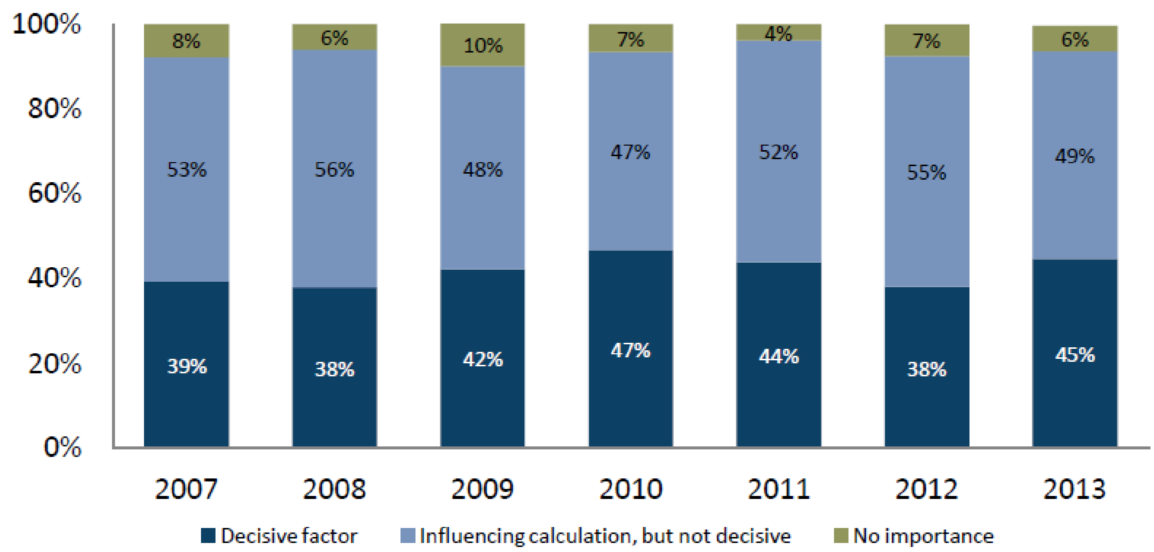


Figure 3-6: Results from questionnaire performed on 173 participants on a question: "How important is the long-term carbon price (in 2020) for new investments in your industry?" Source: [42]

Other findings that could point to where emission markets are about to develop in the future are:

- The majority of respondents think that the carbon price will average €5/t or higher in phase 3 with over 30% saying that the phase 3 price will average above €7/t;
- A large majority of survey participants expect the EU ETS to continue beyond 2020;
- Considering the potential for linking with other markets, survey respondents indicate Australia as the first destination to link with the EU ETS, after regulators from both markets last year announced plans for linkage (in the meantime, Australia stopped its ETS as COP 19 Climate Conference ended with no binding new international agreement in 2013). Similar share believes the EU ETS will link with the California-Quebec scheme than with South Korea by 2020. A third believes the EU ETS will link with carbon markets in China between 2020 and 2030.

Emission trading bursas

There are several European bursas with organized emission trading:

- ICE, London;
- EEX, Leipzig;
- Bluenext, Paris;
- GreenX, London;
- Nordpool, Scandinavia;
- Climex, Amsterdam.

Besides bursas, market participants can trade on out-bursa non-regulated markets, so called OTC markets (Over-The-Counter). Its participants are usually:

- Installations participating in the market;
- Banks;
- Brokers;
- CDM and JI project developers;
- Governments.

3.1.4. Determinants of CO_2 price on ETS

Determinants of the CO_2 price on ETS can be divided in three categories [43]: supply factors, demand factors and factors related to market structure, regulation and intervention (which are also connected to the market maturity).

Supply factors are determined depending on:

- How emission allowances are allocated (in phase I and phase II, total amount of EUAs was laid down in the National Allocation Plans (NAPs) as designed by each Member State and approved by the European Commission; while in phase III there is a single amount on EU level, with allowances then allocated to EU members). In 2013 over 40% of all allowances were set to be auctioned, and the ETS legislation sets the goal of phasing out free allocation completely by 2027. Auctioning is the most transparent allocation method – as it is based on principle that the polluter should pay;
- How CDM credits are converted into EUAs - as CERs are in general cheaper than EUAs, this has a downward effect on the EUA carbon price. But, there are many uncertainties at CDM market over future supply of credits so there is a risk posed, and ETS phase III presented tighter CDM use;
- Possibility of borrowing EUAs – idea of borrowing EUAs from phase III to the phase II;
- Possibility of banking EUAs - opposite of borrowing: transferring EUAs from the first period to the second. Even through it is not allowed, banking of CERs was allowed between phase III and phase IV.

Demand factors

Some of the most important demand factors include estimation of economic growth, weather (temperature because of heating and cooling and rainfall because of hydro power plants generation both have a major impact on emissions of the covered installations), energy prices (like spread between of gas and coal prices), existing abatement options, and many other. An impact of all these factors on ETS market can be seen from Figure 3-7 and Figure 3-8, while Table 3-3 gives an overview of CO_2 price determinants.

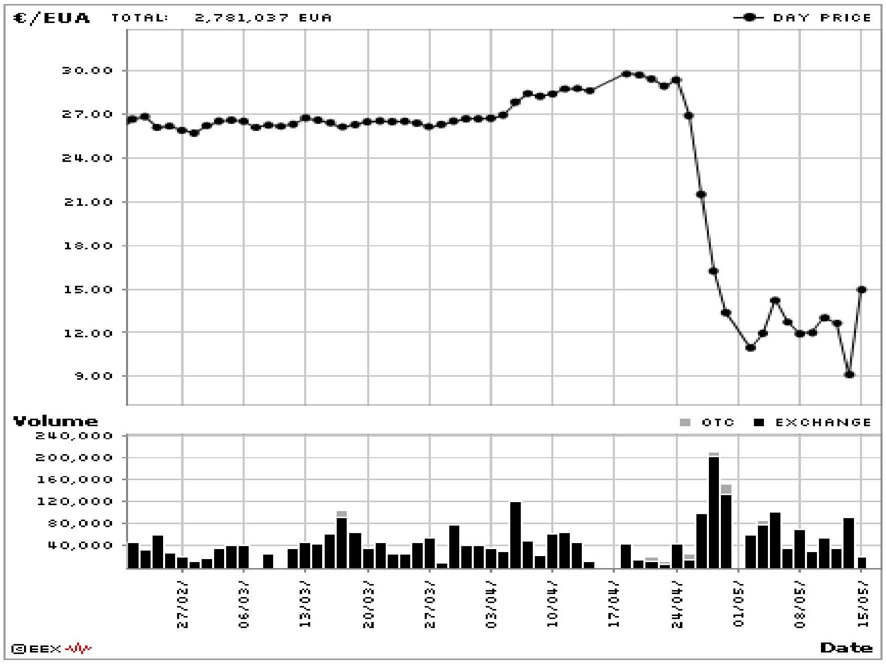


Figure 3-7: First significant drop of emission price on ETS due to surplus allocation and immaturity of market, as in Phase I more EUAs were allocated than needed (Period: 24.02.-16.05.2006., Source: EEX)

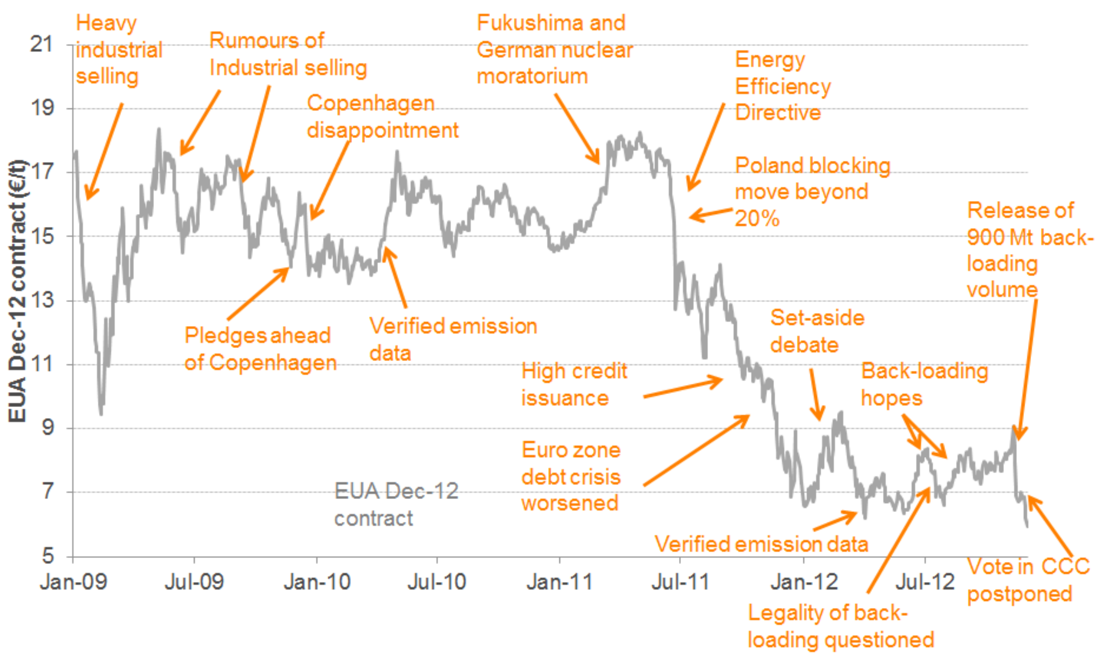


Figure 3-8: Presentation of most important supply-demand factors that influenced traded volume and price on ETS market. Source: [36]

Table 3-3: Summary of CO_2 price determinants. Source: [43]

Factor	Variability	CO_2 price impact[a]	Relation	Remarks
Economic growth	Medium	+	Strong	
Gas-to-coal price	Large	+	Strong	Christiansen (2004) has estimated a CO_2 price sensitivity of 4 €/tCO_2 at a 20% gas price increase, and 3 €/tCO_2 at 20% coal price decrease
Oil price	Medium	+	Strong	Strong due to gas price impact
Temperature summer	Large	+	Medium	
Temperature winter	Large	-	Strong	
Rainfall	Large	-	Strong	
Market uncertainty	Medium	+	Strong	Currently larger variability, but more market certainty expected in mid-term
Info on abatement	Low	-	Weak	
Allocation	Low	-	Strong	Fixed after NAP approval
(expected) CER supply	Large	-	Strong	Christiansen (2004) estimated 3 €/tCO_2 increase at 20 Mt less CER supply
Market power	Medium	+	Medium/-strong	Role expected to decrease with maturing market

a) Impact when factor increases.

3.2. Theoretical approach to emission trading issues in a power system

This subchapter represents introduction to using economic theory in understanding emission trading in a power system – by focusing first on supply/demand curve and relationships on the market. Then, through economic theory emission trading is analyzed in a form of internalizing external costs and analyzed in a form of indirect tax, impacts of elastic and non-elastic demand.

3.2.1. Basics of economic theory in electricity generation

Economic theory states that perfectly competitive market would lead to maximal economic efficiency (maximal benefit for society). Father of modern economy Adam Smith in 18th century describes market force as "invisible hand which renders the annual revenue to society as great as he can" [44].

The supply-demand cross was introduced by Alfred Marshall in 19th century. He found that the point in which demand and supply curve intersect each other's, determines the market balance and sets the price and the quantity that is traded at the market. Supply grows with the growth of market price (as marginal price grows with the quantity produced). On the other side, demand curve shows customers` willingness to pay for products purchased on the market, and it gets lower with supply price increase. Therefore at the equilibrium point, where these two curves meet, both buyers and sellers are content with the quantity and the price met on the market.

Equilibrium is important in economics because it assumes one price for commodity at a time (partial equilibrium if only one commodity is considered, general equilibrium with all commodities included).

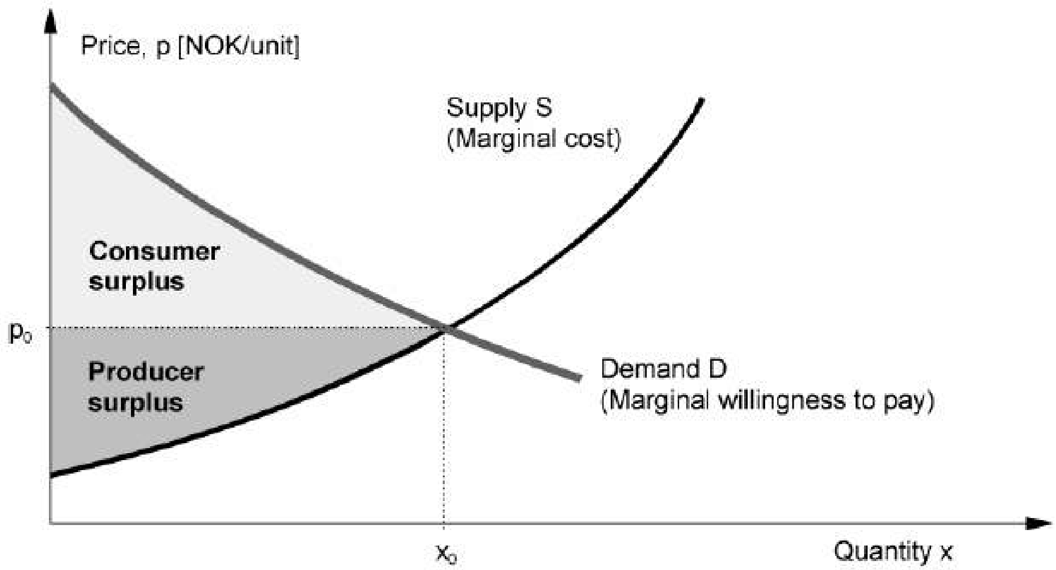


Figure 3-9: Marshall`s supply demand cross. Source: [45]

General equilibrium could also be defined as general optimality, which is called in literature Pareto optimality, after scientist Vilfred Pareto. The idea behind it that nobody can be made better off without someone else being made worse off:

- A competitive equilibrium is Pareto optimum (economic condition of maximum abundance);
- Any Pareto optimum can be sustained as competitive equilibrium.

Anyway, this still doesn't say anything about distribution of wealth, and this distribution can be Pareto efficient even though it is not properly distributed; which is one of the very important pillars of sustainable development and low emission development paradigm (inclusive growth, social perspective).

Shaded areas on the figure above are representing consumer and producer surplus, and their sum gives the total economic surplus of society. The total surplus can be maximized for a price equal to short run marginal costs, when the area under the supply curve represents the variable cost for operation (without covering investment costs and fixed costs). Area showing producer surplus can be used to cover these fixed and investment costs for the production system.

In order to have perfect market competition and maximum economic efficiency, following conditions have to be met (ideal, theoretical case that can be hardly expected in reality):

- All participants must be price takers, i.e. to be too small to influence the market by setting the price;
- All participants need to behave rationally, producers focusing on maximizing profits and customers maximizing their utility;
- There is a free entry possibility for new market participants;
- Trade is performed freely without market transactions.

Function that describes total electricity generation costs with known costs can be described as follows:

$$TC=f(Q), \quad (3.1)$$

where

TC = total electricity generation costs

Q = total generated electricity

As total costs consist of variable and fixed costs, it can also be presented as:

$$TC(Q)=FC+VC(Q), \quad (3.2)$$

Fixed costs don't rely on the quantity that is produced (FC), while variable costs (VC) do. Also, fixed costs don't change in short time period as investment in production in short term is considered fixed. If total costs can be described with linear function:

$$C=aQ+b \quad (3.3)$$

Total costs can be easily described as fixed (b) and variable aQ. With Q=0 (no production), total costs would equal to:

$$C(0)=b \text{ (fixed costs)} \quad (3.4)$$

Average costs are calculated by dividing total costs with the number of produced units. Average costs based on equations are being looked after (costs per production unit), it is:

$$\frac{C}{Q} = a + \frac{b}{Q} \quad (3.5)$$

$$ATC=AVC+AFC \quad (3.6)$$

As seen, average costs consist of average variable costs “a” (or AVC, which are constant) and average fixed costs $\frac{b}{Q}$ (AFC, which are decreasing as the quantity Q rises).

Marginal production costs (MC) are defined as total costs increment induced with increase of production by one unit.

Marginal costs = Total costs increase / Production increase = $\Delta TC/\Delta Q$ (3.7)

In the case of continuous function of total costs, MC presents derivation of total costs function per quantity produced.

$$MC=dTC/dQ \tag{3.8}$$

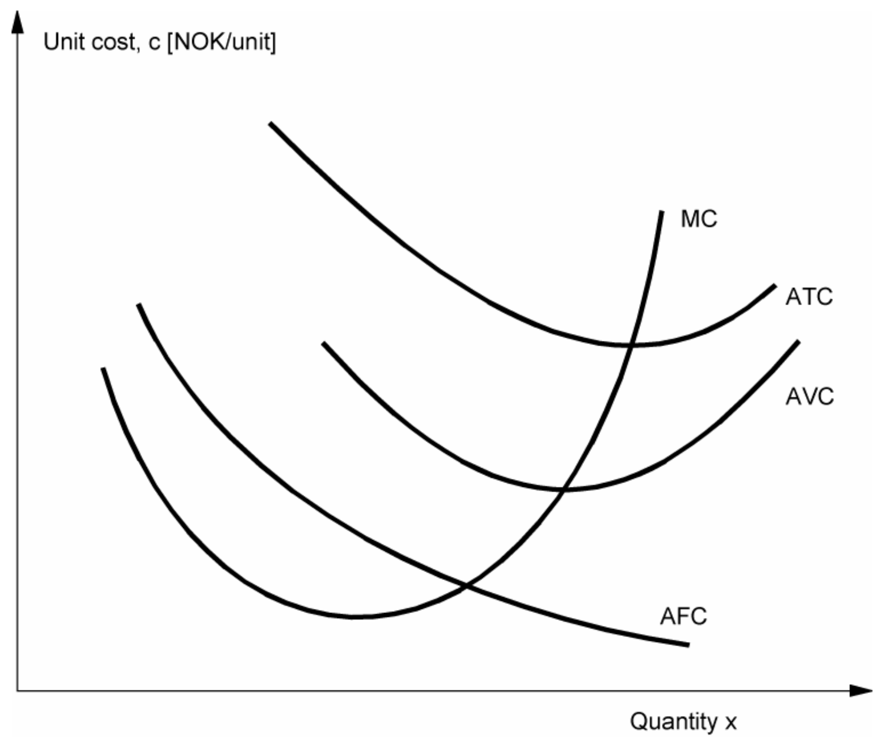


Figure 3-10: Short-run costs - relations between AFC, AVC, ATC and MC curves. Source: [45]

AFC curve is decreasing and is approaching to zero with quantity rise. MC curve decreases faster than other curves, reaches minimum and then rises up again. AVC also decreases to minimum and that rises up, while ATC sums up curves representing average variable and fixed costs (ATC = AFC + AVC). Curves ATC and AVC are reaching minimal points where MC curve intersect with them. This is because ATC reaches minimum when its first derivation equals zero, and its second derivation is positive. This cost curves assume that there is no increase in new production capacities, no investments are taken in account and decision is based only on short-run costs. In order to include long-run thinking, also new investment needs to be added to the cost curve.

3.2.2. Long term average and marginal cost curves

When long term period is analyzed, all production factors are variable and also all the costs are variable costs. In long term it is possible to better combine investments for production factors, as no factors are fixed, they are all variable. That is why in long term there are no bottlenecks which have high impact on high cost increases.

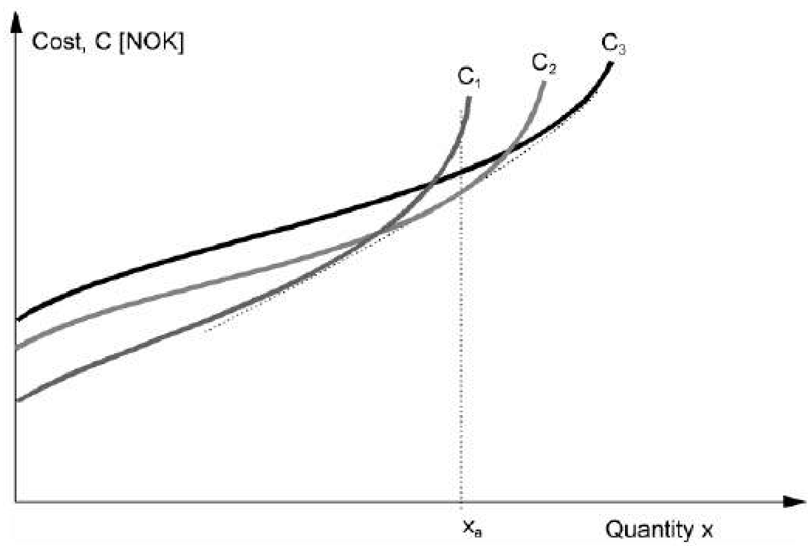


Figure 3-11: Production costs for various levels of investment. Source: [45]

Average long term cost curve is described as the curve that connects minimal points of short term average costs curves. It shows minimal costs per production unit on different production levels – output can be increased at minimum costs by making new investments. At the same way long term marginal cost (LRMC) curve is being constructed (from the long term total cost curve, LRTC):

$$LRMC = \frac{\Delta LRTC}{\Delta Q} \quad (3.9)$$

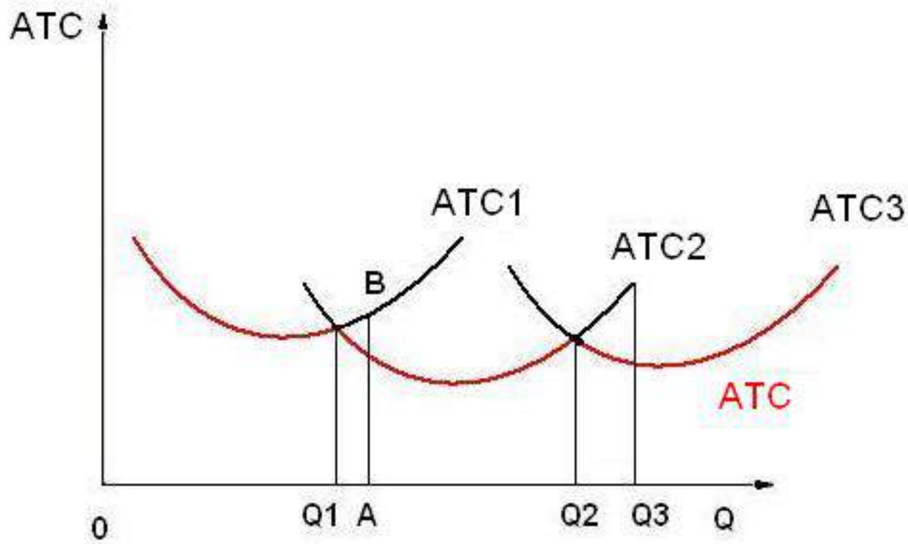


Figure 3-12: Long term average cost. Source: [33]

3.2.3. Theoretical approach to looking emission trading as a means to internalize externalities

By external costs of electricity generation, social, environmental and health damages from electricity generation are addressed, for which they have not been hold responsible. Growing efforts from both policy makers and regulators are aimed to internalize these external costs by using market-based environmental policy instruments. A term external cost has come from English economist Pigou in 1918 [46]. Idea that he imposed was to correct the pollution damage by taxing the producers at such a level that would reflect the value of damage that producers imposed on others. This internalization of damage costs would increase the price of the factory's final product, thus reducing the quantity demanded. Results would be that production levels would fall to a point where the full marginal production cost (with damage costs included) would equal the social value of its output (Figure 3-13).

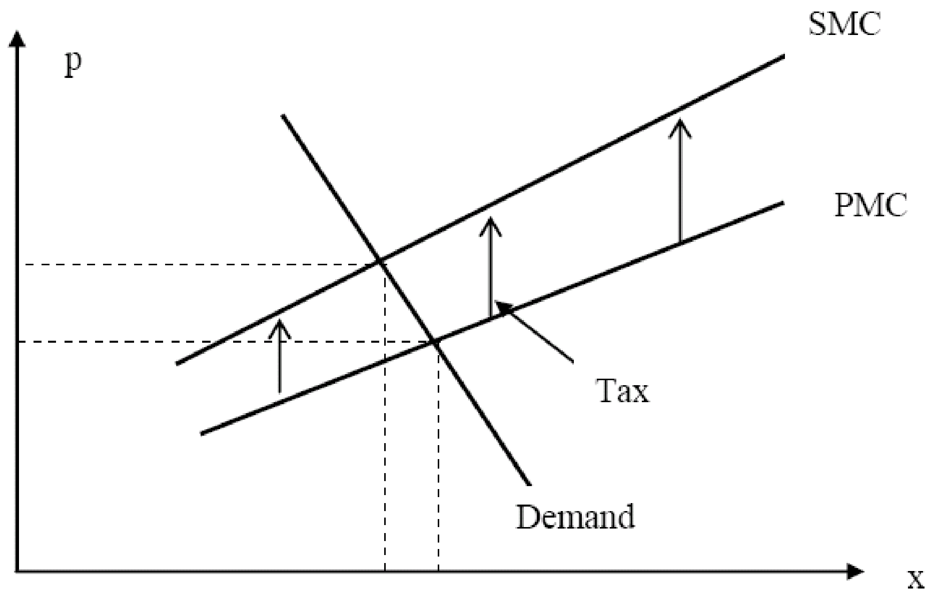


Figure 3-13: Taxation reflecting external costs and change from private marginal costs (PMC) to social marginal costs (SMC). Source: [45]

These environmental policy instruments are considered as a more cost–effective alternative to conventional command-and-control standards which had dominated the previous two decades of environmental laws and regulations [47]. Other advantage of such approach is decentralized decision-making, creation of market signal that would guide firms in developing and evaluating new, more efficient pollution control technologies.

With introduction of climate change concerns, greenhouse gases (GHG) have become external costs (as it wasn't even considered as a damage before climate change concerns), which means that there is a need to internalize these costs by implementing new environmental policies. The result should be putting an appropriate price on carbon, through taxes, trading or regulation that would reflect full social cost of GHG emissions. This will lead individuals and businesses to switch away from high-carbon goods and services, and to invest in low-carbon alternatives.

Climate change is very complex issue, and internalization of GHG is far more complicated externality than (for example) damage caused by local emissions or traffic. Key features of the GHG externality are [48]:

- It is a global externality, as the damage from emissions is broadly the same, regardless of where they are emitted, but the impacts are likely to fall very unevenly around the world;

- Its impacts are not immediately tangible, but are likely to be felt some way into the future. There are significant differences in the short-run and long-run implications of GHG emissions, and once released, carbon dioxide remains in the atmosphere for up to 100 years;
- Uncertainty on scale and timing of the impacts;
- The effects are potentially on a massive scale.

Several ways in which these external costs can be internalized:

Taxes - can be introduced so that emitters would face the full social cost of their emissions. Disadvantage is that it would be too difficult to differentiate and harmonize it at EU level;

Quantity restrictions - can limit the volume of emissions, using a "command and control" approach. This would result in a lot of bureaucracy which presents not very popular measure;

Set of property rights - can be allocated among polluters and/or those affected (in this case including future generations), which can underpin bargaining or trading. Problem here is that this would not lead to lower demand if costumers got property rights for free;

Cap-and-trade systems - a combination of the second and third approach described above. They control the overall quantity of emissions, by establishing binding emissions commitments.

3.2.4. Theoretical approach to looking emission trading as an indirect tax

Emission trading costs can be theoretically analyzed as adding an additional tax (as a form of internalizing costs of GHG emissions), in the electricity generation costs. Adding additional costs from emission trading can be analyzed in a form of additional costs per generation unit (kWh). The difference of this approach and market is that these additional costs don't have fixed value, but their value fluctuates depending on the market. Supply curve will move parallel up for distance T, keeping the same slope.

"Own-price elasticity of demand" explains to which extent costs of emissions will result in higher power prices, depending on sensitivity of electricity demand to price changes; how flexible consumers are to cut their demand if the prices gets higher. For households and other small scale consumers, elasticity is generally low as they have fewer options to cut their demand. But elasticity could be more significant for major end-users such as the power-intensive industries. Also, in the short run price elasticity is lower than in the long run, as in a long run additional energy efficiency options could be used or there are other options to produce own electricity, either from renewable energy (low emission) or other sources. Also, if there is an open market available and consumer can easily switch to other suppliers, this also has an impact on rise of elasticity of demand.

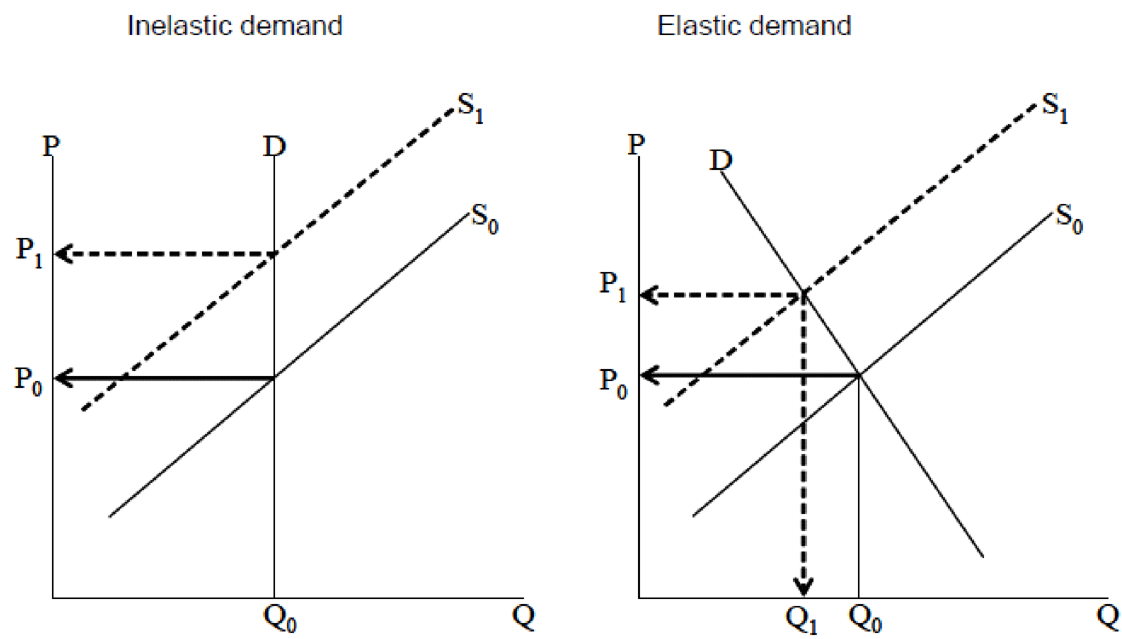


Figure 3-14: Representation of inelastic and elastic demand. Source: [43]

Figure above shows the impact of elastic versus inelastic demand response on passing through carbon costs to the price of electricity under perfect market conditions. In case of inelastic power demand, the change in power price (P1 – P0) is the same as the change in marginal costs due to emissions trading (S1 – S0) which means that the pass through on price here is 100% of costs. In case of elastic power demand, there is a smaller change in power price than the change in marginal costs due to emissions trading.

Additionally, when emission costs are introduced in a form of indirect tax with same elasticity coefficients applied for demand and supply curves (Figure 3-15), it is clear that market price will rise to Pt>P, while the quantity will lower $Q_T<Q$. Total producers surplus will change from OPbQ to OP_ScQ_T. Total emission cost as a result from introducing indirect tax is P_SP_Tac. Therefore, generation unit price for producer will rise for P_T – P, which is lower than total indirect tax induced from emission costs. Producers will not succeed to pass through total emission costs, but will need to take part in it by losing a share of their profit. Producers` profit per generated unit would change for P-P_S.

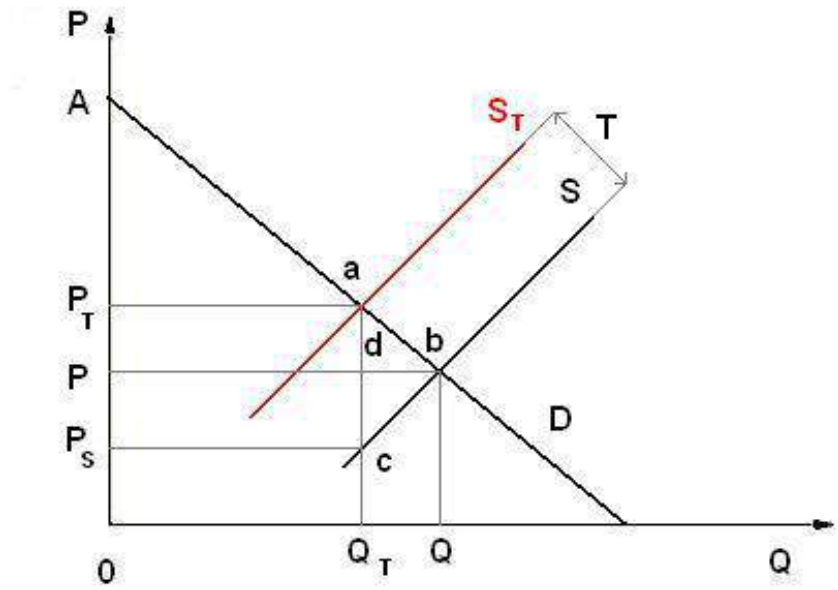


Figure 3-15: Emission costs impact on supply curve. Source: [33]

Both producers and customers will try to minimize impacts of emission costs on their profits and to pass it to the other side. Which side will be influenced more by emission costs depends on supply and demand elasticity. As we have analyzed here the case with identical elasticity coefficients, price that producers are paying because of emission costs (P-P_S) happens to be the same as the price that customers are paying (P_T–P). Therefore it is clear how tax burden will be distributed between producers and customers from relation of supply elasticity and demand elasticity.

$$\frac{\varepsilon S}{\varepsilon D} = \frac{\dfrac{\frac{\Delta Q_S}{Q_S}}{\frac{\Delta P_S}{P}}}{\dfrac{\frac{\Delta Q_D}{Q}}{\frac{\Delta P_T}{P}}} = \frac{\dfrac{\frac{Q_T\,Q}{OQ}}{\frac{PP_S}{Op}}}{\dfrac{\frac{Q_TQ}{OQ}}{\frac{p_{PT}P}{OP}}} = \frac{\frac{Q_TQ}{OQ}\cdot\frac{P_TP}{Op}}{\frac{Q_TQ}{OQ}}\cdot\frac{PP_S}{Op} = \frac{P_TP\cdot OP}{PP_S\cdot OP} = \frac{P_TP}{PP_S} \tag{3.10}$$

If demand elasticity is higher than supply elasticity (as on the figure bellow) then $P - P_S > P_T - P$, it means that the producers will take higher tax burden share than the customers.

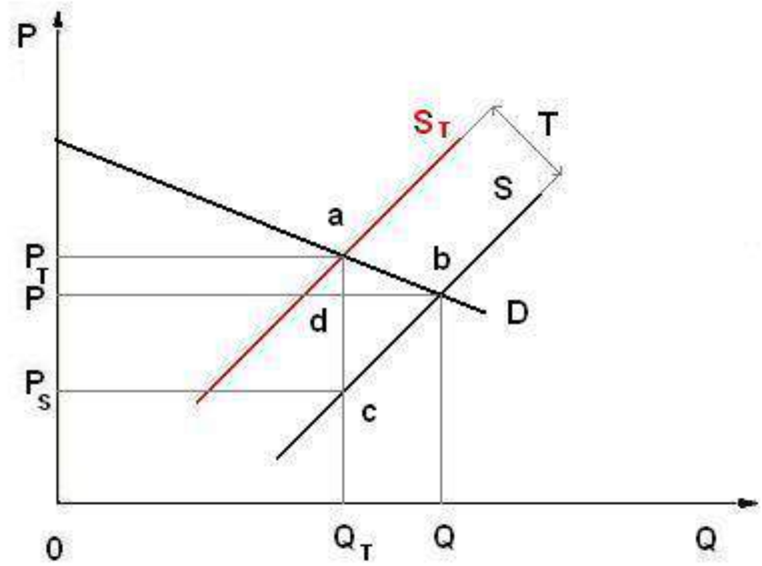


Figure 3-16: Demand elasticity is higher than supply elasticity. Source: [49]

On the contrary, if demand elasticity is lower than the supply elasticity, in that case $P\text{-}P_S<P_T\text{–}P$. The meaning is that the customers are taking higher burden share than the producers because of emission cost taxes (Figure 3-17). This is often the case in electricity markets on a long run, that demand elasticity is very low (on a short run, demand is totally inelastic and therefore customers are responsible for total emission costs introduced in the form of taxes).

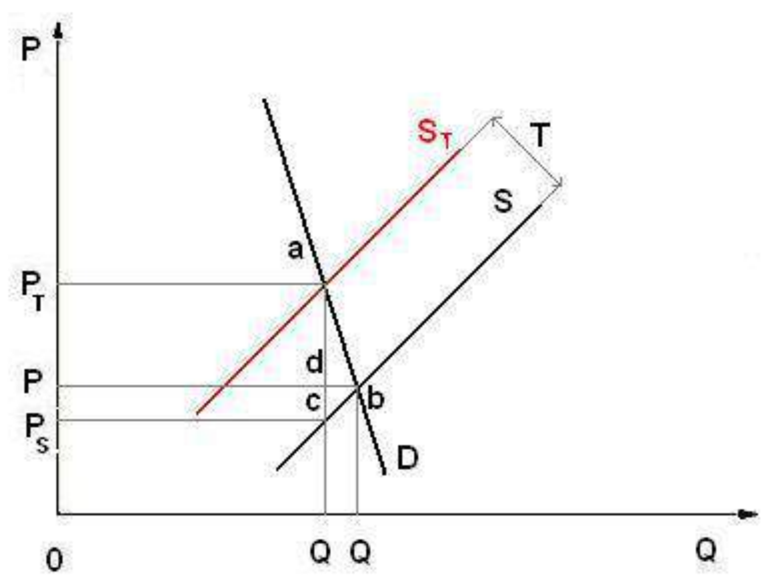


Figure 3-17: Demand elasticity is lower than supply elasticity. Source: [49]

With inelastic supply, total emission cost burden is on the producers (Figure 3-18Figure 3-18).

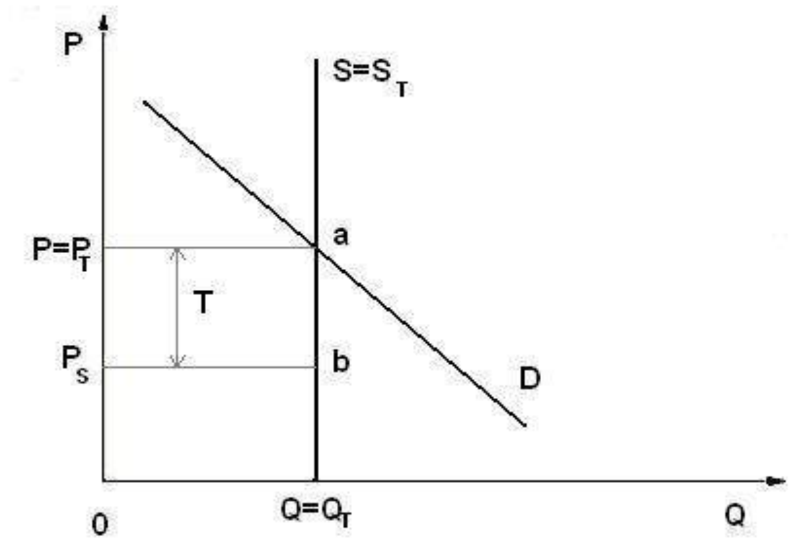


Figure 3-18: Inelastic supply. Source: [49]

3.3. Emission trading impacts on power system

As the idea of emission trading was intentional rise of electricity production costs for fossil fuels based power plants, there was immediate need to understand implications of how emission trading scheme will impact power system. First serious research on these implications appeared from 2003 [50], two years before start of EU ETS. Further research was focused, as presented in this chapter, on different aspects of how market is being set up – allocation, passing costs to consumers, impacts of linking emission markets, what would happen is targets are more loose or straightened, impacts of banking and borrowing emission allowances, etc.

3.3.1. Emission trading impact on electricity production costs

The impact of EU emissions trading on the price of electricity can be determined by three major factors [43]:

- the price of carbon in the EU ETS market,
- the carbon intensity of power production,
- the level of passing through carbon costs.

Or, to put it in relation:

$$\Delta Pe = C * I * L \quad (3.11)$$

where

ΔPe = the change in the price of electricity (expressed in €/MWh),

C = the price of carbon in the EU ETS market (in €/tCO_2),

I = the carbon intensity of power production (in tCO_2/MWh),

L = the level of passing through carbon cost (in %).

As the price of emission allowances is practically the same throughout the EU ETS, change in price of electricity due to emission trading will mostly depend on the other two variables, depending on differences in the major characteristics of the power sector of a specific country as there are differences between the structures of their power markets and the mix.

Level of passing through electricity costs, pass through rate or PTR, depends on the method of allocation of emission allowances and on structure of electricity market.

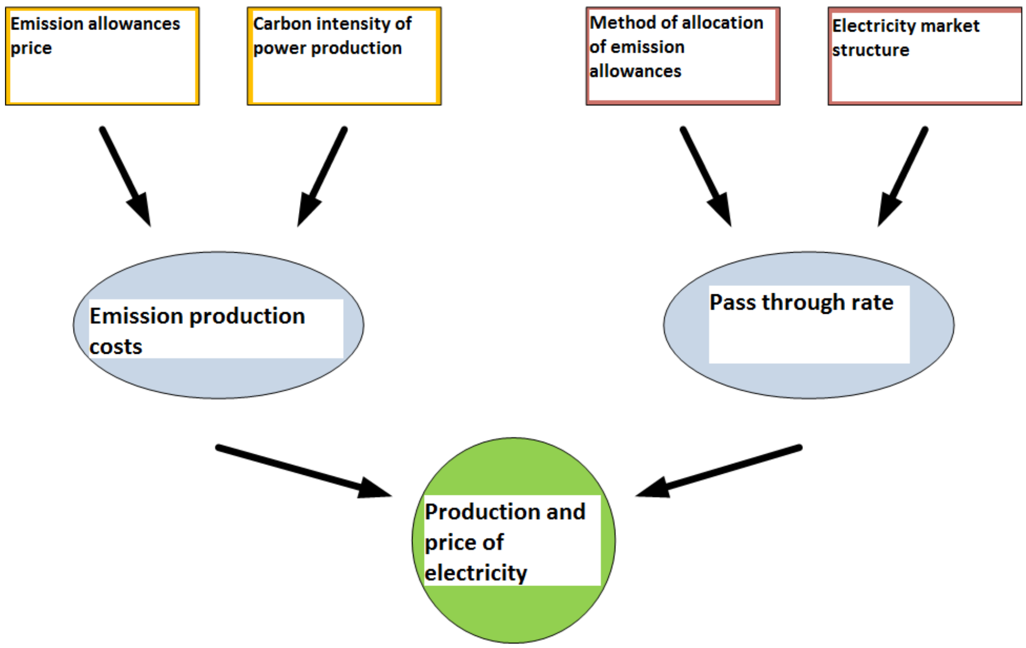


Figure 3-19: Schematic representation of major factors from emission trading on electricity price (author's representation)

With mathematical assessment of impacts of basic factors that define electricity price, participants at the market (or power plant operators) develop their own strategies to participate in the market. For each power plant, with the goal of cost minimization, individual plan for use is being developed such as the proposed one [51].

$$\min_{q_{ith}} \left(\sum_i (c_i \beta_i + b_i + \sum_j S_{ij} C_j^S) q_{ith}\right) \tag{3.12}$$

So that

$$\sum i q_{ith} = Q_{th}^{calc}$$
$$0 \le q_{ith} \le c_i \forall i \qquad (3.13)$$

Where:

b_i = power plant generation costs per energy generated unit

β_i = fixed costs per power installed for power plant *i*

c_i = usable power of power plant *i* during the period *t*

C_j^S = certificate costs per emission units *j*

q_{ith} = quantified electrical energy per power plant *i* within hour *h* within the period *t*

Q_{th}^{calc} = calculated volume of sale in hour *h* during the period *t*

S_{ij} = amount of emissions *j* per unit of produced electrical energy for power plant *i*

Minimal price of supply $p_{th}^{\min}$ for calculated trade amount Q_{th}^{calc} is the highest marginal cost of all analyzed power plants.

$$p_{th}^{\min}(Q_{th}^{calc}) = \max_i((b_i + \sum S_{ij} C_j^S) v_i) \qquad (3.14)$$

Where:

$$v_i = f(q_{ith}) = \begin{cases} 1 & za \ \ q_{ith} > 0 \\ 0 & za \ \ q_{ith} \le 0 \end{cases} \qquad (3.15)$$

3.3.2. Passing through the emission costs to electricity prices

Since the EU ETS became effective on the 1st of January 2005, power prices in EU countries have increased significantly – especially in the phase I of EU ETS. Emission trading was for sure not the only reason, but was one of the most important. To investigate at which extent has emission trading influenced the electricity prices on both wholesale and retail markets, empirical, statistical and modeling analysis started to appear in growing numbers since 2005.

Analyses are showing that power producers on the real markets have indeed passed through the costs of freely allocated CO_2 allowances to electricity prices, and debate is taking place on understanding opportunity costs, windfall profits that power producers collect from emission trading and policy improvements that would modify policy issues in more proper way.

The concept of opportunity costs is fundamental to economics and not restricted to the analysis of using free emission allowances. Concept of emissions trading system is to make emission allowances a scarce and valuable commodity, which means that it can be traded on the market at a certain price. Regardless of whether allowances have been obtained for free or bought on an auction or market, current operational decisions are based on the current opportunity cost (set by the market).

As concept of opportunity costs was known from before, there cannot be surprises when it comes to realization that power producers are generating extra profit from free allocation of emission allowances. If there was someone to blame, that should be policy-makers who made policy in such a way. Power producers have just behaved rationally on the market, by maximizing opportunity costs. It was desired effect, and idea was to include this opportunity costs into marginal costs of power producers. This sends clear incentive to existing power producers and new investors to switch or to invest in low-carbon technologies like more efficient gas-fired plants, nuclear, renewables, carbon capture and storage or other abatement options. Clear message and incentive is also sent to consumers to reduce their demand for carbon-generated electricity, by increasing their energy efficiency and therefore lowering electricity demand. This is intended effect of opportunity costs, and if they are not internalized, least cost abatement options from low-emission generation and energy saving will not be encouraged.

Critics of emission trading system are emphasizing that it didn’t provide wanted domestic emission reductions, but has led to windfall profits by power producers. The term “windfall” refers to the fruit that falls from the tree due to the wind. Hence, it relates to something one gets

for free, an extra bonus without having to make an additional effort and which, usually one did not expect to receive. Term windfall profits has a negative connotation, mainly because it is associated with either 'unfair' or 'unjustified' practices resulting in higher power prices for customers, and transfer of money that from public sector goes to large, private power companies.
Verbruggen discusses [52] that there exists little ground and need for policy to act against genuine windfalls, while opposite is for the other excessive earnings – that's why clear identification and correct language are needed here. He discusses that these profits are not windfall profits, but they do result from deliberately exercising monopoly power that electricity producing companies have on the markets.

If there is a perfect competition in power markets, charging customers for fictive costs (free emission allowances) would be impossible. Participating in the ''global carbon market to fight climate change'' can be seen as a wonderful pretext to hide monopoly profits, as the prices applied on the free given permits are not prices for actual emissions happening. The same term windfall profit is used to describe one more type of profit that comes from climate policy, CDM (flexible Kyoto mechanism Clean Development Mechanism), where excessive profits have been noted for project developers and particular countries. "Payments for HFC-23 abatement by refrigerant manufacturers in China, the Chinese government and to carbon market investors by governments and compliance buyers will in the end total approximately USD 4.7 billion while estimated costs of abatement are likely less than USD 100 million" [53]. These examples show that many problems arise from well-intended policy to save the climate, often missing understanding of real markets and fall short in co-coordinating policies over various issues and sectors. Additional understanding is needed here in order to fix functioning of the market.

As discussed above, pass-through of CO_2 emission costs in the case of free allocations - should raise certain questions or concerns affecting the socio-political acceptability of the EU ETS, especially when lack of domestic emission reduction is taken in account.

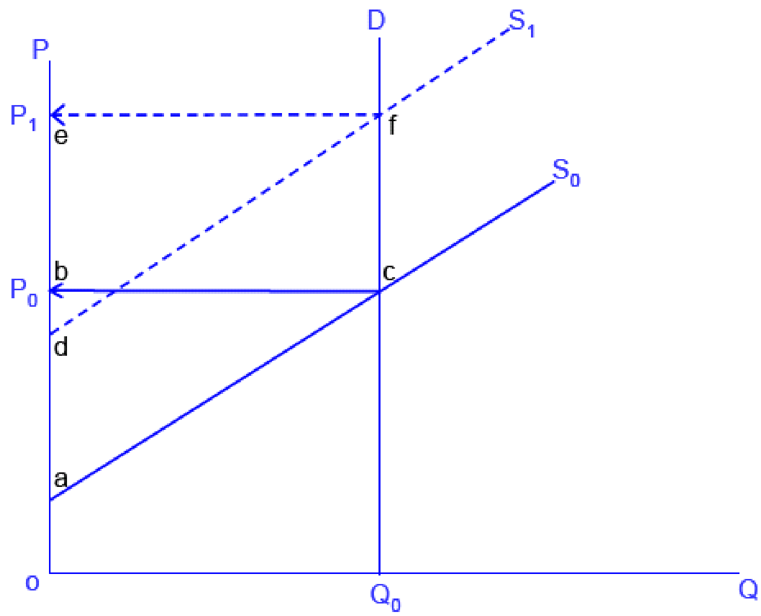


Figure 3-20: Pass through of emission costs to power prices. Source: [54]

Pass-through of the opportunity costs of carbon allowances to power prices is shown on Figure 3-20. Ideal case of perfect auctioning or perfect free allocation is shown, with perfect competition, an inelastic demand curve (D), and a straight, upward supply curve with constant carbon intensities of the generation technologies (So). With included emissions trading, the opportunity costs of carbon allowances are included in production costs, which results in new supply curve S1. Prices rise from P0 to P1, and pass-through rate is 100% since the change in power price is equal to the change in marginal production costs. The producer surplus before emissions trading is equal to the triangle "abc" (difference between total revenues and total variable costs), and this surplus covers investment costs of power production and producers` profits.

With emission trading, there is a big change according to allocation method. In case of auctioning, the producer surplus is equal to "def" (which is the same size as "abc"), meaning there is no change in profits due to emission trading. The total emission costs are equal to the quadrangle "adfc", which are fully passed on to the power consumers by means of higher electricity prices (which results in loss of consumers' surplus). In the case of perfect free allocation, however, the producers get the allowances for free, resulting in an increase in their producer surplus by the quadrangle "adfc". This increase in producer surplus due to emissions trading represents windfall profits, and is here because of free allocation of emission allowances.

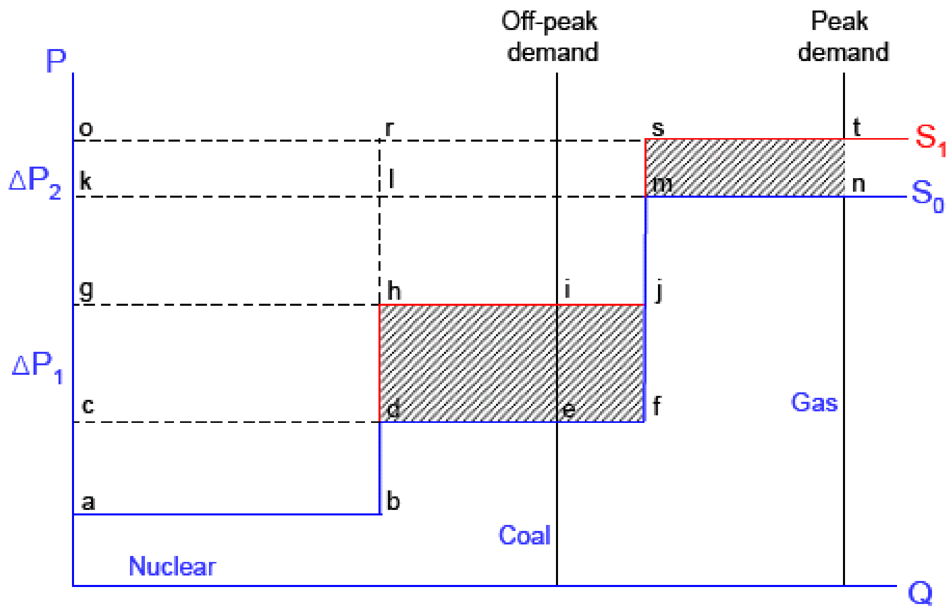


Figure 3-21 Impact of emission price on electricity price during the a) off-peak demand and b) peak demand. Source: [54]

In more realistic approach, with merit order of different technologies as shown in Figure 3-21, two cases are analyzed – one for off-peak demand, and another for peak demand. Like in the previous figure, S0 presents supply curve before emission trading, and S1 is with emission trading, while shadow area stands for opportunity costs of power producers. With no change in merit order, after emission trading off-peak price raises for dP1, and peak price rises for dP2 (which is smaller than dP1 due to lower carbon intensity of gas power plants). The difference between different allowances allocation can be seen here: if we look at off-peak demand, for free allocation coal power plant has an extra profit of area "deih", while in auctioning system there is no extra profit since allowances need to be purchased on the market. The same thing happens during peak demand for gas power plants – with free allocation they receive an extra profit shown by an area "mnts", while in auctioning system this allowances are purchased on the market. But, for an infra-marginal technology like hydro or nuclear (which has no CO_2 emissions), the profitability of power generation during increases regardless of whether the allowances are auctioned or allocated for free. It is clear from the figure that nuclear benefit from the ET-induced increase in both off-peak and peak demand period, regardless on allocation system.

3.3.3. Windfall profits due to emission trading

As explained above, in the case of emissions trading with free allocations, we can distinguish changes in profits of existing producers into two categories according to how these profits change appeared:

- Windfall profit because emission trading – is explained as an extra profit for infra marginal producers like nuclear power plants, and this change occurs irrespective whether eligible companies receive all their allowances for free or have to purchase them at an auction or market;
- Windfall profits due to the free allocation of emission allowances - with high carbon prices and free allocated allowances according to carbon intensity of fuel (high polluters such as coal or lignite plants get more free allowances), producers benefit from passing through of opportunity costs.

First category (extra profit from emission trading) encourages investments in especially low- or non-CO_2 emitting installations, the second category (extra profit from free allocation) induces investments in high-emitting technologies (in case that allowances are allocated for free according to fuel- or technology specific way).

Several reasons why generators do not pass through full CO_2 costs to their power bid prices are analyzed in [54]:

- The expectation of power producers that their current emissions or output will be used as an input factor for the determination of the allocation of allowances in future periods, which creates an incentive to increase today's output and encourages generators not to add on the full allowance price to their energy bids;
- Regulatory threat of governments to intervene in the market if generators make excessive windfall profits from the free allocation might induce generators to limit the add-on;
- Other reasons like market imperfections, time lags or other constraints, including issues like risks, uncertainties, lack of information, and the immaturity or lack of transparency of the carbon market.

With introduction of full auctioning or some other policy which wouldn't provide free allocation to power producers, most of these reasons wouldn't be there anymore and it is expected that allowance prices would be fully passed on customers.

Additional distortion of emissions market is characterized by the following distortions, as discussed in [55] of this ideal type:

- Updating free allocation to power producers - decisions on current activity levels (electricity production and emissions) are affected by the prospects or expectations of future allocations – in first and second ETS phases, companies` emission in the future might be set due to their today` emissions (either by grandfathering or benchmarking system). Such "updating" of free allowances results in higher emissions today, as companies are ready to produce electricity even if their short run marginal costs are not necessary higher that market price (or at least by lowering of their internal opportunity costs), in order to achieve financial value in the future;
- Contingent allocation to plant closures - allocation of allowances during the next period requires that the installation remains open or active for a minimum number of hours during the present period, so that producers cannot benefit from selling large amounts of allowances allocated for free. As a result, older, carbon-inefficient power stations will work as they can pass opportunity costs to electricity price which leads in more power supply, putting downward pressure on electricity prices during this period.
- Free allocation to new entrants - if existing power plants receive allowances, it is also fair that new plants receive them. The problem is that power producers in countries with CO_2 intensive power generators like coal-fired installations receive the highest number of allowances per kW installed (in countries like Germany). It means that incentive has been created to shift production towards more CO_2 intensive generators which would increase CO_2 prices.

To assess impact of CO_2 allowances on power system of Great Britain ICF Consulting's Integrated Planning Model (IPM) was used, which is a linear programming model that selects generating and investment options to meet overall electricity demand today and on an ongoing basis over the chosen planning horizon at minimum cost.

3.3.4. Empirical evidences of pass through rate and windfall profits from EU ETS

Several studies (such as [43,54,55]) presented a review of the literature on the impact of the EU ETS on power prices. Some analyzes are empirical, meaning that they analyzed actual data on carbon and energy prices during the first years of the EU ETS.

Table 3-4: Overview of empirical studies on the impact of the EU ETS price [54]

Study	Country	Market	Period	'Pass-through rate'
Bauer and Zink (2005)	Germany	Forward	Jan.-June 2005	1.0
Bunn and Fezzi (2007)	UK	Spot	2005	0.42
Chernyavs'ka and Gulli (2007)	Italy	Spot	2005	0
			2006	-0.5 to 2.0
Frontier Economics (2006a)	Netherlands	Forward	2005	0.04 to 1.08
Frontier Economics (2006b)	UK,	Forward	2005	0.89-0.98
	Netherlands			0.91-0.96
	Scandinavian countries			0.97-098
Honkatukia et al. (2006)	Finland	Spot	Feb. 2005 - May 2006	0.75 to 0.95
Levy (2005)	France	Forward	January-June 2005	0.56
	Germany			0.48
	UK			1.84
	France	Spot	April-June 2005	2.21
	Germany			3.33
	Italy			2.04
	Spain			3.53
	UK			2.19
Sijm et al.	Germany	Forward	2005	0.60-1.17
(2005, 2006a and 2006b)	Netherlands			0.78-0.80
	Germany	Spot		0.50-2.50

The differences between empirical studies (Table 3-4) made to analyze impacts of ETS on electricity prices mostly depend on the market that was analyzed (forward or spot market), approach used (mostly statistical regression approaches), period that was analyzed and countries in focus. Most authors have estimated pass-through rates defined broadly as the ETS induced change in power prices divided by the ETS induced change in marginal production costs of the marginal unit. Conclusions from review of these studies are saying that a major part of the ETS-induced carbon costs was passed through to power prices. It is important to say that most of the studies were done for liberalized, power markets in West-European countries, but not to more regulated in East-European countries (where, due to regulated electricity price setting PTR is expected to be lower).

Emission trading impact on dark spread/spark spread is also possible, where a dark spread can be simply defined as the difference between the power price and the cost of coal to generate a MWh of electricity, while a spark spread refers to the difference between the power price and the costs of gas to produce a MWh of electricity. An analysis made in 2006 [56] was comparing difference between dark spreads in year 2004 (without ETS) and year 2005 (ETS introduced) on the German spot market, between 3-4 p.m. From the Figure 3-22, it is obvious that in the moment of introduction of EU ETS there are no differences (blue line I showing change in dark spread) while soon it rises along with carbon costs for coal (rose line). Dots are representing electricity price in 40-day average. Analysis concludes that such change in electricity price is due to total pass through of carbon costs.

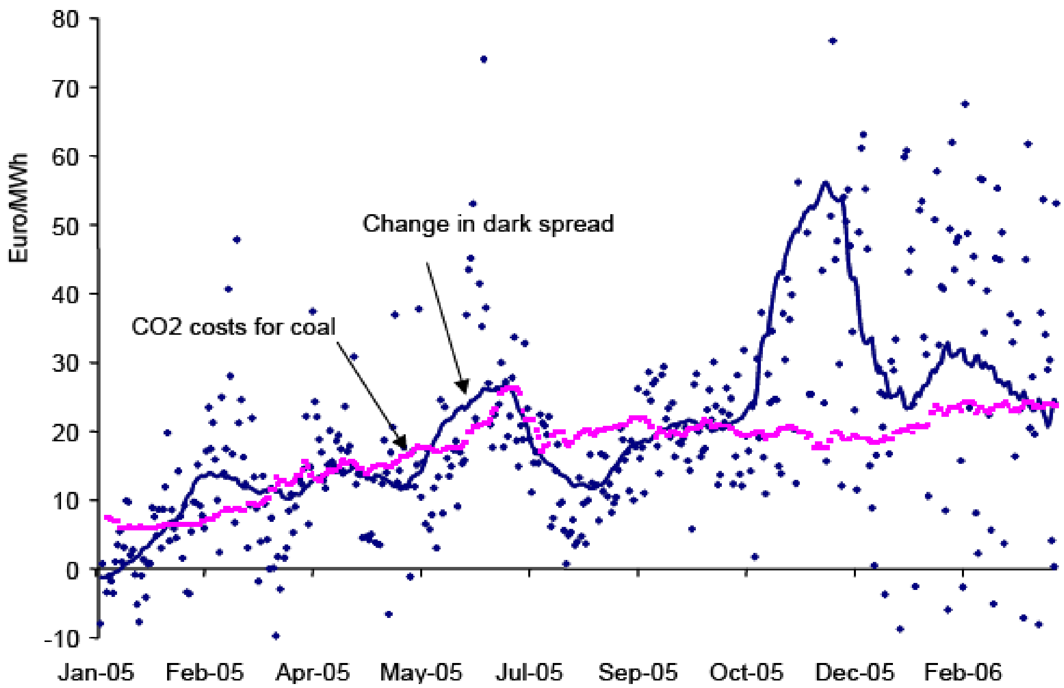


Figure 3-22: Change in dark spread induced by ETS. Source: [56]

Empirical and statistical analyses of PTR on EU power markets in [54] was focused over 2004-2006, and has covered both forward and spot wholesale markets as well as retail markets for electricity end-users in nine selected EU ETS countries (France, Germany, Italy, Poland, Spain, Sweden, the Czech Republic, the Netherlands and the United Kingdom). Together these countries cover a wide variety of power generation and market structures, accounting for some 80% of total electricity output of the EU27. Large amount of data has been gathered and processed, including daily data on carbon and fuel prices, and daily and hourly data on power prices for markets in these nine countries over. Correlation between prices in German is visible on Figure 3-23.

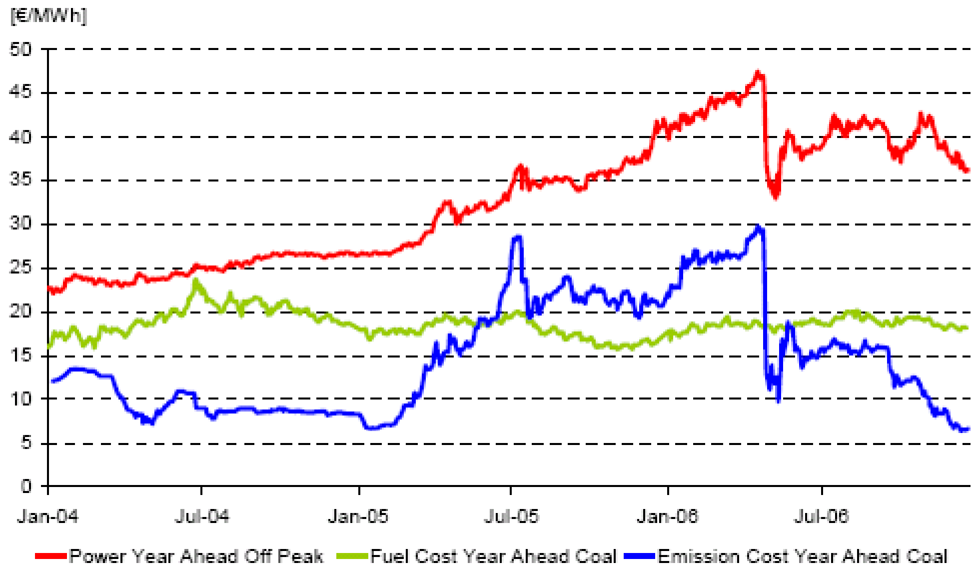


Figure 3-23: Germany forward off-peak power, fuel and emission prices between 2004 and 2006. Source: [56]

3.3.5. Policy solutions for windfall profits

In this chapter, policy solutions that can help in dealing with producer's windfall profits due to emission trading with free allowances will be presented and analyzed. Even though, from climate policy perspective, passing through the costs of CO_2 emissions is a rational and intended effect, it is clear that this policy will not bring emission reduction since producers are receiving windfall profits from free allocated allowances (on liberalized market, because on regulated market producers cannot pass through these costs fully or easily as price is set by regulating authority). Also, question regarding social acceptability of these scheme are raised, as customers are paying higher electricity prices for a scheme that doesn't bring desired emission reductions, but brings higher producers profits.

Auctioning is the most widely suggested option to address in particular the EU ETS-induced windfall profits, and has recently been chosen in ETS for third phase (2013-2020, more on that latter). The idea is to sell the CO_2 emission allowances at an auction rather than allocating them for free. Issues such as environmental effectiveness, economic efficiency, cost pass-through and output price, would remain the same as in free allocation model, but an extra profit from CO_2 emission allowances would in these case go to the public sector, and can be latter used for funding other projects that would lead to carbon mitigation or other social objectives. So, the solution is more acceptable for whole society and leads to CO_2 mitigation, better than subsidizing electricity producers as in the case of free allocations. Disadvantage of this method could be higher electricity prices, as now power producers will fully pass-through costs of allowances.

Allocating free allowances to power consumers – if allowances are allocated directly to consumers, and producers would still have to submit allowances to authority, then consumers could sell their allowances directly to producers. For producers, these method is similar as auctioning (as they have to pay for allowances), but for customers this would be cheaper (as there is no pass through of allowances costs this time). Disadvantage is that it could lead to rise of electricity demand as customers have less incentive to cut their demand.

Free allocation based on benchmarking – allocation based on benchmark, standard emission factor according to quantity or activity level (as electricity produced). It the end it would end up the same as in grandfathering system, if a similar amount of free allowances is allocated in a benchmarking system with a similar fixed cap. Performance between these systems would then be the same, in the terms of environmental effectiveness, economic efficiency, carbon prices, cost pass-through, output prices and windfall profits.

Taxing windfall profits – could be applied either fully or partially. Advantage of this method, comparing to auctioning, is that it can be applied to both categories of windfall profits mentioned (due to emission trading and due to free allowances). Money collect by taxation be used to finance public expenditures. The biggest problem with this method is that it is hard to estimate reliably existing windfall profits, just as it is rather difficult to estimate reliable PTRs and what power prices would have been without emissions trading. Some proposals go for taxation of production of existing nuclear and hydro power, where only windfall profits from emission trading would be addressed (this method in combination with auctioning system would address both policies).

Taxing GHG emissions – handles only with windfall profits from free allocations. But wind fall profits from emission trading (extra profit that nuclear power plants will achieve due to higher electricity prices on the market) still exist and cannot be addressed by this method.

Regulation of power prices – electricity prices could be regulated by an external authority, for instance the national Transmission System Operator (TSO) or the energy market surveillance authority. This would imply that power producers are allowed to pass through only the (average) costs of carbon allowances bought on an auction or but not the opportunity costs of the allowances obtained for free. Anyway this method would not be popular among EU policy makers as it does not fit in the current process of market liberalization, privatization and deregulation in order to achieve competitive, efficient power markets.

Encouraging competition in the power sector – as economic theory shows, in perfect markets power producers pass through 100% of the opportunity costs of carbon allowances, while on monopolistic market they could be higher or lower than 100%. It means that encouraging competition in the power sector doesn't eliminate ETS induced increases in power prices and windfall profits due to free allocation, but can even increase these prices and profits. Another drawback is that if (with free allocations for new entrants on the market) too many new power producers would be attracted to the market (more than is actual need), there would be additional electricity on the market, prices would be too low and there would be no enough interest for energy efficiency and renewable energy (even though, these could be regulated separately).

Policies to mitigate the price of an emission allowance – which could be achieved by controlling the inflow and limit of JI/CDM offset credits, implementing other policies besides emissions trading that reduce emissions of the ETS sectors, (RES, EE) or encouraging the R&D of carbon capture and storage. The disadvantage of these methods could be reduced efficiency to achieve the emission reduction target for which the system has been designed.

3.3.6. Electricity market structure and other important market factors

How emission trading will impact power system depends a lot on market structure of the power market. Other important factors that need to be analyzed are demand elasticity and shape of curve that determines suppliers` marginal costs, market regulation, market imperfection and market strategy. These factors will be analyzed here.

The number of firms active in the market (N), indicating the level of market concentration or market competitiveness. Depending on this number of firms, the market structure is called either monopolistic (N = 1), duopolistic (N = 2), oligopolistic (N = small) or competitive (N = large). As presented on the following figure, level of competition between monopoly and large competition (which present perfect competition) is imperfect competition.

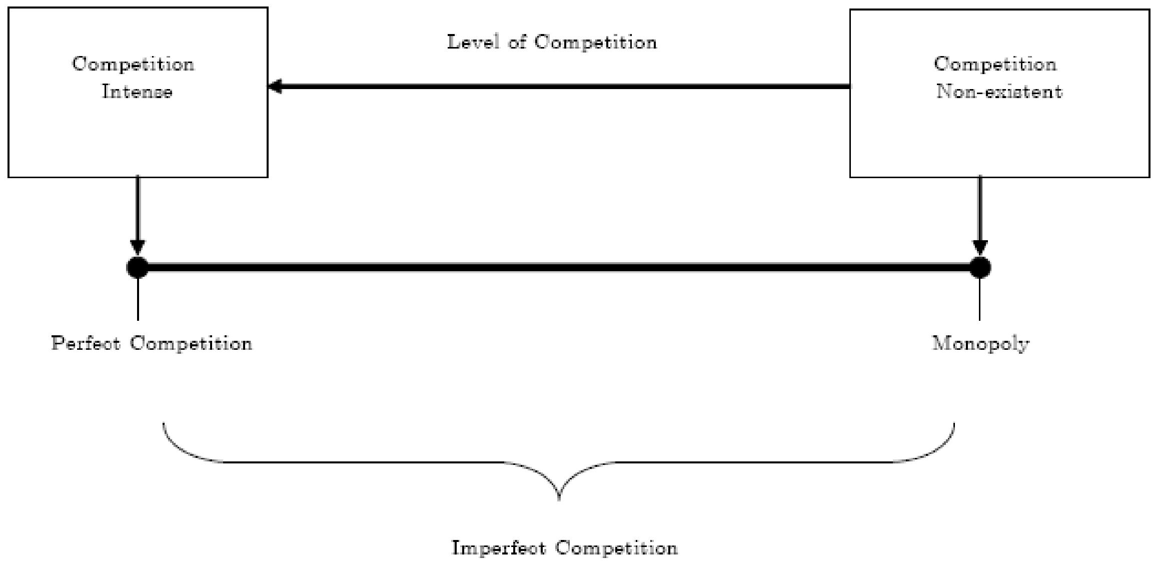


Figure 3-24: Graphical representation on various levels of competition on the market. Source: [57]

Perfect competition is characterized by

i) product homogeneity,
ii) full resource mobility,
iii) perfect information,
iv) price-taking behavior by participants.

Price-taking behavior implies that each individual producer (buyer) in a market, when choosing its production (purchases), assumes that its choice will have no impact on the aggregate demand-supply balance and consequently, no impact on the market price. A perfectly competitive firm's marginal revenue, therefore, is the market price, and profit-maximizing behavior results in producing the output level at which price equals marginal cost. In this case, the actions of other firms are largely irrelevant to an individual firm's profit maximization decision.

Monopoly market structure means no competition, a single producer that faces the entire market demand for a product (Figure 3-24). Entry into this market type is difficult due to barriers for entry of new competitors, such as economies of scale, technology patents, or the monopolist's ability to control access to essential inputs to production. The monopolist maximizes its profit by producing the output level at which its marginal revenue equals marginal cost and charging a price above the socially optimal price, which is marginal cost. The ratio between its profit margin (price less marginal cost) and the price is inversely proportional to the elasticity of market demand.

Imperfectly competitive markets lie between these two extremes and are divisible into two basic market structures, monopolistic competition and oligopoly. A central feature of oligopoly is that a few large firms in the market dominate production and are able to exercise market power by altering their output and/or pricing decisions to their advantage. These barriers to entry help existing companies on the market to exercise market power and to set their prices on levels higher than their marginal production costs. Each individual firm must consider its own set of market actions (such as production and pricing decisions), as well as impact of these actions on its rivals. Also, each firm must account for possible reactions of rivals to its actions and the fact that its rivals will make a similar assessment of their own.

First analyzed case (Figure 3-25) is focused on constant marginal costs (with quantity rise, marginal costs remain constant - perfectly elastic supply) and with linear demand. S0 is supply curve without emission costs, and S1 includes emission costs. Number of firms active in the market, N, is ∞ for the case of perfect competition and N=1 for monopoly.

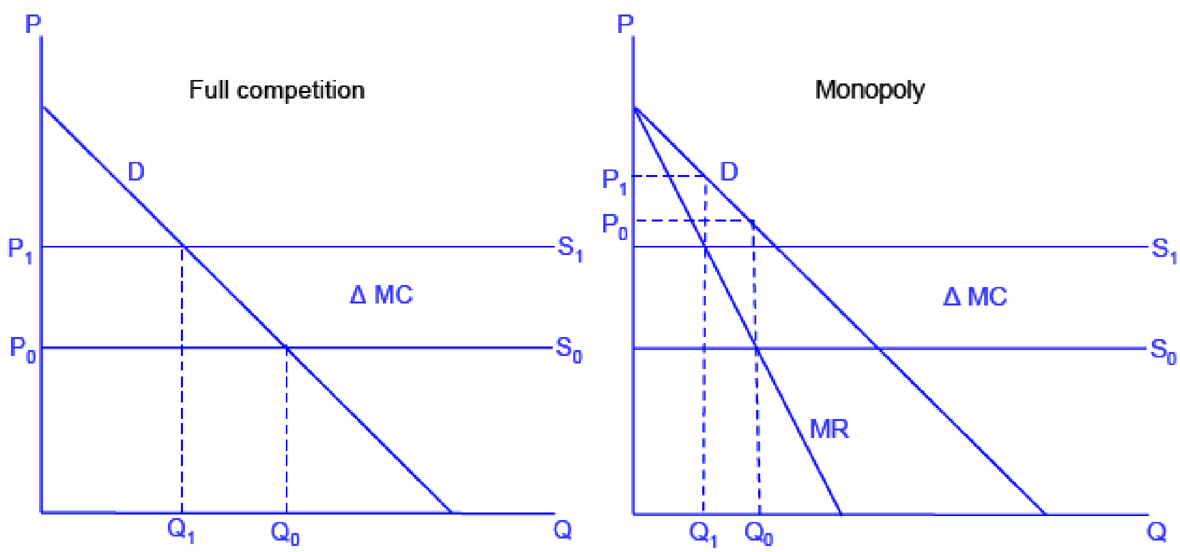


Figure 3-25: Representation between full competition and monopoly on the market with constant marginal costs and with linear demand. Source: [54]

Extent to which emission costs are passed to consumers is defined as pass-through rate, PTR. As recent research has proved [54], PTR can be calculated in this case by using only number of firms active on the market, without using elasticity of supply and demand:

$$PTR = dP/dMC = N/(N+1) \quad (2.14)$$

The results of this formula are showing that for monopoly market structure passes through only 50% of any increase in carbon costs. With more competitive sector (when the number of firms increases), the pass-through rate rises until it is close to 100%. Hence, under linear demand and constant marginal cost, the more competitive the industry, the greater the PTR. In an oligopolistic market structure, the slope of the MR curve is relatively less steep, implying that under linear demand, the PTR would be between these two cases - the cases of monopoly (50%) and perfect competition (100%), and that it increases up to 100% if the degree of market concentration decreases.

Even though one might expect opposite results (that exercising market power in monopoly market structure will bring higher PTR than in perfect market competition), this can be explained by the fact that as an industry becomes more competitive, prices become more aligned with marginal costs, and in perfect competition marginal costs equal marginal revenues and also market prices (MC = MR = P). Therefore, carbon costs will be fully transmitted into higher prices. In less competitive markets with prices higher than marginal costs, these producers can influence market prices by changing their output, their marginal revenues defer from their output prices.

Another analyzed case is with variable marginal costs of power generation (upward sloping curve), and with price responsive linear demand (as presented in Figure 3-26). Due to emissions trading, the supply or marginal cost curve increases from S0 to S1 by the amount c of carbon costs. Under perfect competition, prices are equal to marginal costs, and with increase of marginal costs due to emissions trading, prices in perfectly competitive markets increase proportionally. With price responsive demand, it decreases when prices increase. Less demand implies less supply, but also lower marginal costs as these costs are variable, depending on the output level. Therefore, increase in marginal costs from emissions trading is lower than the increase in carbon costs and also the pass-through to output prices is lower.

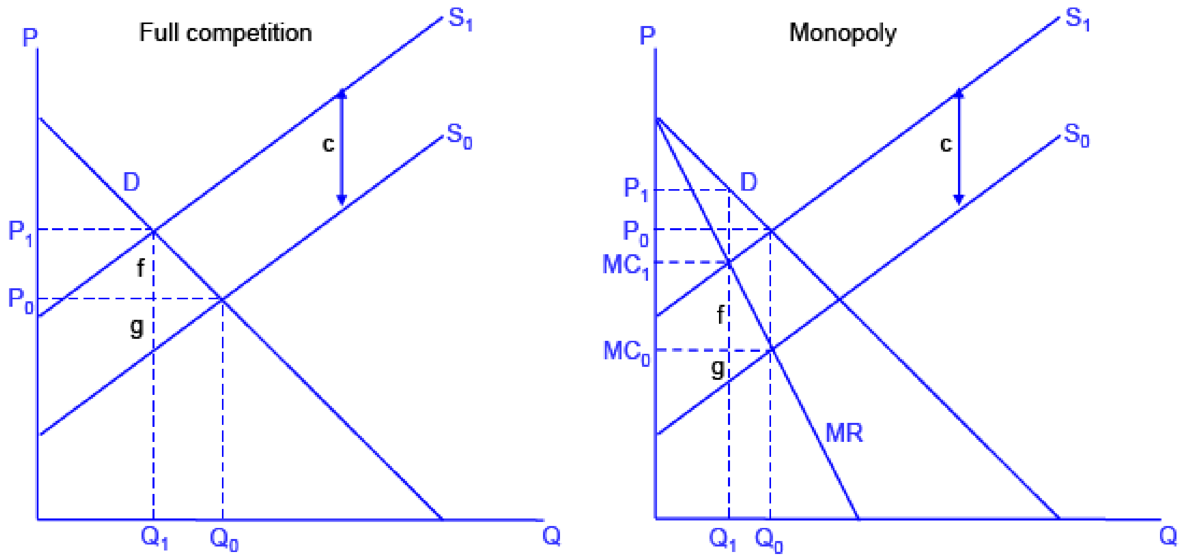


Figure 3-26: Representation between full competition and monopoly on the market with variable marginal costs and with price responsive linear demand. Source: [54]

For the full competition case, carbon cost of emissions trading equals c, the increase in (net) marginal costs due to emissions trading is designated by f, while the difference in increase between these carbon and marginal costs equals g = c – f. Since the increase in these marginal costs is lower than the carbon costs of emissions trading, the cost pass-through is also lower, compared to the last analyzed case (of perfectly elastic or constant marginal costs). If the PTR is defined as difference in price (dP) due to change in carbon costs (dCC), (Sijm, 2008) provides the derivation of the pass-through rate for market structures characterized by N firms facing linear demand and isoelastic supply. Under these conditions, the PTR, is given by the formula:

$$PTR = \frac{dP}{dCC} = \frac{1}{1 + \frac{1}{N} + \varepsilon^{b}\left(\frac{Q}{Q_0}\right)^{b-1}} \tag{3.16}$$

N - number of firms active in the market,

ε - demand elasticity at the competitive equilibrium before emissions trading (Q0, P0),

b - constant elasticity of the supply function,

Q0 and Q - equilibrium output levels before and after emissions trading,

In general, as supply elasticity increases, the PTR increases, if demand elasticity ε < 1.

With implementation of different market strategies, conclusions discussed above can be changed. Understanding of theoretical economy can largely help for analyzing short-term operations in the wholesale power market. In practice, there are other objectives that companies might be having except maximizing profit, objectives that are more focused on medium or long run strategies.

Market regulation can have great influence on the extent to which carbon costs are passed-through to power prices, including regulation of wholesale or retail power prices. Regulators may treat the pass-through of these costs differently depending on whether they are opportunity costs (in the case of free allocations) or real costs (in the case of auctioning or market purchases of allowances). In many cases (for example new EU Member States), markets are not fully liberalized yet, which means that companies cannot set the market price fully. Regulators can also use other threats in order to tax windfall profits or to control market power of some companies. As a result, power companies may be reluctant to pass through such costs.

Other market imperfections that influence emission trading impacts on electricity price are nonexistent full and free information of energy and carbon market performance, different risks and uncertainties in practice, adjustment costs, and significant time lags. Also some technical constraints (production and transmission), such as ‘must-run’ constraints on operation, high costs of starting up or closing down coal plants, line congestion etc. Market imperfection also include a lack of liquid and flexible fuel markets, resulting in a lack of production flexibility and high costs of short-term production adjustments. It is hard to estimate these influences but they have to be taken in account in order to get full picture.

4. EMISSION TRADING IMPACT ON LONG TERM POWER SYSTEM PLANNING

In this chapter, several aspects of emission trading impacts on a long term power system planning are given, with emphasizes on competitiveness of low emission technologies. It starts with presentation of emission trading impacts on short run marginal costs and long term marginal costs; and with assessment of reducing GHG emissions through marginal abatement cost curves. Further, it analyses concept of power system planning in a regulated market – difference between central and decentralized planning and other elements – depending on chosen perspective. Finally, it finishes with overview and characteristics of long term power system planning.

4.1. Power generation technology competitiveness change due to emission trading

4.1.1. SRMC and LRMC

The short-run marginal cost is the change in total cost resulting from a one-unit increase (or decrease) in the output of an existing production facility. Price of emission allowances (CO_2 market price) impacts variable electricity generation costs - short run marginal costs (SRMC). SRMC consist of fuel costs and variable operation and maintenance costs. SRMC represents a floor for electricity prices in liberalized markets. On a daily or weekly basis, companies will not produce electricity if the market price does not cover their variable costs of generation. “In the short run” indicates that adjustments in the capital stock (the collection of power plants) are being ignored.

SRMC are used in cost-based power auctions because they are used to determine the competitive price on the market. Most of European power markets rely on a central day-ahead auction (day-ahead markets) in which generators submit individual bids of quantity and price and the system operator uses these to determine the price of the market based on the consumers’ demand.

On the left side of the Figure 4-1, there is an illustration of merit order of power generation on a market. By including an extra CO_2 emission cost, not only has the market price increased (SRMC), but there has been a change in the order of the plants’ competitiveness. In figure on the right, where CO_2 costs are included (Figure below), plant 2 (gas) offers a better bid than plant 1 (coal), whereas in figure on the right, without the extra cost, plant 1 is more competitive (coal).

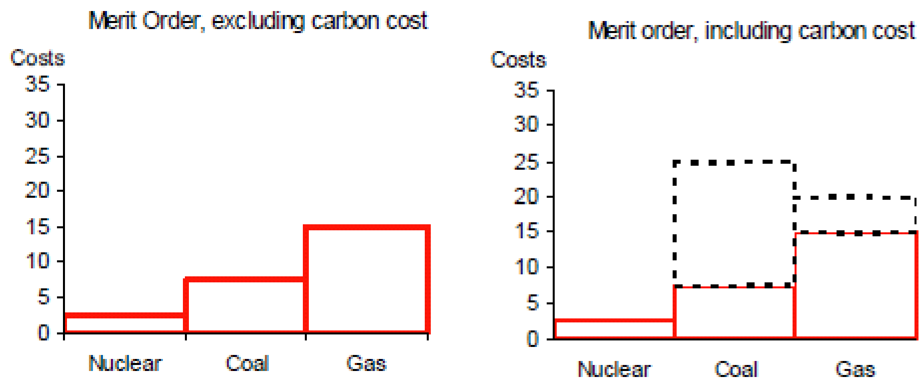


Figure 4-1: Merit order representation excluding carbon costs (left) and including carbon costs (right) (cost in MWh)

When all existing power generation options (individual plants' supply curves) are summed in one graph horizontally, it is used to find the market supply curve. To determine the merit order of the market, a ranking of generators with those with the lowest average variable costs to those with the highest is built.

In order to estimate how CO_2 price would impact electricity prices from wholesale power markets across the EU, bottom-up modeling analysis was performed in 2010 with data from all EU countries [58]. Model used was COmprehensive Market Power in Electricity Transmission and Energy Simulator (COMPETES) model. The analyses showed that a significant part of the costs of (freely allocated) CO_2 emission allowances is passed through to power prices, resulting in higher electricity prices for consumers and additional ('windfall') profits for power producers, even in cases of full auctioning.

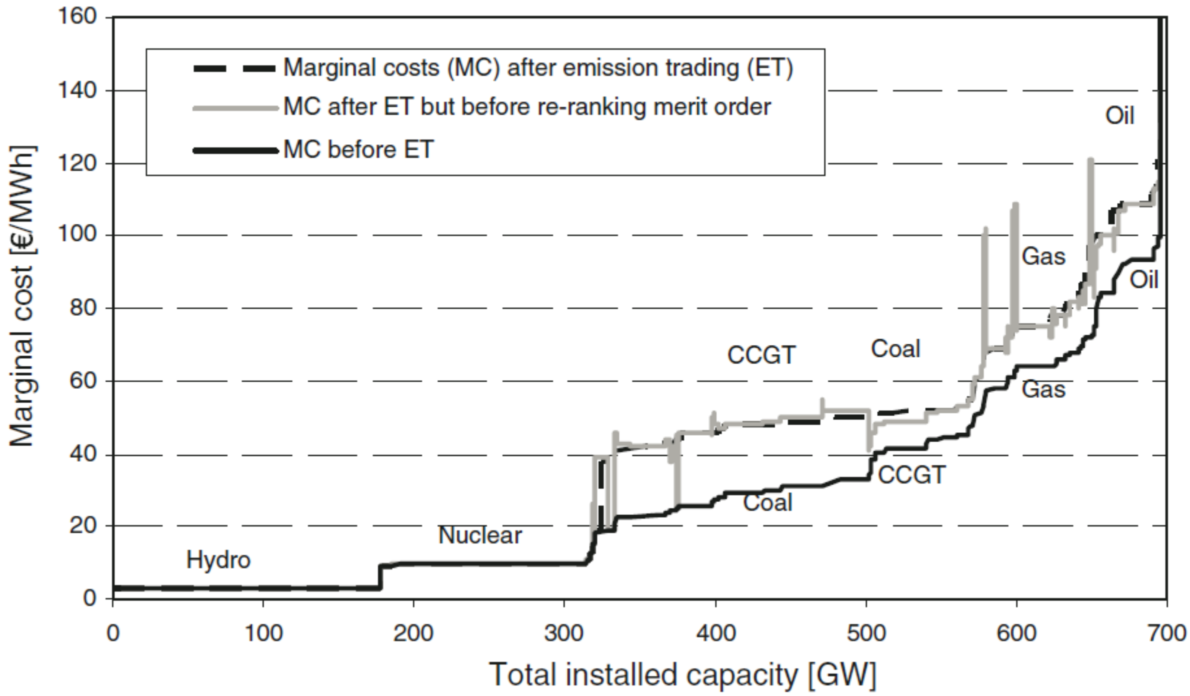


Figure 4-2: Results from COMPETES model: ETS-induced changes in the EU-20 merit order at 20 EUR/tCO_2 and 2006 fuel prices. Source: [58]

From the Figure 4-2, it is visible that due to emissions trading, the marginal production costs of carbon-intensive technologies (in this case coal) increase substantially, whereas carbon-efficient technologies—here CCGT—do not increase so much substantially (grey line) and that, subsequently, the merit order may change significantly—especially at higher emission prices. At the same time, prices for nuclear power and hydro power remain the same. At the end, more carbon intensive technologies (coal) shift to the right in the merit order while more carbon efficient units (CCGT) move to the left; while low-emission technologies (such as renewable energy and nuclear) are becoming even more competitive. This trend is more visible when higher emission price is applied (40 EUR/tCO_2, Figure 4-3).

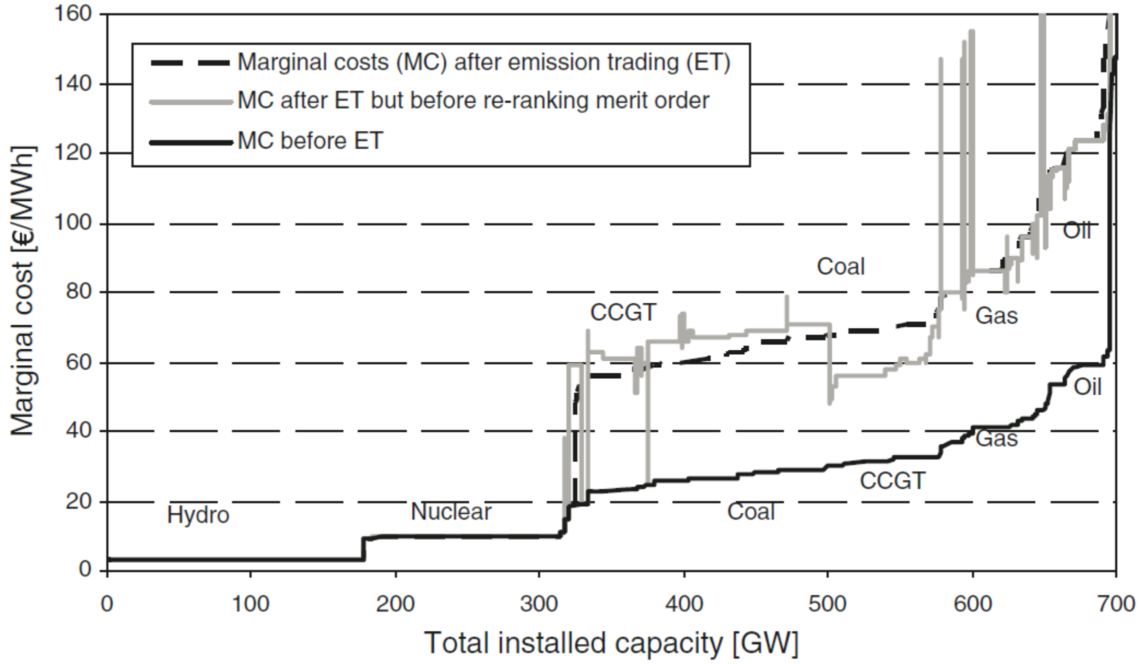


Figure 4-3: Results from COMPETES model: change in merit order with emission price 40 €/tCO_2, for 2006 fuel prices. Source: [58]

Comparing SRMC with LRMC shows at which level it is more profitable to continue operating an existing power plant rather than build a new one. Figure 4-4 illustrates which technology is more competitive in relation to a varying carbon price, based on the cost assumptions. Findings from this Figure could be interpreted with two break-even points; however in reality it is not easy to make decisions based on these interpretations as price on ETS varies:

- Between € 0 and € 18.5 per ton CO_2 - it is more competitive to operate an existing coal-fired plant than an existing CCGT plant. Price of € 18.5/tCO_2 is a break-even point;
- Between € 18.5 and € 23.2 per ton CO_2 - it is more competitive to switch power generation from existing coal-fired plants to existing CCGT plants, (but if there is idle capacity of CCGT available). If this capacity is lacking, installed coal-fired plants will continue to operate up to the breakeven price of 23.2/tCO_2 where the SRMC of an existing coal-fired plant is equal to the LRMC of a new CCGT plant;
- Above € 23.2 per ton CO_2 - it is more profitable for companies to build modern CCGT plants and to shut down their existing coal-fired plants;

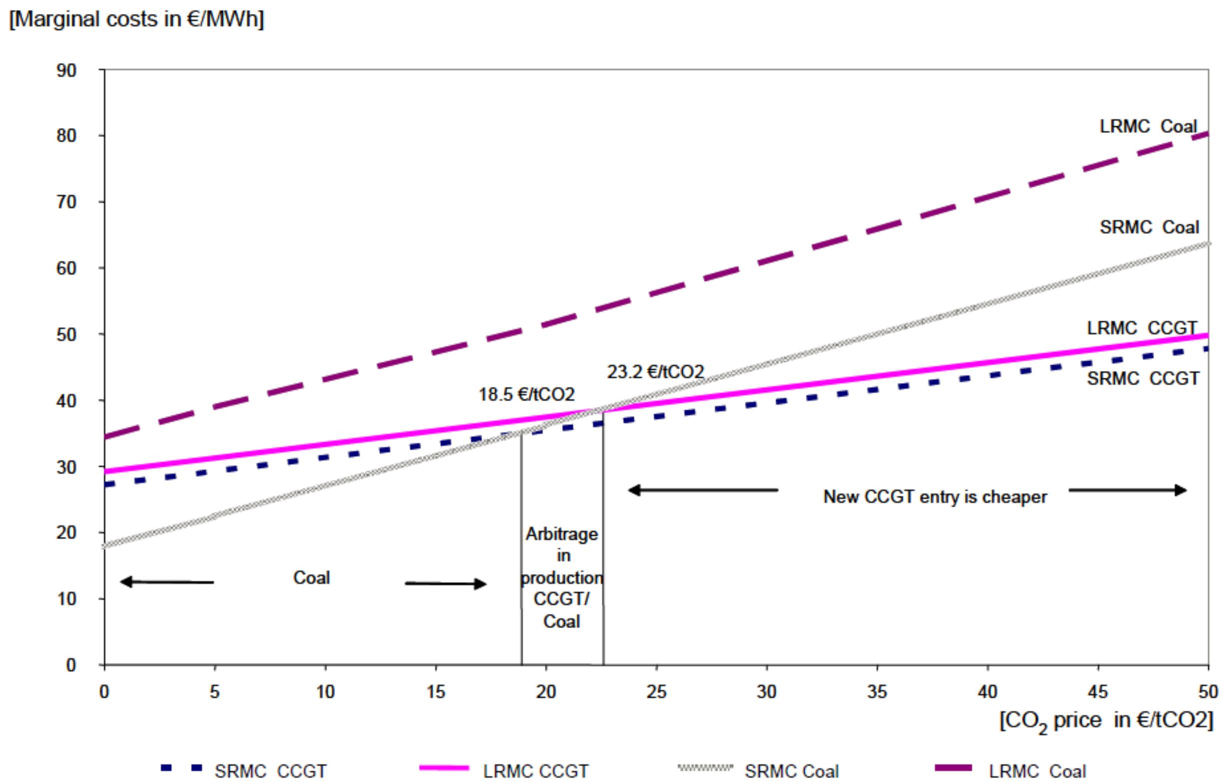


Figure 4-4: Comparison of the competitiveness between existing and new combined cycle gas turbine (CCGT) and coal-fired plants. Source: [43]

Relation between the LRMC and SRMC:

LRMC = SRMC (system is in equilibrium)

LRMC > SRMC (system is over-equipped)

LRMC < SRMC (system is under-equipped)

4.1.2. Marginal cost abatement curve

To understand and present emission trading impact on generation cost of different technologies, global technology-focused marginal abatement cost curves, such as those prepared by McKinsey for this purpose [59] and made them famous – and useful in considering technology priorities and relative costs. Marginal abatement cost curves (MAC curves) on various levels of aggregation can be used as an instrument to estimate abatement costs and potential on the national and global level [60]. Below in Figure 4-5 is a more recent version calculated for the estimation in 2030. The curve in this scenario is highlights the carbon price needed to make certain low-carbon technologies generically financially feasible, but yields other information too.

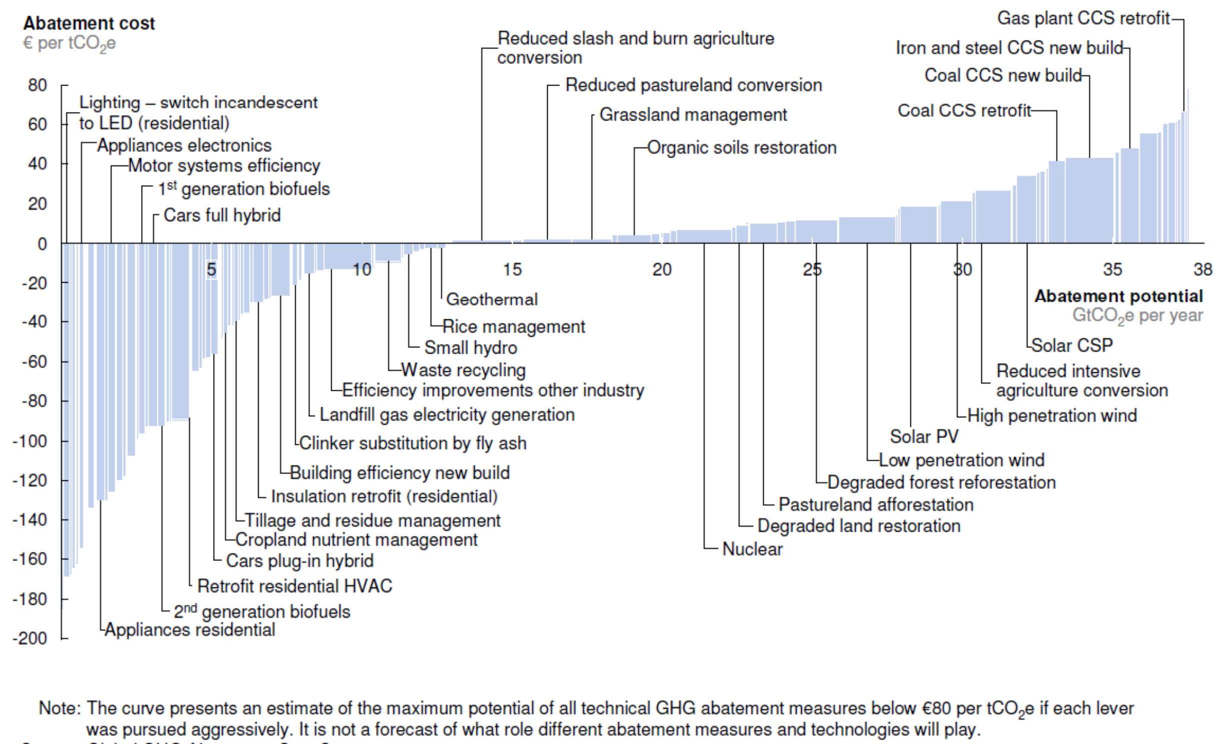


Figure 4-5: Estimation for marginal cost abatement curves in 2030. Source: [61]

The marginal abatement cost is plotted on the y-axis, and the projects ranked against this metric from lowest to highest. The width of the column is equal to the amount of carbon saved by the project, and the area of each column equal to the cost or benefit of the project. Negative MAC values indicate that the project is self-financing, whereas positive MAC values require judgment against the cost of inaction - in this case the cost of the purchase of carbon credits – and/or ethical and marketing considerations.

MAC curves are just as relevant and useful at company level as they are at national level in visualizing the projects necessary to commission in order to hit your business's carbon reduction targets, as well as ranking which projects are best to pursue first in order to gain quick wins and help finance further action. If the MAC of a project is below the cost of buying carbon credits, then the project a financially beneficial alternative to the carbon credit purchase.

4.2. System optimization and planning in restructured power system

In this chapter, regulated and deregulated power systems are assessed from the point how they deliver transition to low emission economy, in order to understand which type of planning brings better results.

4.2.1. Regulated power system and central planning

From a traditional point of view, long term power system planning assumed monopolistic environment and vertically integrated power utilities (which was still the case until few years ago in most of European countries). Power systems used to be taken as single and inseparable part of national economies and therefore, power system planning used to be pointed in that direction.

The main difference between a deregulated and regulated approach is in considering the principles of market competition. The traditional government controlled or heavily regulated investor owned electricity market is considered as a monopoly or vertically integrated utility, as customers have only a single electricity supply company.

The description of the planning problem in regulated system can be stated for the given forecast for electricity consumption: Long term power system development plan needs to be established that minimizes the expected cost of covering the consumption, with all relevant constraints taken into account. The cost (i.e. generation dependent cost) includes [45]:

Generation fuel cost

+ costs for electricity purchasing

- income from electricity sale

- income from sales to interruptible consumption

+ curtailment costs.

If a consumer's demand for firm power is curtailed, the value of this is included in the curtailment cost (and can be expressed as Value of Lost Load, VoLL).

Value of Lost Load (VoLL) represents customers' willingness to pay for electricity service - or avoid curtailment. In electricity markets, VoLL is measured in value (dollars, euros) per MWh. Marginal VoLL represents the marginal value of the next unit of unserved electricity, while average VoLL represents the average value of the unserved electricity and is averaged over a certain time period (one or several years). Average VoLLs are commonly used to inform transmission and generation investment, where it may be more appropriate to estimate customers' willingness to pay over longer periods of time.

In a regulated power system, or a vertically integrated power system, a planning goal is to achieve supply of consumers while at the same time having minimal total costs for achieving that goal. Stability and reliability of the system that need to be met are here to satisfy consumers all the time, delivering desired power quality without blackouts. So there needs to be a constant reserve available in the power system, which might lead to the over-construction of the power system. There are two opposite requirements that need to be met - to minimize the total costs while at the same time maximizing the reliability. Planer or utility company in regulated power system needed to guarantee that installed capacity was able to meet electricity demand within a reasonable Loss of Load Probability (LOLP) or Energy Not Served (ENS) factor at a minimum cost in addition to economic dispatch, generation control, unit commitment and system balance [62].

LOLP is defined as the probability in a given hour the capacity is less than the load or mathematically,

$$LOLP_i = Pr(\Sigma C_j < L_i) \quad (4.1)$$

where

$LOLP_i$ is the LOLP for hour 'i',

C_j is the represents the capacity of generator 'j' in hour 'i' and

L_i is the load in hour 'i'.

ENS is energy that has been lost due to a severe outages (i.e. when $L_{max}>C$).

Calculation of electricity price was done in such a way that all real existing costs needed to be covered - construction, operation and maintenance cost of the power system. Profit for the utility company was not a mandatory requirement.

4.2.2. Deregulated power system and decentralized planning

In a deregulated, restructured or liberalized market (there are slight difference over the terms but in this thesis due to limitations they will be considered as synonyms) there is more than one electricity supply company. Restructuring, deregulation or privatization refers to the introduction of consumer choice and different levels of competition into the electricity market, often called a liberalized electricity market [63]. Such electricity markets can consist of various types of bilateral contracts, futures, options, power exchanges, power pools, power derivatives and ancillary services type arrangements. So when talking about deregulated power system, we can talk about market. Producers have no obligation to serve any specific consumer. Similar restructuring was since 1990 happening in other sectors such as telecommunication, gas sector, transportation sector etc.

The objective for power utility company in deregulated, restructured environment is to generate and sell electricity with maximum profits, which can be formulated in the following way (based on [45]):

For forecasted future market price (which in the long term is a stochastic variable): to establish a production plan (or strategy) that maximizes the expected profit over the planning period, all relevant constraints taken into account.

The profit depends on:

- Income from electricity sales;
- Income from emission trading (with ability of reducing further emissions);
- Costs from electricity purchasing;
- Generation fuel costs.
- Investment costs.

The main problem in application of this theoretical approach as it will be later explained, comes from the fact that perfect market competition is assumed; in other words that producers are price takers and that they don't use their power in the market. The representation of investment timing, long-term uncertainties, policy changes, construction delay and new requirements all have an important impact on the optimal investment decisions.

In liberalized electricity markets the minimization of ENS and a reduction in production costs should be the result in theory – as it was the main driver for deregulation of market and bringing competition. However, new research is showing that this does not always appear to be the case, as the semi-competitive power sector model now operating in the United States and the EU has shown that power system companies can operate more efficiently than before, but it has not delivered significantly greater benefits to consumers than the old model [64]. Financial modelers and policy makers should address those issues whose solution will provide greater benefits to consumers than it is made with existing system.

4.2.3. Regulated vs. deregulated power system in regards to delivering low emission development

What is actually happening is that in restructured or liberalized electricity markets the sale of electricity at a profit is the main business focus where Value of Lost Load (VoLL) has an important role [65]. In reality pricing based on SRMC is not high enough to ensure this, so equilibrium involves a degree of ENS priced at VoLL. Thus the required ENS in a liberalised market is usually higher than acceptable values of LOLP or ENS standard in a regulated, monopoly system. Therefore electricity markets necessitate capacity payment mechanisms or other regulation in order to maintain traditional reliability standards. A review of electricity systems internationally, in both liberalized and monopoly markets indicates that new electricity generation capacity either renewable or thermal generators (like feed-in tariffs for renewable energy sources in most of EU countries, or nuclear power plant Hinkley Point C in UK which is a matter of in-depth investigation of European Commission for its possible impact on the UK and the EU internal energy markets [66].

Thinking about delivering emission reduction from a market, actions are easier from centralized planning. With properly set technologies, results are delivered without setting up specific market mechanisms and policies, repairing and adjusting them to new circumstances (such as taking away emission allowances from the market due to surplus from economic crises). Several proofs to this conclusion are the most recent World Energy Outlook delivered by International Energy Agency which concludes the following [67,68]:

- China through 2035 is expected to build more renewable energy sources than the U.S., European Union and Japan combined;
- In 2013 energy mix in China reached just under 30% for wind, hydro and solar energy, compared with 69% for thermal and 1% for nuclear
- Investments in wind, hydro and solar energy in China in 2013 were almost ten times higher than in USA (55.3 GW vs. 5.9 GW);
- In 2013, China produced more from wind, hydro and solar energy than Germany and France together produced from all their capacities together;
- Today's share of fossil fuels in the global mix, at 82%, is the same as it was 25 years ago; the strong rise of renewables only reduces this to around 75% in 2035. Therefore, radical changes are needed in order to radically change energy sector to low emission one.

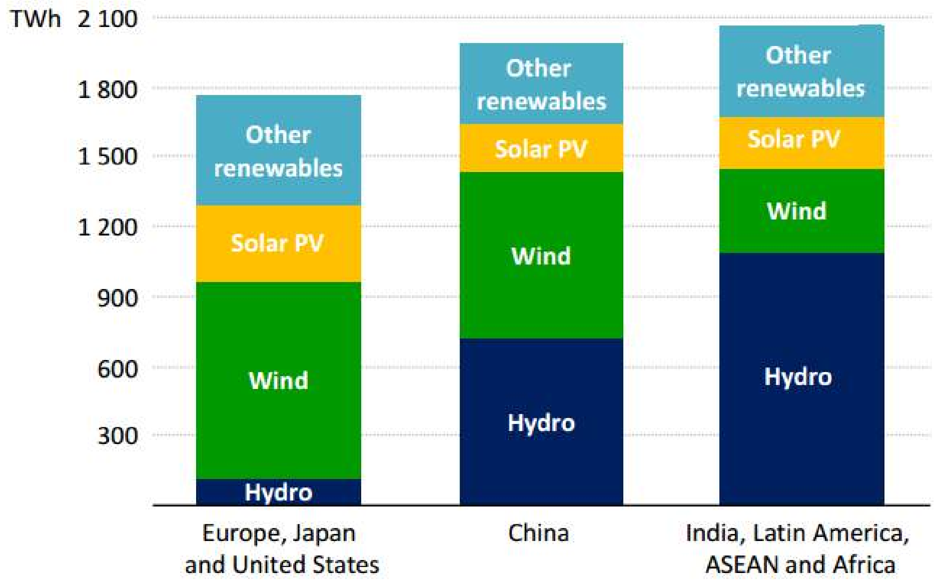


Figure 4-6: Growth in renewable energy electricity generation from renewable energy sources, 2011 – 2035. Source: [67]

The reasons for China as a representative of centralized planning could be understood as issues of energy security and diversity of supply, but also for sure one of the most important are environmental issues which are getting more attention.

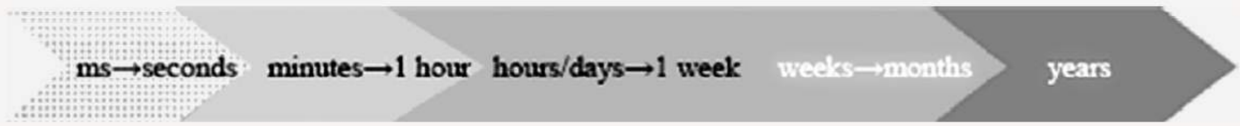
4.3. Long term power system planning

Long term power system planning as it is used in this thesis, refers to finding the optimal combination of new power generation capacities and retirements which minimizes the net present value (NPV) of the total costs of the system over a long-term planning horizon (few years and longer). In this chapter, a process of power system planning will be discussed with the emphasis on challenges in focus of this thesis - a lack of consideration of climate change impacts on power system planning, and change toward low emission technologies imposed by emission trading.

4.3.1. Horizon and challenges in long term power system planning

In broader sense, which is out of limitations and scope of this thesis, long term power system planning also refers to finding optimal combination of transmission upgrades and retirements. To examine the power system the power system planner uses the various management techniques identified in Table below to manage, plan and operate the power system over very short, short, medium and long term.

Table 4-1: Timescales in power systems management, planning and operation. Source: [69]



Time frame	Electricity systems issues	Power systems tools
ms → s	Generator dynamics Motor load dynamics	Transient stability management Power-frequency regulation
min → 1 h	Demand variations	
Very short term	Power interchanges Maintain economic operation Frequency control	Economic dispatch Generation control Power flow Security analysis Fault analysis Voltage stability studies
h/days → 1 week Short term	Weekly generation planning	Demand Weather prediction Unit commitment
weeks → months Medium term	Seasonal generation planning	Demand prediction Maintenance planning Hydro planning Fuel planning
years Long term	Demand growth Plant retirement/refurbishment Investment opportunities Long term hydrological cycles	Generation expansion planning Reliability checks (maintenance) Scenario analysis Production cost modelling

So in a long term perspective, a generation expansion problem should be solved usually for 5-30 years. The reason why it does make sense to focus on such a long period comes from the necessity of trying to capture the conditions in which a plant will work, as a life period of a plant, depending on the type, is between 25 and 60 years, or even more in some cases (such as large hydro power plants or nuclear power plants – especially after refurbishment).

Structure and competitiveness of other surrounding power plants – whole energy and power situation, existing relevant markets, political situation and policy requirements; should be taken in account in order to draw any conclusion about which power plant to build and when to build it. Long term plans which are made are more like backgrounds for building decisions, until the decision is reached about which new power plant (or plants) would be built and when they would be built, from the planning list. As soon as some decision is already made, it has an impact on whole system and new long term power generation plan should be made with included new circumstances. Power system development is a continuous process which every few years generates a new plan.

Prior to the 1973 oil crisis, long term power system planning was much easier that today (taken in account all challenges mentioned in Chapter 1), due to the predictable increases in electricity demand with a shift to predominantly larger generating plants. There has been a consistent increase in electricity generation increases year on year since 1971, with an average annual growth globally of 3.5% [70].

4.3.2. Relevance of long term power system planning in the scope of emission trading, climate change and sustainable development

Power system developers today needs to have in mind three important challenges:

- Decisions on building new power plants which are made today will have impact for the next 30-60 years;
- According to the Fifth Assessment Report by IPCC, serious emission reduction action needs to take place before 2030 in order to limit CO_2 rise in levels which do not bring unmanageable climate changes to the environment (and rise above 2°C);
- Demand and consumption planning should take in account climate change impacts and adaptation issues.

As presented in Chapter 4.1. of the thesis, in order to have impact on a power system development price of emission allowances should be equal the lowest marginal abatement cost. This would send signals to investors for a shift towards a creation of power system that has lower emission intense fuel mix at the cheapest cost. The switch from coal to gas is one of the keys of this mechanism, but switch to renewable energy sources is what has the highest impacts on sustainable development. Closing of GHG emission intensive power plants (such as lignite, oil and coal) and transit to low emission technologies will lead to actual emissions reduction, but markets need to be designed in such a way to support this progress in a long term. But, what research is suggesting (overview is in [69]) is that long term power system planning in today's power system market regimes doesn't appear to be a priority; instead power utilities are driven by short and medium term development plans, which profit driven for the shareholders.

As a conclusion, it is suggested that a revision of energy policy plans, which prioritize long term power system planning and inclusion of three mentioned challenges needs to be considered by governments. Existing policies need to be revised and strengthened, and new mechanisms set up that could provide smaller, but less risky long term financial return on investment with the added benefit of sustainability and investments in power system infrastructure.

5. MODELING OF A POWER SYSTEM AND ITS IMPACT ON SUSTAINABLE DEVELOPMENT

This chapter gives extensive classification of energy and power system models – and focuses on main elements of differentiation. In order to enable long term power system planning and to analyze emission trading impact on competitiveness of low emission solutions, first goal was to identify what kind of models would be most appropriate to use – which type of power system model or maybe even energy model. It also gives introduction to how power system model functions on example of model PLEXOS that was later in the thesis chosen for verification of proposed methodology. It also gives introduction to use of sustainable development indicators to measure the progress in low emission transition – which is also an element in proposed methodology.

5.1. Classification of energy and power system models

5.1.1. Model classification

To achieve better understanding which would help to identify appropriate model to use in this thesis, a comprehensive model classification was performed which resulted in choosing the model to pursue with in testing the methodology. Also an existing experience in using energy and power system models so far in Croatia was performed.

The purpose of energy and power system modeling is to create tools for decision support in energy and power system planning and policy making. An energy or power system model should be the basis for any energy or power system planning decision, as large amount of information needs to be taken in account in planning. First energy system modeling in the past was performed by using economic theories and mathematical models. In the time of first energy crisis in the 1970s [71], growing need was recognized for better description of technical parameters within the energy system. This is when first optimization linear models appeared, which were constructed in order to consider both technical and economical description of energy system. Various models were developed for modeling many parts of energy system (like gas, electrical, district heating) but these are not able to describe the system as concisely as models focused on only one part of energy system, such as power system models.

Focus in this thesis is on modeling power system, emphasizing both technical description and economical parameters relevant for electricity market representations and modeling. Two technical features determine the complexity of such models: the product ‘‘electricity’’ cannot be stored and its transportation requires a physical link (transmission lines). This is why power system modeling usually requires the representation of the underlying technical characteristics and constraints of the production assets. The human mind simply cannot deal with such complexity and these answers cannot be given intuitively, while simple economic or financial models cannot do proper description of electricity market.

Today’s electrical energy field is characterized by new challenges such as deregulation, liberalization of energy markets, increased competition on different energy markets with growing demand for security of supply (together with ever growing percentage of imported energy resources [72,73]. Decentralization and liberalization of the national energy sectors appeared in 1990s [74], and systems that were once nationally owned and integrated have been transformed with the idea that market mechanisms will increase efficiency in energy supply. Old centralized least-cost planning approach does not reflect how investment decisions are made in today’s electricity markets, where generating companies are competing with each other, both in short-run operations and long-run investments [75].

As presented in Chapter 2, the 1992 Rio de Janeiro Earth Summit ended with industrialized countries signing an agreement, Agenda 21 which defines sustainability as “a way of thinking and acting that would not irresponsibly and irreversibly damage the ability of future generations to satisfy their own needs”. Sustainability can be defined in many ways and in relation to different issues such as economic and environmentally sound development, reduction of greenhouse gases, responsible use of natural resources, social equity, etc. Some of challenges concerning sustainability relevant for power system are satisfying minimal production fraction from renewable energy sources, constraints on emissions or minimal energy efficiency goals. Other challenges in energy planning that need to be modeled are price insecurities of investments and energy resources, or CO_2 emission price on emission market. All challenges mentioned above are calling for consideration of various options (like nuclear, coal, gas or renewable scenarios) and better understanding of energy system planning in order to optimize proper energy mix and lead to satisfying development of electrical system.

Existing models have proved not sufficient anymore and there appeared a need for modelers and planners to think differently in order to face present challenges (or those that are about to come). New decision support tools and methodologies are needed, to ensure adequate planning of power supply for the coming decades. Such a model, on the basis on performed simulations, should enable planner to distinguish between different options. It is important to mention that model is just a tool, a decision aid, and the planner is the one who (from the obtained information and from the knowledge of the system and constraints) should bring conclusions. The blackouts and market failures are an indication that power systems and energy markets still lack proper modeling, forecasting and understanding. Modeling is a source of understanding that constantly asks for new approaches, investment in new methodologies, models and data. While the benefits of improvements in models are hard to quantify, the costs are tiny compared to the essential role of electricity systems and markets in our societies.

By term model, mathematical description in the form of mathematical algorithm is implied. Energy models are generalized descriptions of the real energy systems, and depending upon the modeling purpose, the level of detail needed and the assumptions made, system can be modeled by considering different levels of system parameters complexity.

Intention of this chapter is to present broad range of energy and power system models and to further focus on power system models. These models should provide understanding on the topics on which this thesis is focused, as climate change impacts on low emission technologies (and more specifically impacts of generation from intermittent renewable energy sources, influence of emission trading on electrical system) provide basis for multi-criteria analysis of generation system expansion optimized solutions.

With progress of computer technologies (improvement of both hardware and software), expansion of different models was enhanced, but many of them are not satisfying to answer on today's challenges in power system, or didn't have strong financial background so are not used any more. Models were usually developed in research institutions or (less common) in energy companies. Many models however were developed to describe needs of specific energy or power systems and are not appropriate for broad, general use. Up to today, just a limited number of models were developed which can satisfy needs for description of wide-range power systems.

As the area of energy and power system models is under strong development, it is not easy to provide uniform classification of models. This classification is important in order to choose appropriate model, that would fit the needs of the planner and that would give relevant results on how the power system will react in different situations. Depending on the purpose of the specific model, models can be distinguished by various factors, but the most common factors are the following [76,77]:

- Level of detail in modeling the system;
- Spatial or time resolution;
- Focus on one or more energy resources;
- Mathematical approach;
- Methodology used;
- Specific or general models;
- Degree of competition for market modeling;
- Top-down or bottom-up approach;
- Uncertainty modeling;
- Computational tractability;
- Technology representation;
- Empirical verification parameters.

As it is already pointed, model is just an attempt to simplify reality and to describe it within mathematical form. Some of the models mentioned here are those applicable in modeling energy systems, but have little value in modeling power systems and even less in modeling electricity markets.

Specific and general models

Specific models are made to simulate the work of specific region, country or utility and cannot be used in other region, country or utility. There are very few general models that can be used for answering broad range of questions in different regions, technical systems, and markets or simply under different conditions.

Different aspects of model are developed to provide answers depending on the specific focus, such as [78]:

- Unit commitment;
- Risk management (fuel price uncertainties, wind, hydro or solar generation uncertainties);
- Strategic bidding;
- Market power analysis;
- Capacity expansion planning (various development options);

- Congestion management;
- Short-term and long-term hydrothermal coordination;
- Future demand analysis;
- Simulation of market designs;
- Yearly economic planning;
- Simulation of environmental impacts;
- Evaluation of various options;
- Security of supply simulation;
- Influence of CO_2 emissions on electricity production;
- Modeling external costs (environmental impacts);
- Impacts of nuclear power plant generation in the system (new plant);
- Transmission planning opportunities.

Top-down or bottom-up analysis

The main difference between top-down and bottom-up analysis is whether the focus is put more on economic or engineering aspects. In top-down models, the energy or power system is represented with very little technical details - more or less as a black box. It starts with an economic model and represents the relationships between energy consumption and national products by using prices and elasticity as economic indices. These models can be econometric or parametric and are used to describe the relationships and synergies between the energy sector and other sectors of the economy. There is very little possibility to model technical aspects with these models, and their main use is found in energy policy making, technology assessment, predicting future market developments through historical energy-economy interactions and customer's behavior in reaction to changes in prices.

Top-down models start with an economic model and represent the relationships between energy consumption and national products by using prices and elasticity as economic indices. Bottom-up models focus on the activities of the people who deal with energy consumption and production, plus the changes in technologies. Based on detailed descriptions of these items, they calculate the total energy consumption and production from the "bottom-up"

Bottom-up models are showing a fairly detailed representation of different technologies and components of the system. In general, large amounts of information are required to describe such systems and such models with detailed technical representation are sometimes called engineering models. First bottom-up models have been raised by further development of energy production planning models. In most cases, bottom-up models are large scale linear optimization programs that provide solutions for optimal allocation of resources and energy carriers under a set of technical, economic or environmental constraints. With progress of computer technologies, the difference between bottom-up and top-down approaches is decreasing since new hybrid models are appearing which use combination of both approaches.

Degree of competition

Different levels of competition that are used in modeling are monopoly, oligopoly and perfect competition. Each level of competition requires different approach, as perfect competition is modeled as a cost minimization or net benefit maximization problem, while a monopoly can be modeled by the profit maximization program of the monopolistic firm. These models are usually optimization-based, and the price is derived from the demand function. In oligopoly competition, suitability of each model depends on the time scope (short, medium or long). The simplest models are competition-based models for perfect competition, since they consider the price clearing process as exogenous to the optimization problem. More complex are models based on the leader-in-price concept, while the most complex market models are those based on imperfect market equilibrium as they take into account the interaction of all participants.

Time scope

There is no standard definition of for how long does the time last in short, medium or long term within power system models – it mainly depends on the model purpose. For power system models focused on spot market modeling, short term could mean everything from few minutes to few hours, while in generation expansion planning model short term could be from one week to one year. In a model covering one to few years, short term is considered to last few days, medium term last for few weeks or months while long term describes time periods from one to more years. Each time scope involves both different decision variables and different modeling approaches. Models focused on short term operation of the system are usually describing with sufficient details a fixed technical system and a given economic framework. In such models start-ups and shut-downs or ramp rates are becoming significant decision variables, while the maximum capacity of each generator is considered to be fixed. On the other hand, in long term planning models capacity-investment decisions are the main decision variables while unit commitment decisions are usually neglected. Long term simulation models used in strategic planning are used to analyze long term technological and socio-economic developments.

Modeling uncertainties

Modeling uncertainties (price uncertainties, production from intermittent renewable energy sources like hydro or wind, levels of demand) is usually done by either running more scenarios with different variables or by using random values which can be associated with variables in the model. Analytical tools need improved ways to model uncertainties and its effect on the investment decisions [79]. With higher risks or with improperly understood risks which are not allocated fairly among investors and consumers, investments in energy or power systems are difficult to happen. Better modeling of the uncertainties and the adaptability of future investments to these uncertainties can help to build a consensus on the risks and sharing of the risks of power system infrastructure investment. In probabilistic, dynamic models the uncertain nature of random variables is incorporated using probabilistic distributions, which results in large-scale stochastic problems that require complex solution techniques. Models in which expected values are considered are static or deterministic models, and these models are especially suited to calculate least-cost strategies under certain boundary conditions.

Technology representation

Depending on the model purpose, technology can be modeled under general assumptions or very explicitly. The difference on technology representation can be most easily found in transmission, where two main types of transmission representation in electrical system models [76] are used. Single-node models are the most common and usually used within electricity market models. In such a models, constraints in transmission lines or loses are not taken in account. On the other side, transmission network models have good consideration of both of Kirchhoff's laws, transmission loses and constraints, and therefore can provide better description of reality in the model.

Computational tractability

Optimization-based models are using optimization algorithms (Linear Programming (LP), Dynamic Programming (DP), Quadratic Programming (DP), and Mixed Integer Linear Programming (MILP)) and have ability for more detailed modeling. Equilibrium-based models need complex mathematical programming methods, while simulation models are very specific, and based on assumptions that are particular depending on the model.

Empirical verification parameters

Verification of model results can be done by comparing results with those from some other, reliable models (lab data), regression analysis, literature and expert judgment.

Methodology used

Methodology used in models can be described in various ways, so the one presented below is just one of them, analyzed by different methodology types. Some of methodologies presented can be used for modeling energy sector but are not applicable in power system modeling, while methodologies that have better technical representation or computational possibilities are widely used for power system modeling.

Econometric models

Econometric models are using statistical approach to solve economic problems. They use statistical methods to extrapolate history trends for use in the future. Depending on the model variables availability results are more or less correct. First models for demand-forecasting developed were econometric models. These models don’t have description of technology, require a lot of input data and economic stability since results depend on historic trends. Due to specific nature of electricity, these models are very poor in description of electricity market models.

Macro-economic models

Macro-economic models are used to analyze total economy and interactions between sectors. As energy sector is just one of sectors applied in analyzing the total economy, these models cannot be really called energy models (even though they can be used to model energy sector), but are irrelevant for modeling power system.

General equilibrium models

While econometric and macro-economic models are usually used for short term and medium term analysis, general equilibrium models are used for long term analysis. They are based on a fact that all agents are optimizing their market behavior, and their market mechanism works on market clearing concept (there are no surpluses of demand or supply on the market). As they don’t take in account technological description, they can provide general conclusions but not exact market description (like in the form of electricity price on the market in specific time period).

Optimization models

These models are used for reaching optimal investment or resource allocation strategies. Techniques that are usually used to get results include LP, DP, QP and MILP. They take into account relevant operational constraints of the generation system as well as the price clearing process. Depending on price clearing process is represented; these models can be classified by price being modeled as an exogenous variable and by price modeled as a function of the demand supplied.

Exogenous variable present the lowest level of such modeling since the system marginal price is an input parameter for the optimization program. As these models are neglecting influence of companies on market price, they are applicable only for perfect market conditions.

Other group of models that considers companies` influences on market price is based on microeconomic theory, by the so-called leader-in-price model (which describes the behavior of one firm that pursues its maximum profit taking as given the demand curve and the supply curve of the rest of competitors). The problem with optimization models is that this kind of approach is realistic only to some point (although they have good use in short-term modeling), while in long term planning they need to include additional market strategies. Most of the optimization models that are used within power system share the following structure [80]:

- An economic objective, such as "minimize the variable cost of generation" for short term model, or "minimize the present worth of capital costs, operating costs, and outage costs" in a resource planning model;
- A set of decision variables representing the design options open to the utility (in short term modeling the loads carried by each generating unit, or in long term modeling, resource amounts and timing, fuel sources, environmental constraints…);
- A set of constraints defining which values of the decision variables are feasible - constraints derived from physical processes and capacity limitations, environmental regulations, financial and economic constraints that relate expenditures, prices and demands.

Equilibrium models

Approaches which explicitly consider market equilibrium within a traditional mathematical programming framework are grouped together into the equilibrium models category. Of two commonest types of equilibrium models, one is based on Cournot competition (where firms compete in quantity) and another one is the supply function equilibrium approach (SFE) [81], where firms compete both in quantity and price. Although these approaches differ in regard to the strategic variable (quantities vs. offer curves), both are based on the concept of Nash equilibrium—the market reaches equilibrium when each firm's strategy is the best response to the strategies actually employed by its opponents.

Cournot is more flexible and tractable, and for this reason it has attracted more interest (Cournot equilibrium is easier to compute than SFE because the mathematical structure of Cournot models turns out to be a set of algebraic equations, while the mathematical structure of SFE models turns out to be a set of differential equations).

Simulation models

When the problem under consideration is too complex to be addressed within a formal equilibrium framework (a set of too many equations that is complex to solve), simulation models are providing good alternative. What distinct these models is the possibility to analyze each agent's strategic decision dynamics and simulate different what-if scenarios. Disadvantage might be the fact that final results don't provide answers on all questions, nor do they provide the most optimal solution. Simulation models are based on logical description of a system, which might get very complex. This is also their biggest disadvantage, as sometimes model is trying to combine description in too many details (which might lead to system breakup), or in too little details (which leads to lower authenticity).

Very often, simulation models are related to some equilibrium models [75] (like in description of profit maximization objective of several generation firms) while taking in account the technical constraints that affect generation units and transmission constraints. The decisions taken by the generation firms are derived with an iterative procedure.

Multi-criteria models

Multi-criteria models are analyzing the situation where the available options have to be judged against several criteria (economical, ecological, social…). Different types of multi-criteria problems are [82]:

- Choice problems: when a simple choice must be made from a set of possible actions (or decision alternatives);

- Sorting problems: when actions must be sorted into classes or categories such as ‘definitely acceptable’, ‘possibly acceptable but needing more information’, and ‘definitely unacceptable’;
- Ranking problems: when actions must be ranked according to some sort of preference order, which might not necessarily be complete;
- Learning (descriptive) problems: when actions and their consequences must be described in a formalized manner so that decision-makers can evaluate them;
- Design problems: which imply searching, identifying or creating new decision alternatives to meet the goals and aspirations identified through the MCDA process;
- Portfolio problems: when a subset of alternatives must be chosen from a large set of possibilities, taking into account not only the characteristics of the individual alternatives but also the manner in which they interact and the positive or negative synergies between them.

The problem of decision making in the electrical sector under availability of many criteria is far from being investigated [83]. One of options is to combine multi-criteria modeling with results from other models, such as optimization or simulation models.

Multi-agent models

Static models are unrealistic because they seem to neglect the fact that agents base their decisions on their past experience, that they improve their decision-making and adapt to changes in the environment. Need for description of such agent behavior has been met with multi-agent systems (systems having two or more software agents). Software agent is a piece of software that represents a participant and acts as one (in our case this participants might be market operators, traders, producers, suppliers or something else). These adaptive agent-based simulation techniques can analyze features of electricity markets that static models cannot handle. First multi-agent models use in simulation of electricity markets started very recently – in year 2000 [84], and was focused only to short term planning. New models are enabling more realistic simulation and are today also used in long term planning. Their advantage is to simulate many market participants with centralized decision making, ability to modify, wide possibility to implement market strategies, and possibility to influence other market participants (by communication). Another advantage is possibility to analyze profit maximization of different market participants (with different strategies and goals) on deregulated market which differs from profit minimization which was dominant planning goal on centralized market.

5.1.2. Representation of different energy and power system model classes

It is already mentioned that different authors tend to make model classification by taking in account different aspects. Here, existing model classes will be presented taking three different classifications approaches – **first one** is author`s own representation in Figure 5-1.

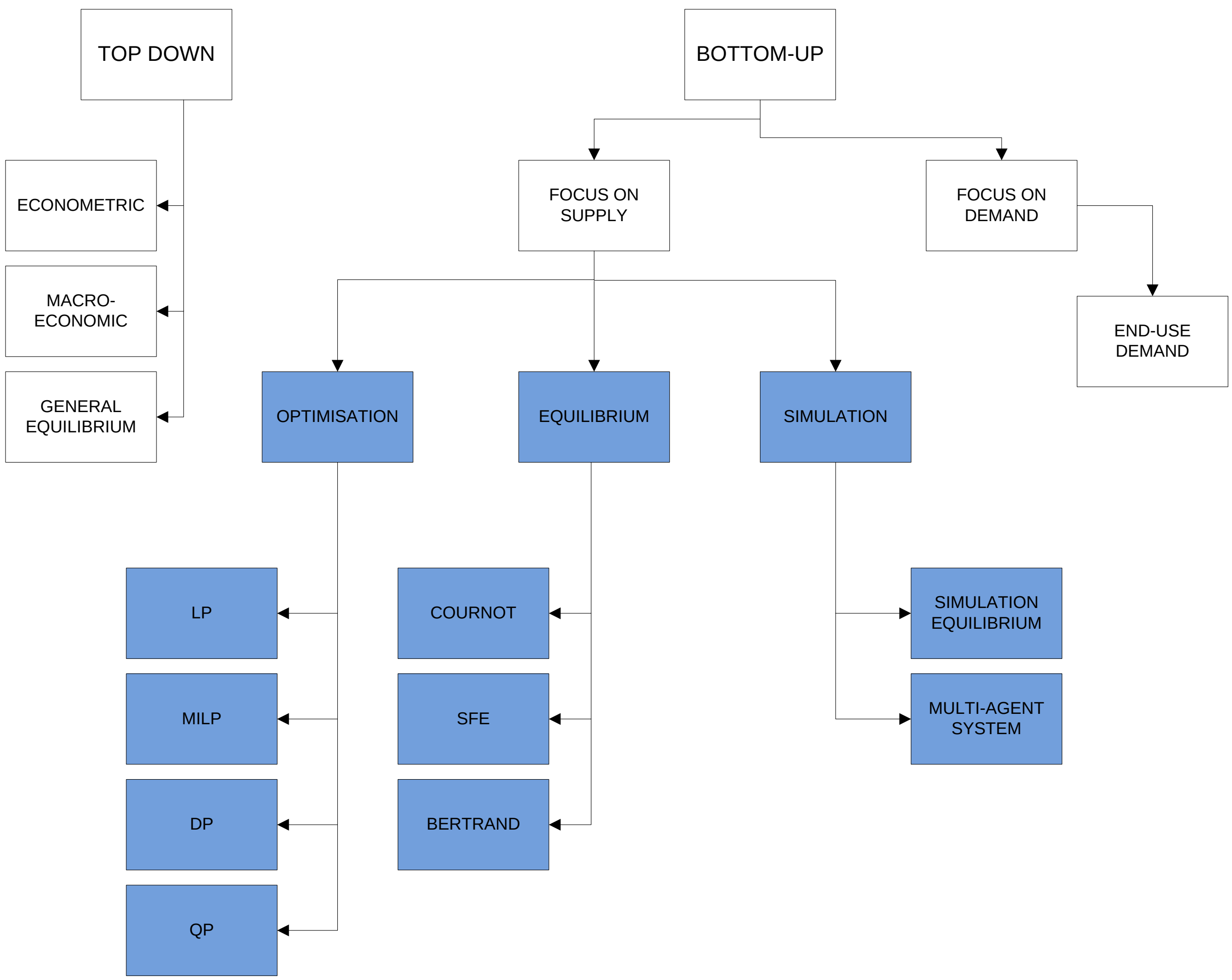


Figure 5-1: Classification of different energy and power system model classes correlated with definition of models presented in this chapter. Those marked with blue are suitable for modeling power system, while those marked with white are suitable for energy models. Source: own schematic representation

Second approach for classification of models is based on a paper [76] who proposed representation of electricity market modeling trends by focusing on approach “who uses the model”. It is presented in Figure 5-2.

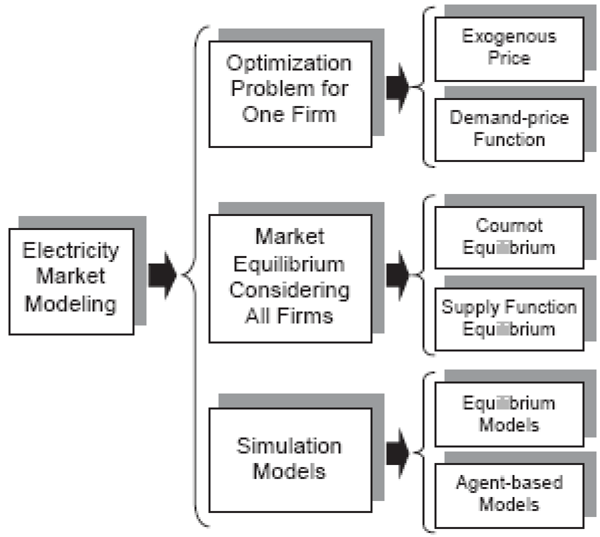


Figure 5-2: Representation of classes for electricity market models. Source: [76]

In this representation, objective of one firm is profit maximization. Mathematical structure of such models is a single optimization function that is a subject to a set of technical and economic constraints. It can further be differentiate by putting exogenous price (the lowest level of market modeling when system marginal price is an input parameter for the optimization program) and demand price function (which explicitly considers the influence of a firm's production on price). Approaches which explicitly consider market equilibrium within a traditional mathematical programming framework are grouped together into the equilibrium models category. As mentioned earlier, there are two main types of equilibrium models. The commonest type is based on Cournot competition, in which firms compete in quantity strategies, whereas the most complex type is based on SFE, where firms compete in offer curve strategies. Both types are based on the concept of Nash equilibrium—the market reaches equilibrium when each firm's strategy is the best response to the strategies actually employed by its opponents. Simulation models are an alternative to equilibrium models when the problem under consideration is too complex to be addressed within a formal equilibrium framework. Simulation models usually represent each agent's strategic decision dynamics by a set of sequential rules that can range from scheduling generation units to constructing offer curves that include a reaction to previous offers submitted by competitors.

Third approach for classification of models is based on programing method used [69], which defines main approaches:

- Stochastic Optimization (SO) – which uses algorithms that incorporate stochastic probabilistic elements, either in the objective function and the constraints, or in the algorithm for random parameter values and random choices, or in both. It includes MILP, LP, NP and ILP, and usually this type of optimization requires a solver and code;
- Dynamic Programming (DP) methods - a method used to solve complex problems by dividing them into simpler sub problems (e.g. shortest path). DP algorithms are typically implemented in special purpose software finding least cost expansion plan;
- Other techniques that use artificial intelligence theory, Genetic Algorithms, game theory, network flow theory and fuzzy set theory.

5.1.3. Models used in power system modeling

Models for energy system description and assessment are in most of the cases optimization models. In these models, demand is an input, and model is using mathematical programming and least-cost approach in order to find optimal solution. For description of power system and modeling electricity markets, these features alone are not enough and such models need to have other possibilities. List of these models studied for their application in proposed methodology is presented in ANNEX 2: A LIST OF MODELS USED IN POWER SYSTEM MODELING.

5.1.4. Existing experiences with power system modeling in Croatia

Power system modeling in Croatia has started together with energy system modeling in 1980`s by first using general equilibrium techniques and then developing domestic model SIPRA [71]. Models MAED and WASP were introduced by IAEA seminars and these models were used in Croatia during late 1980`s.

After Croatian independence, during economy transition and democratic changes, in year 1994 project PROHES started (Program for development and organization of Croatian energy sector). Main goals of the project were to reorganize energy sector according to energy, economical, legislative and organizational aspects. On this basis, TC project (Technical Cooperation) named "Energy and Nuclear Power Planning Study" was started which lasted from 1997 to 1998. Integrated study on energy sector and power system planning was done with IAEA software package ENPEP (MAED, WASP, BALANCE, IMPACTS). Results from the project were also used in development of Croatian Energy Strategy in 1998. Model WASP was used in 1998 for preparation of "Master Plan for long-term development of electrical energy sector". Results of power system modeling were further compared with other, previously used models (SIPRA, LOGOS). Use of different models from planning package ENPEP (MAED, WASP, BALANCE, IMPACTS) within PROHES project is shown on the figure bellow. With dashed line, connection between models and national energy programs or studies is presented (for these studies, results from ENPEP models were used).

Other models used in Croatia to model energy system are MESSAGE and MARKAL, while for electrical system modeling DECADES/DECPAC was used.

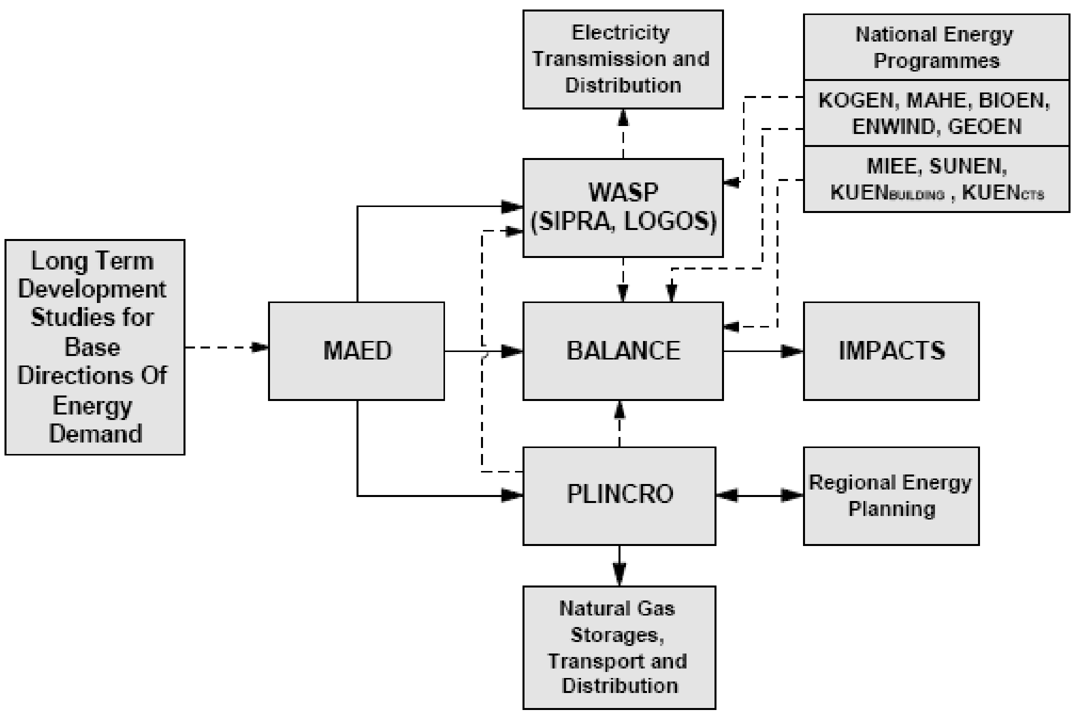


Figure 5-3: Use of different models from ENPEP package within project PROHES. Source: [71]

In year 2005 model PLEXOS was purchased for modeling use at University of Zagreb, Faculty of Electrical Engineering and Computing. PLEXOS capabilities were studied to analyze Croatian electrical system in two joint projects with Croatian power utility HEP Group – “Analysis of Croatian Electricity Market with Market Simulator” [85] where they are not found satisfying, and then in project “Simulator Development for Analysis of Emission Trading Impacts on Electricity Market” [78] where more comprehensive understanding of model was achieved, as well as confidence in model developers. Up from year 2007, PLEXOS has also been used, upon these positive experiences, in Energy Institute "Hrvoje Pozar" in Zagreb, and more recently in Faculty of Electrical Engineering in Osijek (starting from 2009). HEP Group has purchased multi-agent EMCAS simulator, but further activities and application for modeling Croatian electrical system were suspended. In year 2012, HEP Group purchased PLEXOS for modeling Croatian power system.

Within the studies performed at Faculty of Electrical Engineering and Computing [78, 86], need for further work on power system simulator was recognized and emphasized in order to achieve better understanding and provide modeling tool for Croatian power system planning. There are many market or technology features that have not been properly understood or modeled so far within Croatian power systems, and which need to be addressed using a model such as PLEXOS that can do proper representation of them.

Needs for better power system representation in model were also recognized within SSG-WI study conducted in 2003 for Western USA region [79], that had objective of identifying opportunities where the development of additional power and transmission facilities could further facilitate competitive and efficient markets. During the project, the following list of "opportunities for improvement "in long-term modeling was identified:

- Modeling the physics and economics of resource adequacy and reliability;
- Modeling dynamic dispatch of cascaded hydro plants, wind and solar;
- Accounting for uncertainty in inter-temporal decision logic affecting longer-term resource acquisition, hydro storage, annual maintenance scheduling and unit commitment decisions in an appropriate manner;
- Simulating spatial and temporally correlated uncertainty in hydro inflows, runoff, and bus bar loads in stochastic manner;
- Simulating short- and long- term uncertainty in fuel prices and load growth in stochastic manner;
- Tracking net revenues and costs to owners and end-users;
- Simulating gaming market-power behavior;
- Simulating multi-year study horizons;
- Dynamically scheduling annual maintenance;
- Evaluating system performance under high risk, low probability events, e.g., severe weather excursions, etc;

- Adapting program formulation to changes in constraints, decision logic, dimensionality, advances in technology.

All these requirements also need to be addressed in modeling Croatian power system. There are very few state-of-the-art software products available to address some or many of the desired model improvements described above. One of them is PLEXOS, which will be used as a part of proposed methodology within this thesis, for modeling power system, and which will be described later in this chapter.

From 2010 model GAMS is being used at University of Zagreb, Faculty of Electrical Engineering and Computing. Main purpose of model use is modeling hydro power plants in Croatia [87] – cascades, assessment of projects for building new planned hydro power plants etc.

5.1.5. Experiences with modeling impacts of GHG emissions on a power system

Within project “Assessment and Improvement of Methodologies used for GHG Projections” [88] in 2008, various EU climate change policies and measures were analyzed (EU-ETS, renewables directive, CHP directive, directive on the improvement of end use energy efficiency, biofuels directive). Project goal was to make an overview on the methods used to quantify these policies and measures in EU member states.

Figure 5-4: Use of different model types in power system within EU member states. Colors in legend follow as: Econometric, Optimization, Engineering, Simulation, No info provided. Source: [88]

Table5-1. Overview of model use for EU ETS simulation in EU member states. Sources: [88]

Country	Type of model	EU ETS in theory	Country	Type of model	EU ETS in theory
Austria	Econometric	partial	Ireland	Engineering	no
Belgium	Engineering	yes	Italy	Optimization	CO_2 tax
Bulgaria	End-use demand	no	Latvia	Optimization	CO_2 tax
Cyprus	Simulation	partial	Lithuania	End-use demand	yes
Czech R.	Optimization	CO_2 tax	Netherlands	Engineering	yes
Denmark	Econometric	partial	Poland	Simulation	partial
Estonia	Optimization	CO_2 tax	Portugal	Simulation	partial
Finland	Optimization	CO_2 tax	Romania	Simulation	partial
France	End-use demand	yes	Slovakia	Simulation	partial
Germany	Engineering	yes	Slovenia	Engineering	yes
Greece	Simulation	partial	Spain	Engineering	yes
Hungary	Econometric	partial	Sweden	Engineering	yes
U. Kingdom	Econometric	partial			

Project results are showing that models are being used in most of EU member states for modeling impacts of renewable energy sources and combined heat and power (CHP). On the other side, modeling is less used for modeling emission trading scheme, even less for flexible Kyoto mechanisms (JI&CDM), while modeling energy efficiency was reported only in Belgium.

5.1.6. Modeling pass through rate and windfall profits from EU ETS, phase 1 and phase 2

Presented studies have applied a power system and electricity market model to simulate impacts of EU ETS on the performance of the power system in specific countries, including its impact on electricity prices. As one of the set hypotheses is that emission trading are rising competitiveness of low emission technologies in a power system, it needs to be modeled according to the methodology set later in the thesis.

Table 5-2: Overview of modeling studies on the impact of the EU ETS price during the EU ETS phase 1. Source: [54]

Study	Country	Model	CO_2 price	ETS-induced increase in power price [€/MWh]
IPA (2005)	UK	Dynamic	15-25	5-16
Kara et al. (2007)	Finland	Static	20	15
Linares et al. (2006)	Spain	Dynamic	7-15	3-5
Oranen (2006)[a]	Nordic area	Static	20	1-8
Sijm et al. (2005)[a]	Belgium	Static	20	7-4
	France			2-5
	Germany			10-19
	The Netherlands			5-11

IPA, 2005 [89] – the study uses model called ECLIPSE, and simulates the complex interactions in the UK market, including the interface with renewables obligations, environmental regulations and emissions trading. Another model, European Power System Model (EPSYM) is used in order to compare the impact of the EU ETS on wholesale power prices in Great Britain and Northern Ireland to the impact on similar prices in France, Germany, Italy, and Spain. Modeling analyzed impact of the EU ETS on power prices over 2005-2020 according to three scenarios, a Base Case (assuming 15 €/tCO_2 for Phase I, 20 for Phase II and 25 for Phase III), a Low Case (with lower CO_2 prices per ton) and a High Case (higher CO_2 prices).

Kara et al., 2007 [90] – analyzed impacts of the EU ETS on power plant operators, energy-intensive industries and other consumer groups, specifically in Finland as well as, more generally, in the other countries of the common Nordic electricity system. The model balances the generation of electricity between thermal, hydro power and other power sources in order to minimize total variable costs. Results show that annual average electricity price in the Nordic area is estimated to rise by 0.74 €/MWh for every 1 €/tCO_2 allowance costs, meaning full pass through of carbon prices.

Linares et al., 2006 [91] – study uses model called ESPAM, a technology-detailed, oligopolistic market model of the Spanish power system which simulates expansion of generation capacity and endogenously determines CO_2 allowance prices (based on some stringent supply and demand assumptions). Modeled period is 2007-2014, and price projected in 2014 is 15.2 €/tCO_2, resulting in a power price increase of 5.4 €/MWh.

Lindboe et al., 2007 [92] – study uses Balmorel model, which covers the electricity and district heat sector of Germany and the Nordic countries (Denmark, Finland, Norway and Sweden). Balmorel is a dynamic partial equilibrium model that simulates welfare-economic optimal dispatch of generation capacity, consumption, transmission as well as performing investments in generation technology. Some of the findings from study show that allocation to new entrants is a substantial investment subsidy. For example, at 20 €/tCO_2 in Germany, the income from the sale of allowances is able to cover more than 60% of the total capital costs of a new plant!

Oranen, 2006 [93] - aims to find out how dominant firms in Nord Pool will react to the EU ETS and how this will affect the price of electricity in the Nordic countries. Cournot oligopolistic market model based on a Nordic merit order supply curve and a constant elasticity demand function is used.

Table 5-3: Results from modeling ETS impacts on Nordic power system, using Cournot's competition (CC) and perfect competition (PC). Number 20 inPC20 and CC20 indicates emission price 20 €/tCO_2. Source: [93]

		Winter[a]				Summer			
Elasticity 0.05		PC	PC20	CC	CC20	PC	PC20	CC	CC20
Marginal technology		CHP biofuel	Gas	CHP biofuel	Gas	CHP coal	CHP coal	CHP coal	CHP coal
Power price	[€/MWh]	39	43.3	56.68	98.93	15	22.82	15	22.82
Pass-through	[%]		59		578		100		100
Elasticity 0.1									
Marginal technology		CHP biofuel	Gas	CHP biofuel	Gas	CHP coal	CHP coal	CHP coal	CHP coal
Power price	[€/MWh]	39	43.3	46.19	62.43	15	22.82	15	22.82
Pass-through	[%]		59		223		100		100
Elasticity 0.4									
Marginal technology		CHP biofuel	Gas	CHP biofuel	Gas	CHP coal	CHP coal	CHP coal	CHP coal
Power price	[€/MWh]	39	43.3	40.29	44.04	18.96	22.82	18.96	22.82
Pass-through	[%]		59		51		49		49
Elasticity 1.0									
Marginal technology		CHP biofuel	Peat	CHP biofuel	Peat	Peat	CHP coal	Peat	CHP coal
Power price	[€/MWh]	39.2	40.91	39.44	42.58	22.56	24.32	22.39	24.45
Pass-through	[%]		8		16		26		26

Two demand levels were analyzed in study and presented in Table 5-3 – *(i)* winter with higher demand, and *(ii)* summer. Higher demand results with bigger differences between perfect and Cournot's competition, but also leads to higher Pass-Through-Rate (PTR) than in lower demand period. With tight elasticity 0.05, PTR in winter time gets high to 578, which is probably resulting in limited available capacity. Results are saying that inclusion of costs due to emissions trading does increase price levels, and this increase can be severely exacerbated by the exercise of market power when demand is unresponsive to price changes.

Sijm et al., 2005 [43] - study uses model COMPETES to simulate and analyze the impact of strategic behavior of large producers on the wholesale market under different market structure scenarios (varying from perfect competition to oligopolistic and monopolistic market conditions, with different levels of price elasticity of power demand ranging from 0.0 to 0.2). Analyzed parameters were the impact of CO_2 emissions trading on power prices, firm profits and other issues related to the wholesale power market in four countries of continental North-western Europe (Belgium, France, Germany and the Netherlands). Under all scenarios considered, power prices increase significantly due to CO_2 emissions trading. In the case of a CO_2 price of 20 €/tone, these increases are generally highest in Germany (13-19 €/MWh) and lowest in France (1-5 €/MWh). Such a range results mainly from differences in the technology mix between countries or, more specifically, from differences between countries in the carbon efficiency (that's why carbon induced price is lowest in France which has the lowest carbon intensity due to large share of nuclear in the system, while the highest is in Germany due to large share of coal power plants).

Chen, 2008 [54] – new study performed using COMPETES model this time includes 20 EU member states models, analyzes scenarios with same demand elasticity, market structure as previous COMPETES modeling [43], and emission prices 20 and 40 €/tCO_2. Following characteristics were analyzed: power prices, carbon cost pass-through, power sales, power trade, carbon emissions, change in merit order and power generators' profits. Shift in the merit order occurs in particular markets depending not only on the emission price - or the relative fuel prices, but also on differences in the mix and carbon efficiency of generation technologies. At a emission price of 20 or 40 €/tCO_2, there are almost no any technology switching in Finland, Hungary, Portugal, Slovenia, Sweden and Switzerland while, there is significant shifts in generation technologies in Germany and the UK (because of major share of both coal and CCGT technologies). With 2006 fuel prices, CCGT is nearly competitive compared to coal in these countries.

Point Carbon, 2008 [94] – performed study to assess the potential and scale of windfall profits due to free allocation in the power sector in five countries (UK, Germany, Spain, Italy and Poland) during Phase II of ETS. Study is analyzed using Point Carbons CO_2 market forecasting model, Carbon Market Trader (CMT). The CMT model estimates emissions from power system using detailed database for each plant covered by the EU ETS. The level of windfall profits estimated is significant and for these five countries, with price of emission allowances between 21 and 32 €/tCO_2, it ranges between 23 and 71 billion €, in total (during 2008 – 2012). Highest levels of windfall profits for generation is in Germany (between €14-34 billion) and UK (€6-15 billion), because of high PTR level and high level of emission intensity of marginal plant. Results are shown in Table 5-4. Windfall profits were calculated using simple formula:

$$\text{Windfall profit} = TRt - TCt \qquad (5.1)$$

$$TRt = TGEN * PCO_2 * PTR * EFpsp \qquad (5.2)$$

$$TCt = (Et - FALt) * PCO_2 \qquad (5.3)$$

Where: (TR = Total Revenue; TC = Total Cost; TGEN = Thermal Generation; PCO_2 = CO_2 price; PTR = pass through rate; EF = Emissions factor; E = Emissions; FAL = Free Allocation)

Subscript: (t = thermal plant; psp = price setting plant)

Table 5-4: Assumptions used for windfall profit calculation. Source: [94]

	UK	Germany	Spain	Italy	Poland
CO_2 price levels	€21 - €32/tonne[1]				
Level of power sector emissions - Mt CO_2/year	178	338	105	152	156
Free level of power sector NAP allocation - Mt CO_2/year	107	230	54	100	106
% time coal / gas spent on the margin	35 / 65	75 / 25	25 / 40[2]	20 / 70[3]	95 / 5
Range of pass-through	75 – 100%	75 - 100%	75 – 100%	0 - 75%[4]	45 - 65%

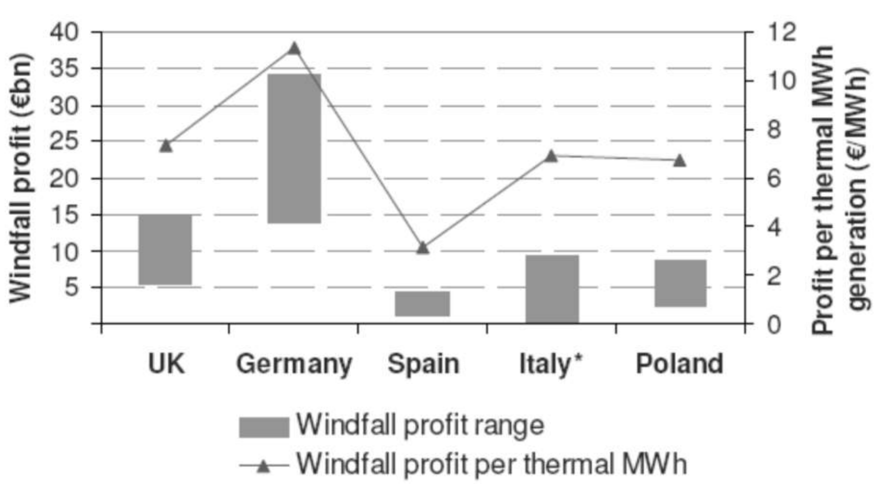


Figure 5-5: Range of estimated windfall profits and profits per thermal MWh generation with used emission price of EUA 21-32 EUR/tCO_2. Source: [94]

New carbon finance, 2008 [95] - modeled how introduction of auctioning in the EU ETS post 2012 is likely to affect power prices in four key European countries (Germany, Poland, Czech Republic and Hungary). Analysis was performed in order to understand how EC's 100 percent auctioning proposals will influence on economies with regulated wholesale electricity markets (such as in Poland or Hungary) and compare it with regulated markets (such as in Germany and Czech Republic). In regulated wholesale electricity markets, PTR is much lower than 1 as companies are not able to transfer these costs to customers (to pass full opportunity cost of emission allowances like power producers in liberalized markets). Therefore the introduction of full auctioning of emission allowances would be expected to increase electricity prices in these countries, which is even bigger worry because of their high level of carbon intensity of power system.

Table 5-5: Influence of different allocation methods in EU ETS for year 2013 with CO_2 price 61 €/tCO_2. Source: [95]

	Poland		Germany		Czech Republic	
Price Scenario	Price €/MWh	Indexed (100)	Price €/MWh	Indexed (100)	Price €/MWh	Indexed (100)
2008	57	63	66	80	68	72
2013 no EU ETS	37	42	54	65	32	32
2013 + EU ETS, existing regulatory structure, free allocation	71	78	83	100	85	89
2013 + EU ETS, expected regulatory structure, free allocation. (base case)	91	100	83	100	95	100
2013 + EU ETS, expected regulatory structure, full auctioning	91	100	83	100	95	100

The results from table above are showing that for liberalized market such as German wholesale power market, it makes no difference which type of allocation is used – price in 2013 is the same (83 €/MWh). The difference from non-ETS to ETS is seen in change of electricity price of 29 €/MWh. Situation in Poland is much different, and depends a lot regarding regulatory structure. With existing regulatory structure, difference in price grows for 34 €/MWh (total of 71 €/MWh). But study concludes that they expect liberalization of Polish power sector by year 2013, which means that in this case price would rise to 91 €/MWh (total change 54 €/MWh from non-ETS and non-regulation). In this case, it would be irrelevant which allocation method is used, since on liberalized market opportunity costs are fully passed to costumers. Study also calculated maximum direct cost of meeting phase III targets for Poland and the Czech Republic to be between €0.5 and €1.0bn per year based on calculated average phase III EUA price of €61/t. This would be less than 0.1 percent of GDP in both countries.

Chapin, 2008 [96] - Analyzes carried in direction to estimate long term impact of CO_2 emission-trading on CO_2 emissions in power system generation was presented in socio-technical systems-perspective. The impact of emission trading on CO_2 emissions by Dutch power production and its generation portfolio was shown to be both relatively small and late. Paper also presented expected new generation capacities to be built in the near future in Netherlands and Germany, available on public sources (renewables are not fully presented). From Table 5-6 it is obvious that coal and gas still play major role in future investments. Taking in account long lifetime of these power plants (20-60 years), one can understand how important is it to get change in new installed capacities now, and that existing policy is not good enough to give incentive to low-carbon technologies.

Table 5-6: Expected new capacities build in near future, according to public data. Source: [96]

Country	Energy source	Capacity [MWe]	% of plans per country	Operational in
The Netherlands	Natural gas	4390	45.6%	2008–2010
	Coal	4415–5000	45.9–52.0%	2011–2012
	Biomass	<685	<7.1%	2008–2013
	Offshore wind	228	2.4%	2006–2007
	Total	9618		
Germany	Natural gas	12,830	29.7%	2007–unknown
	Coal	29,245	67.6%	2008–unknown
	Nuclear	60	0.14%	2007–unknown
	Other	1,102	2.55%	2007–unknown
	Total	43,237		

ECN - COMPETES EU20 Model, **2010** [58] - bottom-up modeling in COMPETES model for the implications of emissions trading for the performance of the wholesale power market in 20 European countries (Figure 5-6). The analyses show that a significant part of the costs of (freely allocated) CO_2 emission allowances is passed through to power prices, resulting in windfall profits for power producers, even in cases of full auctioning. In addition, they show that the ETS-induced increases in power prices depend not only on the level of CO_2 prices but also on the structure of the power market. Finally, the analyses show that the internalization and pass-through of carbon costs are crucial elements in a policy regime to reduce CO_2 emissions by both changing the mix of power generation technologies and lowering total electricity demand.

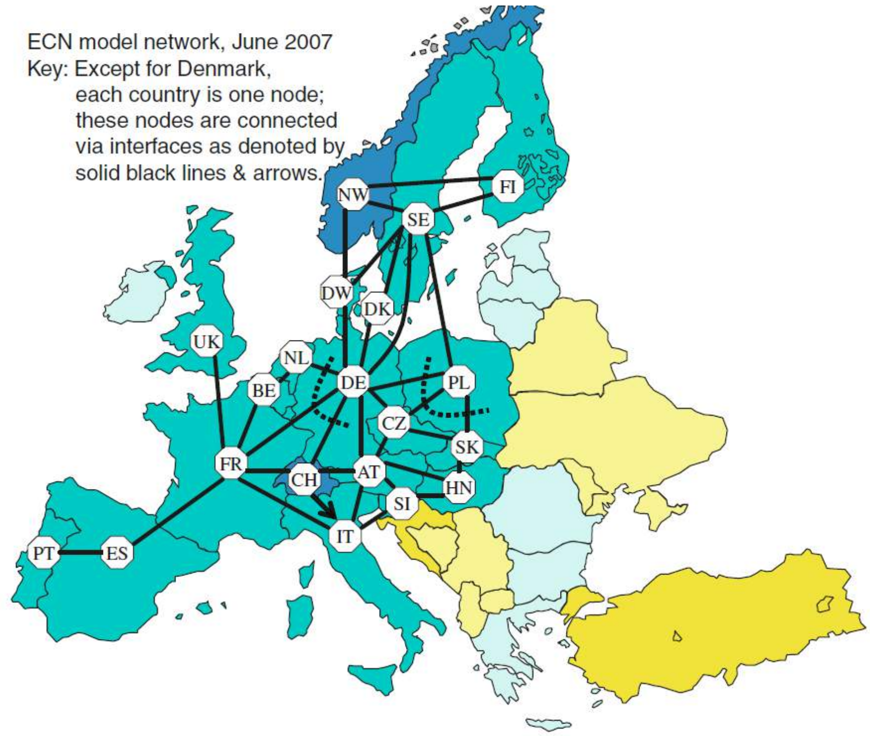


Figure 5-6: Representation of the electricity network in COMPETES (dashed lines represent constraints on the sum of flows on the links shown). Source: [58]

5.2. Power system model PLEXOS

In this chapter, a brief introduction will be given to power system model that is, after presented throughout research of existing and available models for long term energy and power system planning chosen for application in methodology later proposed in the thesis (full list of researched models is given in ANNEX 2: A LIST OF MODELS USED IN POWER SYSTEM MODELING.

5.2.1. PLEXOS introduction

PLEXOS is an electricity market simulation model developed by Drayton Analytics, the company that changed its name recently to Energy Exemplar [97]. Model PLEXOS has users in more than 25 countries by many of the world`s largest utilities and system operators, including transmission operators, generating companies, transmission companies, regulators, and consultants. The software has been used extensively for analyzing electricity market in Australia, by the CAISO (California Independent System Operator), it has been featured in filings to the US FERC (Federal Energy Regulatory Commission) and official market simulator for the Irish

SEM. Some of the bigger systems modeled with PLEXOS are WECC (Western Electricity Coordinating Council, covering Western Canada and Western United States), Iberian Peninsula and Benelux [97].

5.2.2. Simulation model architecture

The idea behind PLEXOS is to be simulation model that is easily and efficiently maintained, extended, and modified and can be applied with no customization to every electricity market and modeling project. In most of simulators, modeling is done in three steps: data preparation and data input in simulation model, than simulation itself, and the last step is the overview of results from simulation model. Simulation model PLEXOS is also divided in three parts and each one covers one of simulation steps mentioned above: user interface is used for data input; simulation engine performs simulation, while user interface is used for access to simulation results. Simulation models for electrical system require large amount of data, and results are typically large databases. Therefore database is essential part of such models. In PLEXOS, both interfaces were until recently based on Microsoft Access database, but new, more practical possibility is using Extensible Markup Language (XML) (output data in Access database can be very large, like hourly representation of load or hourly defined production from some power plant). PLEXOS is based on .NET technology and is run on Windows operating system.

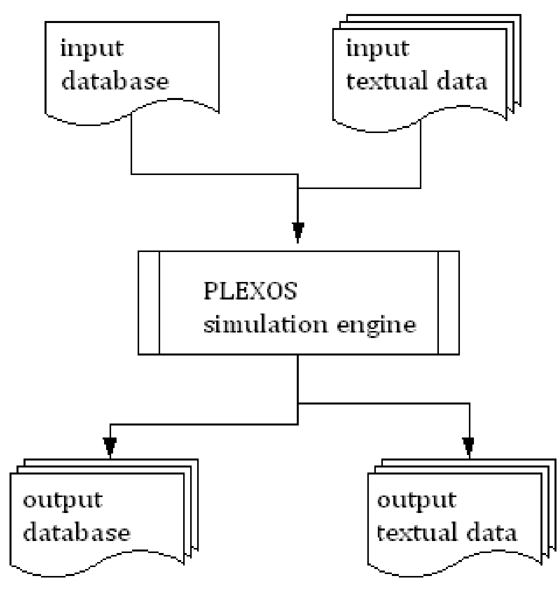


Figure 5-7: PLEXOS model architecture. Source: PLEXOS Wiki [97]

Simulation results can be simply presented using various time steps (periods can last from five minutes to one year). Level of information (results) that are being processed through simulation can be configured in detail. As more the simulation is detailed, the running time gets longer and the result database gets larger. Interface and configuration are given in Figure 5-8 and Figure 5-9.

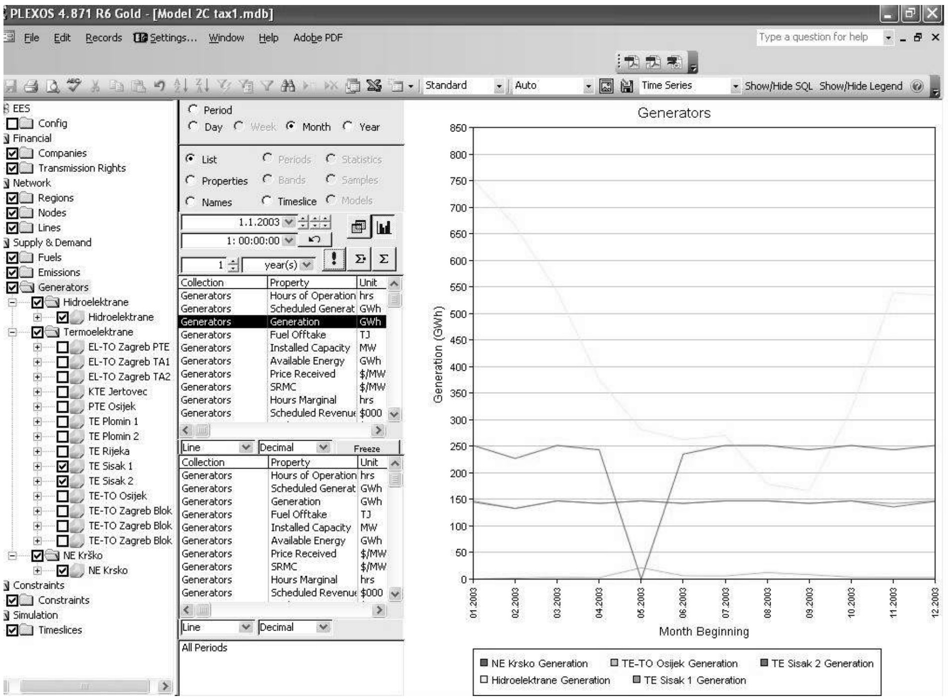


Figure 5-8: Graphical output interface (printscreen)

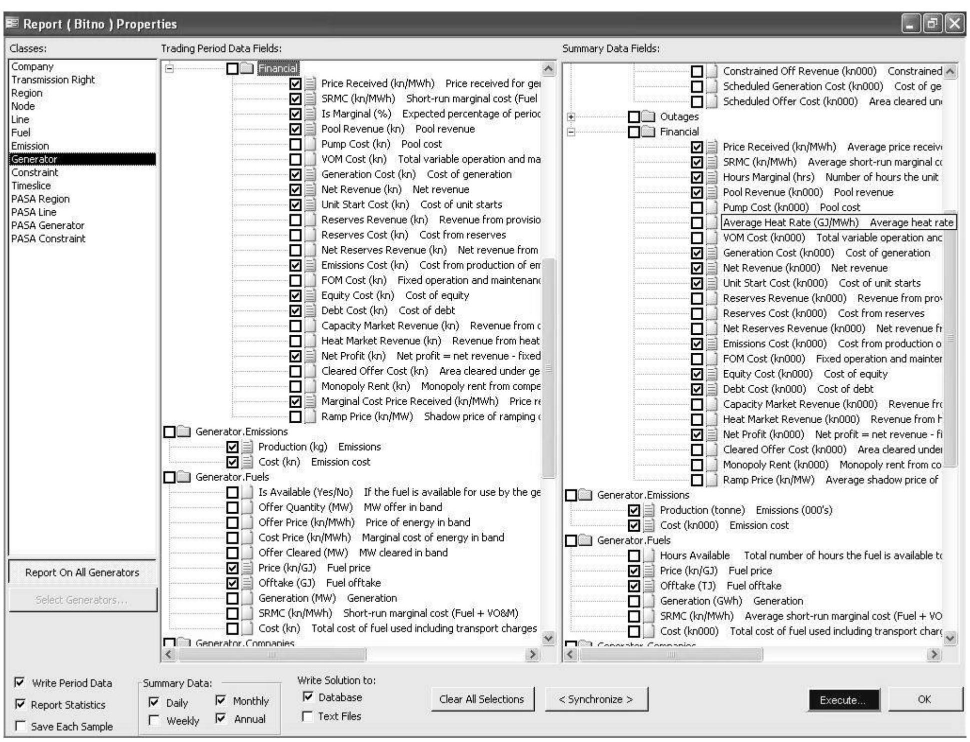


Figure 5-9: Configuration of variables for simulation (printscreen)

5.2.3. Simulation flowchart

There are four basic simulation engines in PLEXOS: LT Plan, PASA, MT Schedule and ST Schedule. Each one of them can be used separately as in Figure 5-10, but they can also be used sequentially. In that way, each one of them gathers results from the previous one as an input. After preparation of input parameters from Microsoft Access and input textual data, AMMO optimization core is being used for dynamic formulation of the mathematical problem. After problem formulation, commercial MOSEK software is being started for solving large mathematical optimization problems. MOSEK is the default solver, but it is also possible to choose two other solvers, CPLEX or Xpress-MP. After problem is being solved, PLEXOS engine prepares data for interpretation in output users' interface.

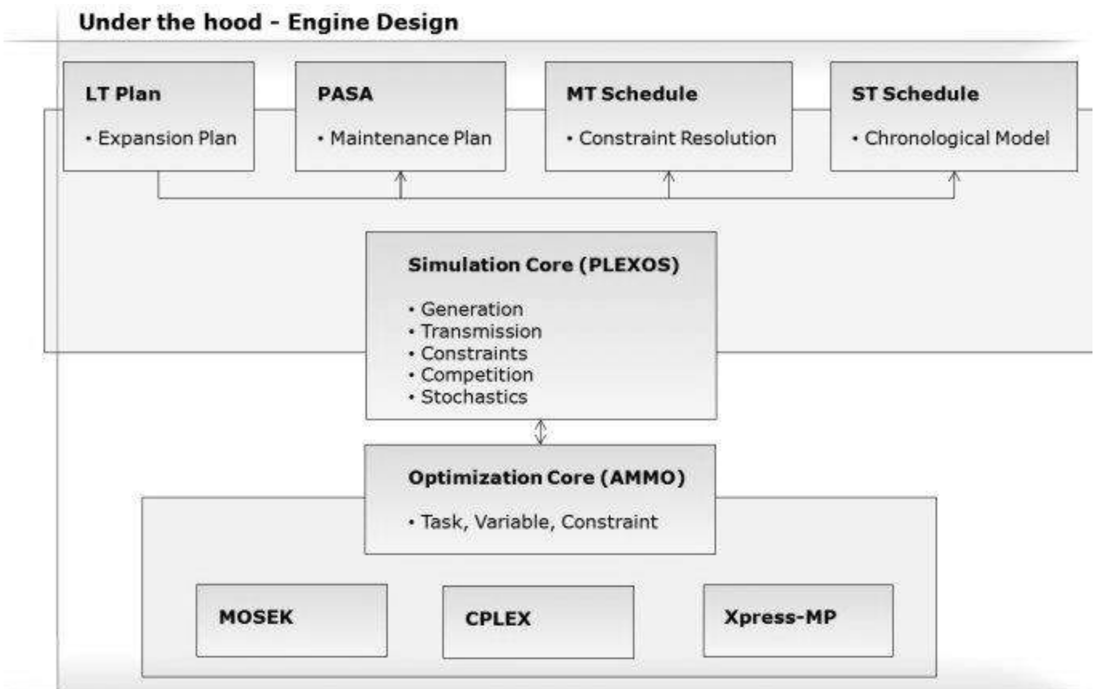


Figure 5-10: Schematic representation of engine design for PLEXOS, Source: PLEXOS Wiki [97]

1. System Initialization Phase

In the first simulation check it is important to run data validation. If some data are missing or are incorrect, this should be clarified in this step and simulation should be stopped. Graphic interpretation of steps is given in Figure 5-11.

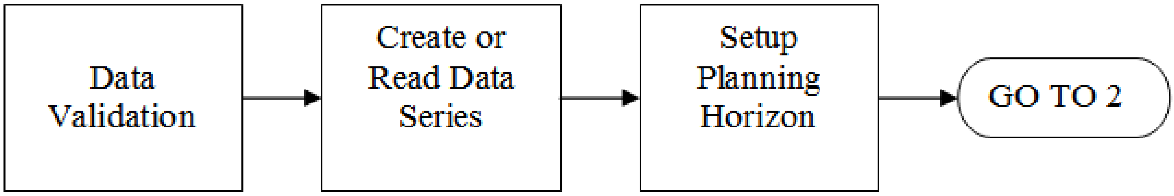


Figure 5-11: Schematic representation of initialization phase

2. LT Plan Phase

The purpose of the LT Plan model is to find the optimal combination of generation new builds and retirements and transmission upgrades or retirements that minimizes the net present value of the total costs of the system over a long-term planning horizon. That is, to simultaneously solve a generation and transmission capacity expansion problem and a dispatch problem from a central planning, long-term perspective. Planning horizons for the LT Plan model are user-defined and are typically expected to be in the range of 10 to 30 years. LT Plan appropriately deals with discounting and end-year effects.

LT Plan runs before other phases (PASA/MT Schedule/ST Schedule), and is fully integrated with them. Thus, LT Plan can be run either separately or in sequence with these other simulation phases in a single simulation. In the latter role, the long-term build/retirement decisions made by LT Plan will be automatically passed down to the other phases, providing a seamless solution. In either role, the output of LT Plan can be accessed using the solution viewing capability of PLEXOS. LT Plan provides modeling constraints, emissions, fuel variables, and ancillary services. It can be run in deterministic or stochastic modes (in stochastic mode it can be used for example to model the management of long-term hydro storages under uncertain inflow conditions).

The following types of expansion/retirements and features are supported:

- Building new generating plant;
- Retiring existing generating plant;
- Multi-stage projects;
- Building new AC or DC transmission lines;
- Retiring existing AC or DC transmission lines;
- Multi-stage transmission projects;
- Expanding the capacity on existing transmission interfaces;
- Taking up new physical generation contracts;

- Taking up new physical load contracts;
- Deterministic or stochastic optimization.

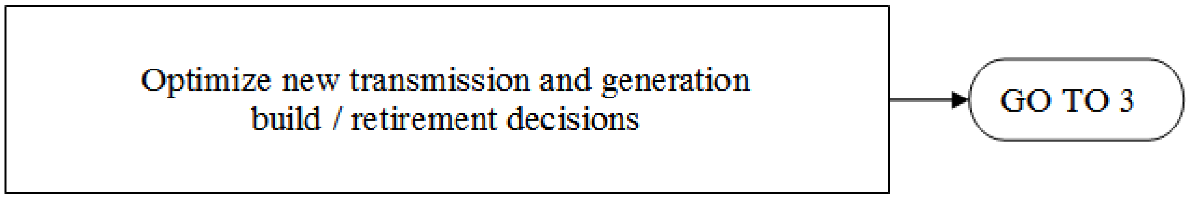


Figure 5-12: Schematic representation of LT Plan phase

3. PASA and Preschedule Phase

PASA is an acronym for Projected Assessment of System Adequacy. In PLEXOS, the PASA is a simulation that focuses on the balance of supply and demand in the medium term. When PASA is run alone it produces output such as the projected reserve (capacity in excess of load) on a region by region basis. In multi-region models PASA also calculates the optimal amount of reserve that should be shared between the regions. The PASA does this by formulating the problem of equalizing regional reserves as a linear programming (LP) problem. When used in combination with MT and/or ST Schedule, the primary purpose of the PASA is to determine, where and when maintenance outages must occur, taking into account load, available capacity, transmission capacity, and any other constraints including transmission constraints. Several different scenarios for description of outages are available: they can involve prescheduled maintenance and also unplanned, forced outages.

The PASA algorithm has two resolution settings: daily or weekly steps. The daily option is preferred for accuracy but if the algorithm is running slow on a very large system, it is better to set the resolution to weekly.

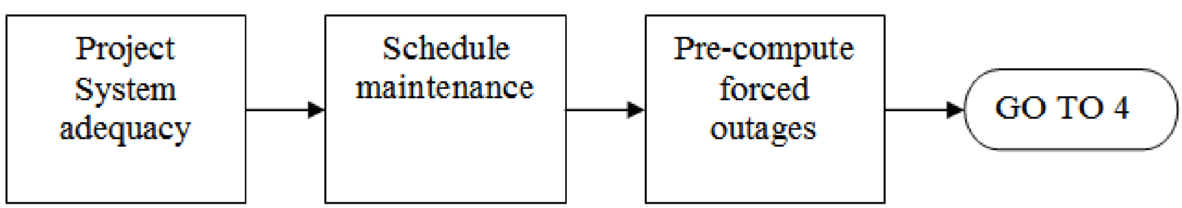


Figure 5-13: Schematic representation of LT Plan phase

4. MT Schedule Phase

MT Schedule address a key challenge in power system modeling, and that is to model medium to long term decisions in a computationally efficient manner. Primarily this means hydro, but also includes emission and fuel constraints, among others. The reason that elements like hydro create such a challenge is because they imply that the simulation must optimize decisions over multiple time periods simultaneously. In a case when there is no hydro or other intertemporal problems, generators can start/stop instantly and cannot “save” energy for some latter time. In this case the optimal dispatch of the system is simulated by formulating a mathematical program representing a single hour. After problem optimization, it is repeated for all hours of the horizon until all hours are simulated.

Hydro resources e.g. pump storage, as well as long- and short-term storages are optimized, even detailed cascading hydro networks may be modeled. For example, some hydro system might need to be optimized with a “look-ahead” of a year or even more. In a case if, for example, a mathematical program is made that includes all 8760 hours of a year, a the single hour problem might be a linear program with perhaps 100,000 coefficients, thus the annual problem would have 876 million coefficients. This is many times more than computer memory can hold or any current-day algorithm can solve on a personal computer. That’s why there is a need for a way of decomposing medium and long term constraints and decisions down to shorter time periods that can be solved feasibly. MT Schedule models automatically "decomposes" fuel, emission and any other user-definable constraints to shorter term constraints suitable for detailed modeling in ST Schedule.

Some modelers use only the MT Schedule to produce their final simulation results. This is because MT Schedule models the system (nearly) identically to ST Schedule – the only approximation is in the way the chronology is represented. The distinct advantage of MT Schedule is execution speed. It is possible to produce results across a long timeframe on a large model in a matter of minutes, whereas the full chronological ST Schedule model might take several hours to run over the same timeframe.

The MT Schedule considers each day/week/month as a load duration curve (LDC) made up of a number of load blocks. The solver then schedules generation to meet the load and / or clear offers and bids inside these discrete blocks. All system constraints are applied, except those that deal with generator unit commitment and other intertemporal constraints.

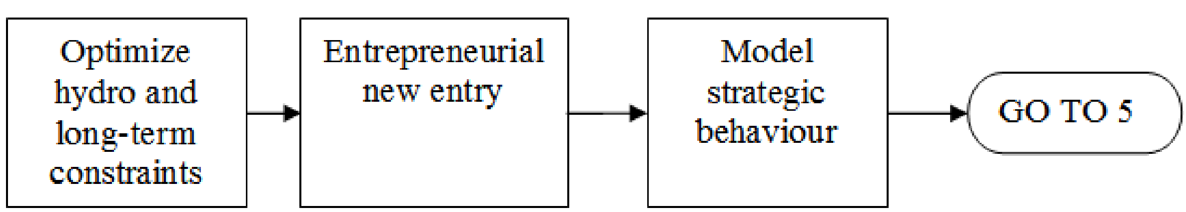


Figure5-14: Schematic representation of LT Plan phase

5. ST Schedule Phase

ST Schedule is mixed-integer programming (MIP) based chronological optimization. Time resolution is usually hourly, but can also get as detailed as 5-minute time resolution. It can emulate the dispatch and pricing of real market-clearing engines, but it provides a wealth of additional functionality to deal with:

- Unit commitment;
- Constraint modeling;
- Financial/portfolio optimization; and
- Monte Carlo simulation.

Emulation of real market-clearing engines involves clearing generator offers against forecast load accounting for transmission and other constraints to produce a dispatch and pricing outcome. ST Schedule can do this but PLEXOS extends this basic functionality by allowing specification of fundamental data (like generator start costs and constraints, heat-rate curves, fuel costs), in addition to market data such as generator offers, and the dynamic formulation engine in the AMMO software. This allows to mixing market data with fundamental data as desired – relying on PLEXOS to compute the appropriate market representation at runtime, and maximize simulation efficiency.

ST Schedule provides two methods for modeling the time chronology:

Full Chronology - every trading period inside the ST Schedule horizon is modeled explicitly. In this mode, ST Schedule runs every trading period and maintains chronological consistency across the horizon. For example it can model generator start-ups and shutdowns and track the status of units across time.

Typical Week - one week is modeled per each month in the horizon and results are applied to the other weeks. Running in this mode reduces the amount of simulation work for ST Schedule by more than a factor of four, but PASA and MT Schedule are still run in exactly the same manner.

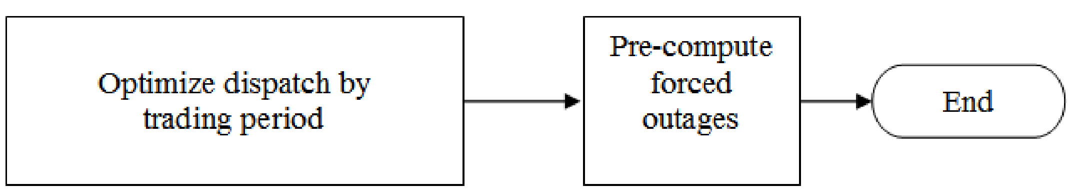


Figure 5-15: Schematic representation of LT Plan phase

5.2.4. Mathematical problem solving in PLEXOS

The solution simulations are founded in mathematical programming (MP) techniques:

LP – linear programming

QP – quadratic programming

MIP – mixed integer programming

DP – dynamic programming,

This ensures the simulation outcomes are robust, consistent across scenarios, justifiable, and auditable. Optimization code speed is improving as fast as computer speed, thus simulation performance is increasing rapidly. The traditional approach to simulation is to decide the solution method, then build the model to populate the required data. In contrast, Dynamic Formulation (DF) developed by PLEXOS lead author Glenn Drayton in 1996 and implemented in the model, allows PLEXOS to decide the solution approach and formulation based on data at runtime. In this approach the data model is a framework for describing the "problem", and the "engine" dynamically builds the optimization problem at runtime from the very start.

The advantages of this approach are (Plexos wiki, [97]):

i) the software can scale to any problem size;

ii) the analyst controls simulation performance by "switching" data on/off – thus allowing exploration of tradeoffs between simulation runtime and result accuracy;

iii) there is no hardwired functional specification – model capabilities can be expanded at will;

iv) simulation performance is maximized (problem size minimized) because the optimization problems are built at runtime to suit the data;

v) the analyst may define any "generic" constraint which can involve a combination of decision variables or input data used inside the simulation.

PLEXOS includes a comprehensive Monte Carlo model for generator and transmission forced outage modeling. Maintenance timing is also dynamic and can be optimized to account for transmission availability i.e. reserve sharing between areas. Any input can be stochastic – commonly used examples are demand, hydro, and fuel prices.

5.2.5. Market modeling in PLEXOS

There are several options available to model competitive behavior or bidding strategies in PLEXOS. It is done in the MT Schedule step of the simulation, so it sets the medium term game played by strategic entities.

Perfect Competition - generators trading in the market expect to recover their variable costs of operation in every period – referred to as their short-run marginal cost (SRMC).

LRMC / Revenue Recovery – taking only short-run marginal costs in account is not realistic enough, as in the medium term companies must also cover fixed operating costs, make contributions to debt servicing, and return a profit to shareholders. These fixed cost charges are expressed as a per kW capacity charge across some period of time in PLEXOS, generally one year. The combined charge (variable plus fixed) is often referred to as long-run marginal cost (LRMC). One way to model the recovery of fixed costs (and often the only method available with most market simulation software) is for the analyst to input a set of energy offers that in some way reflect fixed cost charges. This could be based on historical offering patterns – if they seem to result in recovery of those costs – or some another method.

The PLEXOS cost recovery method is a sophisticated and automated price modification heuristic in which the price of generation from each generator that belongs to some company is modified to reflect the fixed cost burden of the Company as a whole. This price modification is dynamic and designed to be consistent with the goal of recovering fixed costs across an annual time period. The algorithm is to run MT Schedule with ‘default’ pricing (user-defined offers plus SRMC offers for plant with no user-defined offer), and to calculate (for each company) total annual net profit. Then, within each simulation period, premium that each generator inside every firm should charge to recover the amount of loss allocated to that period is calculated. After that, all generators from one firm (depending on their marginal cost position) charge extra amount in order to recover these losses.

Nash-Cournot Competition - PLEXOS includes a comprehensive and well integrated implementation of Nash-Cournot competition. In Cournot competition, quantity is the strategic variable, and firms choose quantities simultaneously, under the assumption that other firm’s quantities are fixed.

PLEXOS makes available to analyst both a single-period Cournot game, with ‘no arbitrage’ and ‘exogenous arbitrage’ options, and a multi-period game. The single period game is suitable for a static analysis, while the multi-period game is intended for use in ‘standard’ market simulation studies where the analyst wishes to model Cournot competition with an ‘equilibrium period’ of more than one trading period.

Development of the multi-period Nash-Cournot implementation presented several challenges:

- The Cournot game is static, i.e. there is no element of time in the game;
- The game requires the specification of a linear demand curve for each node in the network, inconsistent with the highly inelastic demand curves seen in real market-clearing situations;
- The Cournot games, account for many but, certainly not all, possible constraints on generation, transmission, etc.

Bertrand game is the one in which firms determine the price component of their generation offer, assuming that offer quantities are fixed. It is this assumption that makes this game more suited to modeling short-term pricing behavior than medium-term behavior. Hence in PLEXOS, the Bertrand game is played in every trading period. The advantage of this is that the Bertrand Game can be simulated for any horizon length, from a single trading period or for a period of longer duration. The disadvantage is that the game makes no reference to the medium term effect on pricing. The basic mechanism of the Bertrand Game involves 'shadow pricing' i.e. pricing generation up to the next firm's marginal cost in the relevant merit order.

Residual Supply Analysis - is a technique developed by the California ISO, and has general applicability. The bid functions were based on regression analyses relating calculated bid mark-ups to the Residual Supply Index (RSI) and other variables representing market conditions [98]. Bid markups were calculated by comparing actual hourly real-time prices for California’s three pricing zones with prices that would result from cost-based bidding.

5.2.6. Modeling in PLEXOS

PLEXOS is constructed around an object model, which defines a set of classes (listed in Table 5-7), collections, and properties. This model is based around three basic elements:

- Objects (classes like Generator or Company and names of different objects in the class like Generator1);
- Memberships (also called ‘relationships’, whose function is to define the functional and logical relationships between objects);

- Properties (to store the data associated with a system e.g. load, generation capability, transmission data, etc).

Table 5-7: List of classes in PLEXOS. Source: [97]

Class Name	Description
System	Represents complex system that is analyzed with simulator. One system per database.
Company	Several generators, lines and/or purchasers that are under common possession.
Region	Region defined with joint transmission network
Zone	Zone in transmission network
Node	Node or bay in transmission network
Line	Transmission line
Transformer	Energy transformer
Phase Shifter	Phase shifter
Interface	Connection between two systems
Reserve	Additional services
Purchaser	Purchaser on electricity market
Fuel	Fuel used in power plants
Storage	Water accumulation
Waterway	Waterway between accumulations or accumulation and hydro power plant
Emission	Emission defined at will (CO_2, SOx, NOx, etc)
Generator	Generating unit (also a market player)
Power Station	Power plant for energy production
Data File	Input data file
Constraint	General constraint
Financial Contract	Contract between two market players

Escalator	Changed value of input parameters during the time passes
Variable	Stochastically variable
Option	General simulation option
Scenario	Scenario for simulation performing – it is possible to define several scenarios upon which simulation results depend
Model	Combination of parameters and scenarios
Project	Project or several models that are being accomplished together
Market	Market modeling
Transmission Right	Defining transmission rights
Cournot	Defining conditions for Nash-Cournots optimization
Fuel Contract	Definition of fuel contracts
Purchaser	Closer definition of purchasers characteristic

5.2.7. Modeling renewable energy sources in PLEXOS

Very few analytical tools dynamically model such energy-constrained resources as hydro and wind power. A thermal dispatch around a hard-wired scenario of these energy-constrained resources does not realistically depict the constraints or flexibilities of these resources participating in the marketplace. Therefore, models that dynamically model energy-constraint resources depict generation injections into the power system in a more realistic manner. Modeling can be performed to analyze how intermittent renewables will impact generation, or how regulation can satisfy system requirements with large-scale intermittent renewables capacity.

Scenarios are a very flexible tool to scale and configure modeling by setting for example:

- Scenarios to switch between different profiles and stochastic treatment of RES;
- Model scenarios to switch between LT and ST settings;
- Scenarios to switch different pricing;
- Scenarios to switch off nodes, power plants and regions.

With scenarios, one database can be configured to serve for various purposes.

In more details, hydro generation modeling is presented in this chapter. There are a multitude of ways to model hydro generators and networks of storage in the PLEXOS software. The classes that provide the fundamental building blocks (in order of importance) are:

- Generator;
- Storage;
- Waterway;
- Constraint.

Generators: The simplest approach is to define energy constraints to approximate the availability of water (using Generator [Max Energy Day|Week|Month|Year], and [Max Capacity Factor Day|Week|Month|Year]), and a profile of minimum operating levels that represent run-of-river generation (Generator [Min Load]) as in Table below. Head and Tail storage can also be defined for more detailed modeling.

Table 5-8: Simple energy-constrained hydro. Source: print screen from PLEXOS model

Property	Value	Units	Date From	Date To	Pattern
Units	1	-			
Max Capacity	60	MW			
Min Load	5	MW			M1-4,10-12
Min Load	15	MW			M5-9
Max Energy MONTH	15	GWh			M1-4,10-12
Max Energy MONTH	27	GWh			M5-9

Hydro generator efficiency is expressed in megawatts per cubic metre second (MW/cumec) i.e. it is the rate of production that results from a flow rate through the turbine of one cubic meter per second. This efficiency is input via the property Generator [Efficiency Incr]. It can vary according to the generation level. Storages can represent reservoirs with short, medium, or long-term storage, or even simple junctions in a river-chain. Storage objects are created in the same way as any other object. Each of the storages can connect to one or more generators or waterways to create a model of a river chain. The Hydro Model selection sets the units used to define hydro storage and hydro generator efficiency. There are three options available:

- Energy (Potential Energy);
- Level;
- Volume.

Waterway objects either:

- Connect the storages in their [Storage From] and [Storage To] collections; or
- Spill water from the [Storage From] ‘to the sea’.

Combinations of Storage, Waterway, and Generator objects are used to create models of cascading hydro networks with canals and spillways modeled with waterways. Constraint objects are used to define custom constraints on elements or combination of elements in your hydro system. Constraints can include Generators, Storages, and Waterways in any combination.

5.3. Measuring sustainable development indicators

To ensure transition to low emission economy and shift of investments towards low emission technologies with emission trading and other policy instruments, indicators are needed to show and track these policy inputs. In this chapter, a wide range of indicators to measure transition to low emission economy developed and proposed in recent years will be presented and discussed. Then, indicators will be proposed for use in Croatia – based on existing data, national circumstances, perceived need etc.

5.3.1. Indicators for environmental, economic and social tracking of progress to low emission economy

Indicators are just a tool which enables identification, prioritization and tracking, they provide information on the historical and current state of the system, and highlight trends that can shed light on causality to better detect key drivers and pressures [99].

Such indicators should enable assessment of progress towards targets in social, economic and environmental state; they should provide information on the previous and current state of the system, and help in predicting how to better detect key drivers and pressures. Important issue is that they could be measured and tracked – and if they are based on some standard calculation methodology, it makes them possible to compare the progress of different countries, cities, businesses etc. They should also define and describe multiple interrelations between social, demographic, economic, energy and environment. A comparation of such indicators from three different sources (recommendations from UNEP, indicators chosen for Czech Republic and those in European development strategy “Europe 2020”) is given in Table 5-9.

The 2012 United Nations Conference on Sustainable Development (UNCSD), or “Rio+20 Summit”, concludes that in order to seriously move towards low emission economy, there is also a need for establishing new measures and metrics that not only reflect these goals, but also inspire action.

Table 5-9: Proposed indicators for environmental, economic and social tracking of progress to low emission economy from three sources. Sources: [99,100,101]

Type of indicators	UNEP	Europe 2020	Czech Republic
Environmental	Greenhouse gas emissions	Greenhouse gas emissions	Greenhouse gas emissions
	Share of renewable energy in power supply	Share of renewable energy in gross final energy consumption	Greenhouse gas emissions - households
	Energy consumption per capita	Primary energy consumption	Share of renewable energy in gross final energy consumption
	Forestland		Waste treatment
	Water stress		Water stress
	Land and marine conservation area		Forestland
	Waste collection		Bird species noticed (biodiversity)
	Waste recycling and reuse		Renewable drinking water storages
	Waste generation		
	Level of harmful chemicals in drinking water		
Economic	Energy intensity	Gross domestic expenditure on R&D	Level of savings
	Level of R&D in green technologies		Energy intensity
	Green taxes		Agricultural output
	GHG emissions price		Coal sources
	Value of ecosystem services		Sustainability in forestry
	Expenditure in sustainable procurement		Patents in green sectors
	Training expenditure for green jobs		Number of green jobs
	Number of people trained for green jobs		Expenditure on environmental protection
	Value of natural resource stocks		Environmental taxes
			Energy prices
Social	Share of population employed in construction sector	1.Employment rate by sex, age group 20-64	Level of employment of elderly people
	Income generated from employment	Population exposed to poverty	Population exposed to poverty
	Gini coefficient	Population living in households with low work intensity	Share of older people in population and their dependence
	Environmental goods and services sector (value added, employment, CO_2 and material productivity)	Population suffering from serious material deprivation	Access to water/sanitation
	Literacy rate	Household debts on paying accommodation	Expected life duration

	Modern energy access	Household debts on paying taxes	Level of formal education
	Access to water	Percentage of population that leaves education early	Number of people hospitalized due to air pollution
	Access to sanitation	Exposure to air pollution	
	Access to public health	Air quality in urban area	
	Number of people hospitalized due to air pollution	Air quality in rural area	
	Road traffic fatalities per 100.000 inhabitants	Energy poverty	

In order to try to simplify complexities of the socio-economic and environmental systems under analysis and many existing cross-sectorial relations and feedbacks, there are attempts to the assessment of progress to low emission development with a single metric, a single indicator. One of such is the Global Green Economy Index (GGEI); an indicator that informs on national and city level green economy progress, by combining both:

- Performances - assessment based on the opinions of experts judgments;
- Perceptions - objective, data-based, national green economy performance index.

If there would be only one objective indicator which represents a mix of other indicators, this could be a risk to send misleading policy messages, especially if such mix are constructed based on poor methodology or misinterpreted. Since aggregated indices and rating systems are prone to subjectivity despite the relative objectivity of the methods employed in assessing sustainability, the existence of a value system is a prerequisite of any approach to measuring progress towards sustainability. As a result, methodological pluralism coupled with stakeholder participation seems a safer and more objective way forward [102].

5.3.2. Proposed indicators for tracking low emission development in Croatia

Indicators proposed in this subchapter are specifically adopted for Croatia – as they reflect already existing indicators or those which could be calculated with existing data. They were proposed in “Framework for Low Emission Development Strategy of Croatia" [103], and except authors contribution, these indicators are a result of a work from three experts with economic, social and environmental background. As these are the first time ever proposed indicators to track progress towards low emission development, they also represent a contribution to further development of measuring progress towards low emission economy.

Environmental indicators

1. **GHG emissions** (tCO_2) – annual GHG emission amounts; tracking of this indicator in Croatia is already regulated with Air Protection Law [104] and Governance on tracking GHG emissions in Croatia [105].
2. **Share of renewable energy sources in final energy consumption (%)** – as renewable energy sources have specific benefits to achieving sustainable development, with impacts on all three pillars. These data already is a part of Croatian annual energy overview [106].
3. **Energy consumption per citizen** – measured in toe; important to track as it can point to energy intensity and consumption patterns and trends. This indicator is also already a part of Croatian annual energy overview.
4. **Wood resources, annual increase of wood resources** – this indicator gives information on total wood resources in Croatia, and is important to track sustainable biomass use. This indicator already exists and is based on National list of forest indicators [107].
5. **Efficiency in water use** – is important indicator as it can show relationship between delivered and taken water amounts. These data are tracked in Croatian Bureau of Statistics [108], and are very high for Croatia – in 2010 it was 66% of total delivered water amount.
6. **Area under ecological agricultural production** – to track trends and share of ecological agriculture in total agriculture. These data are available at Ministry of Agriculture [109].

Social indicators

1. **Employment rate** – total number of employed people between 15 and 64 is already being tracked on annual basis by Croatian Bureau of Statistics [110].
2. **Citizens exposed to poverty risk** – share of citizens whose household`s incomes are lower than poverty line. This indicator is already tracked by Croatian Bureau of Statistics in its publication „Poverty indicators“[111].
3. **Citizens exposed to serious material deprivation** – share of households that cannot either pay their rent or monthly household expenses, either to heat their home adequately. This indicator is already tracked by Croatian Bureau of Statistics in its publication „Poverty indicators“[111].
4. **Exposure to polluted air** – is being measured through two already existing indicators, both on a National list of indicators: a) air quality in urban areas (number of days in a

year with exceeded limit for SO_2, NO_2, PM_{10} i O_3 emissions; b) air quality in urban areas (number of days in a year with exceeded limit for SO_2, NO_2, PM_{10} i O_3 emissions;

5. **Energy poverty** – there are several definitions / methodologies for identifying energy poverty line; the one tracked for this purpose is based on UK methodology – each household that spends more than 10% of its income on energy costs is considered as energy poor.

Economic indicators

1.. **Energy intensity of total consumption** – is a relationship between total energy consumption (measured in *toe*) and gross domestic product (GDP). This indicator is already tracked in [106].

2. **Ecological taxes and subsidies** – three different ecological taxes are the most common in EU – fuel tax, transportation tax and tax on pollution. Subsidies are coming from the total amount spent on feed-in tariff for renewable energy sources and other subsidizes for heat energy from renewables and energy efficiency. This indicator would need to be calculated.

3. **Share of green taxes in total tax amount** – this indicator can be found on Eurostat, based on a Eurostat publication with methodology how to calculate it [112].

4. **Share of GDP spent on energy costs** – this indicator needs to be calculated (methodology based on [113]).

5. **Material productivity** – is defined as GDP divided with domestic material consumption (DMC), calculated in EUR per kilo weight. This indicator is already tracked on Eurostat [114].

6. PROPOSED METHODOLOGY AND MODELS

In order to assess set of hypotheses and overall research objective of this thesis - how climate change and emission trading would impact competitiveness of low emission technologies and its impact on sustainable development, the methodology is proposed that will be presented within this chapter. Both climate change and emission trading impact on competitiveness of low emission technologies is measured through proposed sustainable development indicators. With use of future climate change modeling (of different scenarios), possible long-term climate change impact on a power system can be understood and compared to historical data.

This way, proposed methodology gives more holistic approach to addresses complexity of long term power system planning influenced by both climate change mitigation and adaptation.

6.1. Description of proposed methodology

6.1.1. Schematic description of proposed methodology

There are a wide variety of analytical models developed to analyze climate change policy at national, regional, and global levels. However, their number keeps increasing as they evolve from simple models to those able to cover more sectors, wider area of impacts, new measures and technologies, different starting assumptions etc. The IPCC Fourth Assessment Report [1] found that there are over 750 emissions scenarios in the literature, and all of them consider different portfolios of technologies. Such models and methodologies aim in helping “to identify the mix of early technology investments that will satisfy multiple social goals (national energy security, environmental quality, equity, and a robust economy) - given conditions of deep uncertainty” [115].

Both climate change mitigation and adaptation have impacts on a power system planning and development. Emission trading is raising generation costs for fossil fuels based technologies, which makes low-emission technologies and measures more competitive. Technologies that wouldn’t be competitive without internalization of emission costs at the certain level of CO_2 price are becoming more competitive than technologies based on fossil fuels. This has an impact on the long term power system development. Expected CO_2 price on emission markets in the future represents a signal to investors – if regulator intends to keep low emission technologies competitive, emission market needs careful understanding and regulation. Assessing climate change impacts on a power system development is another issue which is in the focus of proposed methodology – as power plants are more and more dependent on the adaptation issues (such as less hydro production because of less precipitation, or having sufficient water for cooling thermal power plants).

On a Figure 6-1, schematic representation is given of methodology proposed in this thesis. It starts with modeling long term power system planning (after input of all necessary data describing power system, scenarios with different emission prices, list of new power plants candidates, etc.). Several scenarios with different emission price levels are being modeled and their results compared so that emission price impact on a power system could be understood. To analyze climate change impact on power system development, these modeling results are combined with modeling climate change vulnerability and impacts on power system, and this represents an iteration and influences starting inputs to modeling power system development. Once again it is modeled with different emission prices, results are compared with previous results (those without climate change impact on power system development). Results from all scenarios are then modeled towards their impact on sustainable development, leading to comparation of sustainable development indicators and comparation of marginal abatement costs. Low emission technologies are then prioritized according to their impacts on sustainable development indicators, and these results in adjusting inputs back to the model for long term power system planning.

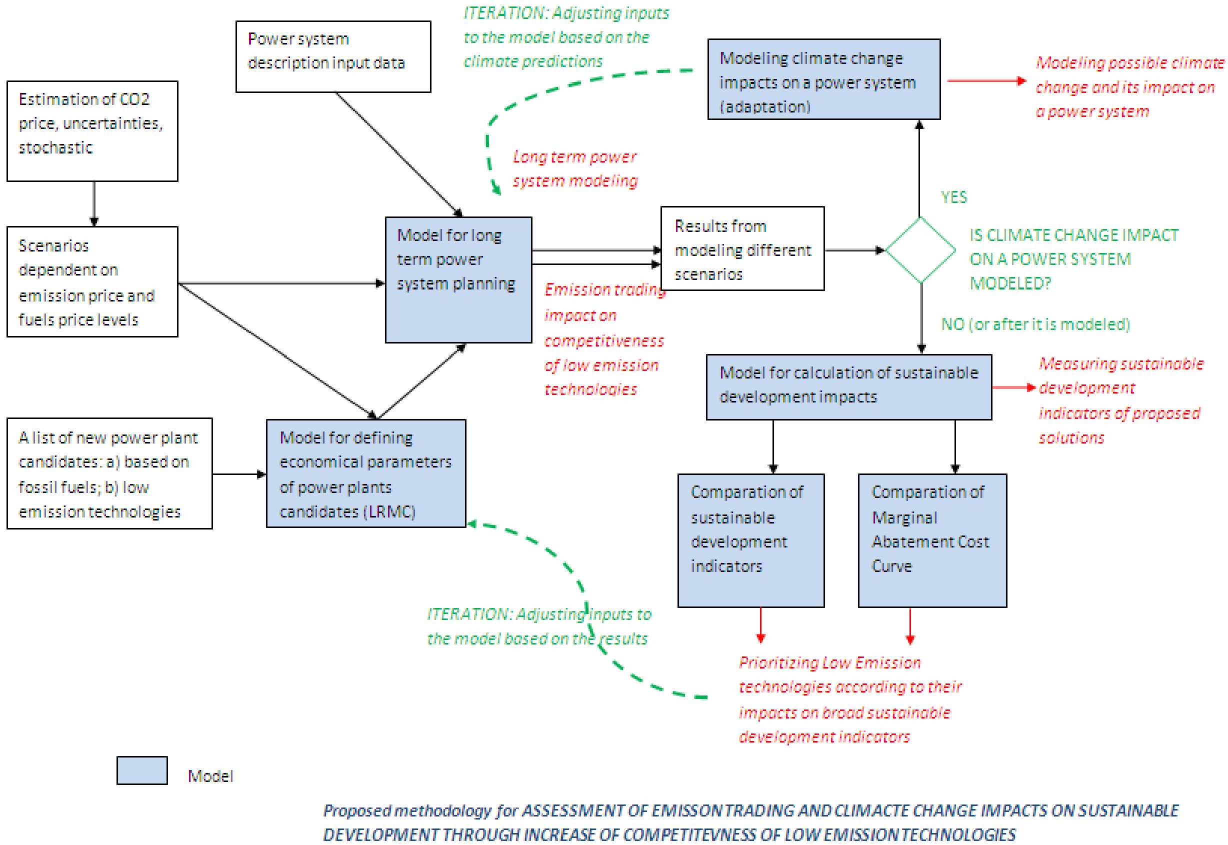


Figure 6-1: Schematic representation of proposed methodology. Author`s representation.

6.1.2. Long term power system modeling

First step in proposed methodology is enabling modeling emission trading impact on long term power system development. First time period target is set on medium period, 2020, where forecast is the easiest as not big technology changes are expected – but investment costs can still vary a lot for technologies whose price per generation unit decreases substantially such as photovoltaic. Second target is set on 2030 where existing technologies are expected to become more efficient and affordable, some existing low emission power producing technologies are become more widely used and their investment price decreased due to additional research, learning curve and mass production (such as wind offshore, tidal, or more infrastructure intensive such as CHP coal power plants with large district heating networks, large scale CCS on coal power plants or fourth generation of nuclear power plants). By setting target on modeling 2050 all sorts of new technologies and new ways of development of energy sector are foreseen (increased DSM, transmission interconnectivity, high-scale distributed generation, electric vehicles) and here a person that models power system planning gets to *terra incognita* for estimation and modeling low emission power generation technologies that might be expected. A list of such and similar low emission solutions (technologies and/or measures) with defined technological and economical parameters are set and serve as an input for power system model. A list of new power plant candidates, fossil fuel based, that will be used in long term modeling is defined separately and serves as an input to the model.

6.1.3. Low emission technologies and solutions

Conclusion made by Energy Supply Contribution Team for Mitigation of Climate Change in Fourth IPCC report [1] was that "the world is not on course to achieve a sustainable energy future, and the global energy supply will continue to be dominated by fossil fuels for several decades". Further conclusion is that reducing GHG emissions will require a transition to zero- and low-carbon technologies that will require "policy intervention with respect to the complex and interrelated issues of: security of energy supply; removal of structural advantages for fossil fuels; minimizing related environmental impacts, and achieving the goals for sustainable development".

Fifth IPCC Report [5] concludes there has happened important increase in installed low emission capacities worldwide, and is more brave in their future prospects. An overview of more than 900 scenarios from the Report concludes:

- The energy supply sector offers a multitude of options to reduce GHG emissions, including energy efficiency improvements and fugitive emission reductions in fuel extraction as well as in energy conversion, transmission, and distribution systems; fossil fuel switching; and low GHG energy supply technologies such as renewable energy (RE), nuclear power, and CCS;
- The stabilization of greenhouse gas concentrations at low levels requires a fundamental transformation of the energy supply system, including the long-term phase-out of unabated fossil fuel conversion technologies and their substitution by low-GHG alternatives;
- Reduction of subsidies to fossil energy can achieve significant emission reductions at negative social cost;
- Mitigation scenarios that stabilize atmospheric CO_2eq concentrations in the range from 430 to 530 ppm CO_2eq by 2100 during the period 2010–2029 means conventional fossil fuelled power plants and fossil fuel extraction would decline by USD 30 (2 to 166)

billion per year (roughly 20%), while investment in low emissions generation technologies (renewable, nuclear, and fossil fuels with CCS) would increase by USD 147 (31 to 360) billion per year (roughly 100%) during the same period in combination with an increase by USD 336 (1 to 641) in energy efficiency investments in the building, transport and industry sectors.

Low emission technologies will become massively used when they become competitive to fossil fuels. There are two ways which both lead to that point:

- By further investing in development of low emission technologies (R&D, subsidizing, promoting…), until competitive price is achieved;
- By making fossil fuels more expensive through removing subsidizes and through setting emission price.

Even though emphasis of this thesis is on how emission price leads to increased competitiveness of low emission technologies due to higher energy costs based on increased fossil fuels, there are also high uncertainties regarding prices of fossil fuels, nuclear technology, low emission technologies... If fossil fuel prices remain high, demand may decrease temporarily when their non-standard reserves become economically competitive (such as those in the form of oil sands, oil shales) which are already reducing gas prices today and transferring from importing gas markets to exporting ones (reference for USA). If this happens, emissions will further rise as the carbon intensity increases, and this is the moment when carbon capture and storage (CCS) will become more important, but it would also increase the cost of generated electricity from cola and gas power plants. High fossil fuel prices might also trigger more nuclear energy where there are additional uncertainties on concerns about safety, weapons proliferation and nuclear waste management (especially in post-Fukushima environment).

Report from IEA in 2014 [67] estimates that (if energy demand continues to grow along the current trajectory), an improved infrastructure and conversion system will, by 2035, require a total cumulative investment of over 48 trillion (in US$2005).

On a global level, no single low emission solution/technology will enable a large-scale transition to the low emission energy-supply systems, but on a country or regional level one or just two technologies might be largely dominant. Modeling performed by the Energy Supply Contribution Team for Mitigation of Climate Change in the same Report, gives a wide range of mitigation options that are available and cost effective at emission prices of <20 US$/t$CO_2$ (including fuel switching and power-plant efficiency improvements, nuclear power and renewable energy systems). Estimation for CCS is that it will become cost effective at higher emission prices (Table 6-1 – for coal power plants, between 20 and 50 US$/t$CO_2$). Other mitigation options under development include advanced nuclear power, advanced renewables, second-generation biofuels and, in the longer term, the possible use of hydrogen as an energy carrier (their categorization according to their maturity is given in Figure 6-2. This typology is useful in bridging resource abatement analysis to public policy.

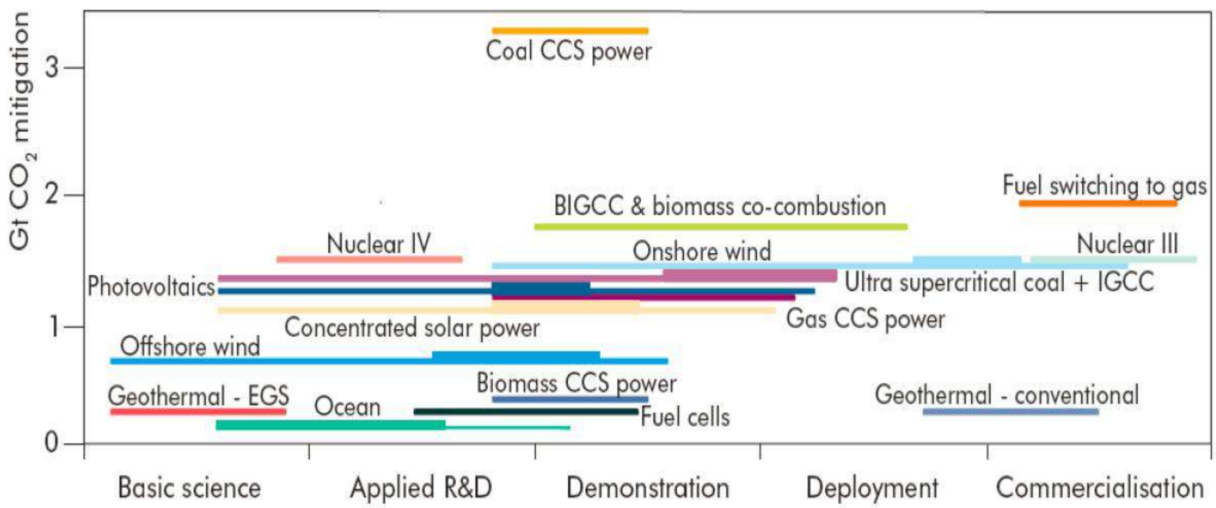


Figure 6-2: Categorization of power sector technologies and their mitigation potential. Source: [116]

For simulated long term planning goals (2020, 2030 and 2050), some of the expected results from modeling that will be used in next steps of proposed methodology are:

- How does the CO_2 price influences fuel switch, competitiveness of low emission technologies and proposed list of candidates power plants?
- For which CO_2 prices tipping points occur when switch to low emission technologies could be expected?
- How does the increased use of low emission technologies is expected to have impact on fossil fuels based generating capacities and which specifically?
- How does the CO_2 price influences total emissions from the power system and an average electricity price?
- Which of the low emission technologies or measures are profiting the most due to CO_2 price increase (renewable energy sources, nuclear, CCS in thermal power plants, energy efficiency?)

- Amount of energy produced /saved with each of low emission technologies?

Table 6-1: Potential GHG emissions avoided by 2030 with estimated mitigation potential shares spread across each cost range, expressed in 2006 US$/t$CO_2$eq). Source: [117]

	Regional groupings	Mitigation potential; total emissions saved in 2030 ($GtCO_2$-eq)	Mitigation potential (%) for specific carbon price ranges (US$/t$CO_2$-eq avoided)				
			<0	0-20	20-50	50-100	>100
Fuel switch and plant efficiency	OECD[a]	0.39		100			
	EIT[b]	0.04		100			
	Non-OECD	0.64		100			
	World	1.07					
Nuclear	OECD	0.93	50	50			
	EIT	0.23	50	50			
	Non-OECD	0.72	50	50			
	World	1.88					
Hydro	OECD	0.39	85	15			
	EIT	0.00					
	Non-OECD	0.48	25	35	40		
	World	0.87					
Wind	OECD	0.45	35	40	25		
	EIT	0.06	35	45	20		
	Non-OECD	0.42	35	50	15		
	World	0.93					
Bio-energy	OECD	0.20	20	25	40	15	
	EIT	0.07	20	25	40	15	
	Non-OECD	0.95	20	30	45	5	
	World	1.22					
Geothermal	OECD	0.09	35	40	25		
	EIT	0.03	35	45	20		
	Non-OECD	0.31	35	50	15		
	World	0.43					
Solar PV and concentrated solar power	OECD	0.03				20	80
	EIT	0.01				20	80
	Non-OECD	0.21				25	75
	World	0.25					
CCS + coal	OECD	0.28			100		
	EIT	0.01			100		
	Non-OECD	0.20			100		
	World	0.49					
CCS + gas	OECD	0.09				100	
	EIT	0.04			30	70	
	Non-OECD	0.19				100	
	World	0.32					

Those results will be further used as an input for holistic sustainable development assessment. In a world of growing complexities, power system development becomes even more complex and calls for holistic approach. Such approach should make sure that the benefits from new generation capacities are not only visible in merely energy and power characteristics, but also on how they influence surrounding environment and social aspects.

Long term power system model used within the methodology needs to include emission price in the variable generation costs, so that the merit order considers emission trading as a part of generation costs. With rise of CO_2 price, fossil based power plants from the list of power plant candidates are getting less competitive while low emission technologies are becoming more competitive. Several scenarios are developed to serve as an input to the model, based on different estimations of future CO_2 price so that more *tipping points* can be assessed – under which CO_2 prices, emission trading impact on a power system results in fuel change (SRMC) and investment decisions (LRMC) in favor of low emission technologies. Important step in modeling is description of a power system that is to be simulated. As inputs to the model are entered power system economical and technical details, description of existing generation and transmission capacities, market conditions, interconnectivities etc. More precise power system description will lead to more valid expected results, but will increase complexity and necessary time for calculations. Therefore, it would be optimal to model power system in proper data resolution that represents reliable results but can be calculated practically, and deliver reasonable output data to enable comparation for different set of scenarios. For example, modeling transmission capacities could be simplified by modeling only 400 kV lines and therefore maximally exclude transmission losses, but it could go down to 35 kV and drastically increase not only a number of lines modeled but also modeling calculation time and output database.

6.1.4. Modeling sustainable development indicators from scenarios

In the next step, outputs from the power system modeling serve as inputs for a model that is enabled to quantify low emission technologies against a desired set of indicators representing social, economic or environmental aspects (such as number of jobs created, emissions reduction, size of investment, amount of energy produced, amount of installed capacity etc). By quantifying these values, further comparation between different low emission solutions becomes possible. It is also possible to assess how emission price is influencing transition towards sustainable development.

Moreover, model enables adding financial value to calculated sustainable development indicators that can be entered as an input to the model. One of the features would be assessment of how will the financial value be added to these indicators. Some of them could be directly financially valued, such as price of emissions – not only price of GHG emissions that is given on the emission trading market, but also direct price could be given to other emissions if there is an existing tax on such emissions (SO2, NOx…). Giving financial value to the indicators such as new created jobs depends from the modelers' perspective – what is the value, what are the financial benefits of new created working place? This topic is already described previously, which is also the case when it comes to adding financial benefits to indicators that are more complicated to be modeled as there is no clear financial value for them (indicators such as value of biodiversity, or rural development). With adding financial values to sustainable development indictors, it is possible to understand which low emission solutions lead to the highest increase of desired indicators, and then to optimize power system planning for the given CO_2 price by manipulating which low emission solutions will be used. Specific long term power system planning optimization strategies could be developed with such approach that favors for example maximum employment or holistic maximum sustainable development.

A model also can give a time perspective, so it is possible to model when some low emission technologies are planned to happen and to track change of sustainable development indicators. Each low emission solution that is modeled can be analyzed separately. Outputs from this model are further used as inputs for two other models which allow comparation of sustainable development indicators, according to a number of indicators or only on investment costs. Another purpose is to enable visualization of results, in order to better communicate or compare them, so that modeling process can be influenced in new iteration by changing input data to the first model.

First of these models enables comparation and visualization of marginal abatement costs for the evaluated low emission solutions arriving as results from power system model. It is also tracking based on different emission price scenarios, and enables calculation of financial instruments such as payback, net present value (NPV) or internal rate of return (IRR). The use of MAC curves for this purpose was made famous by McKinsey & Company, and was described in chapter 4.1. of this thesis.

The second model enables visualization and prioritization of different low emission technologies by using several indicators at the same time.

Depending on the results from these models, the planner can change the input data that are entering the power system model. In next iteration, it is possible to adjust which input data not only by lessons learned but also a focus can be given to creation of broad range of scenarios such as:

- Scenario of low emission technologies mix that leads to the maximal value of chosen indicator (for example the highest number of new created jobs);
- Uncertainties analysis – creation of several sub-scenarios that consider a range of investment costs or change of any other indicators;

- Appliance with some other constrains (such as maximal amount of emissions from the power system or size of investment);
- Comparation of impacts that happen due to some input data change.

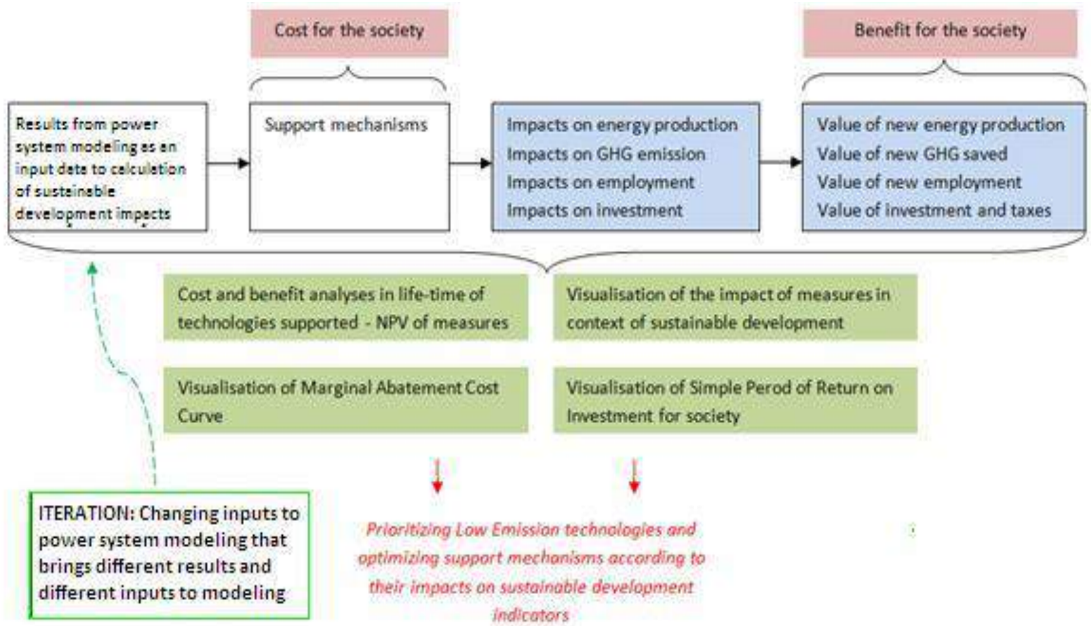


Figure 6-3: Scheme of the methodology description for evaluation of calculating impact of different scenarios on sustainable development indicators. Source: [118]

6.1.5. Modeling impacts on job creation

When classifying green jobs, it is necessary to distinguish three different types of jobs - direct employment (equipment production and maintenance), indirect (accompanying industry) and induced employment (new jobs that occur because of daily consumption of directly and indirectly employed persons) [119].

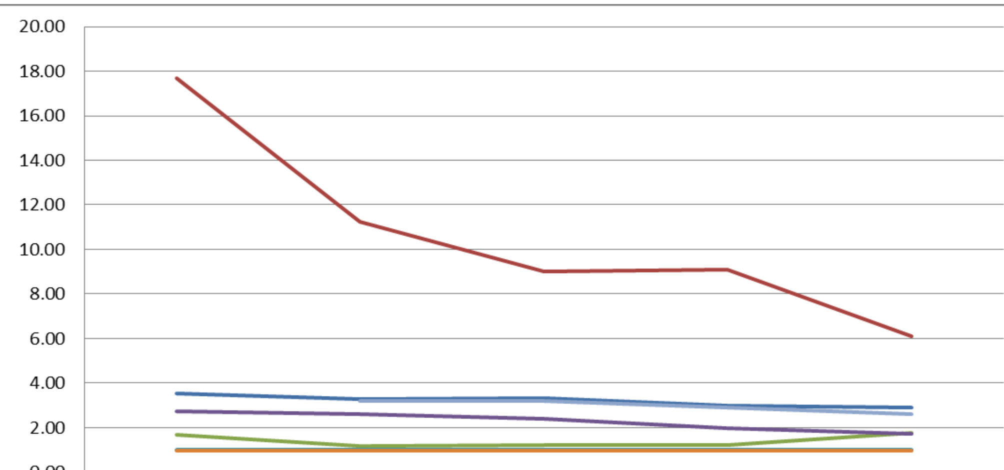
Currently there are over 5.7 million employees in the field of renewable energy sources in the world [120]. Half of the number of employees refers to the area of biomass and bio-fuels, then to the production of solar thermal systems, wind energy, production of photovoltaic systems… Also it is estimated that only in the U.S. in the sector of energy efficiency there was a total of 8 million green jobs in 2006 [119]. Employment growth in the renewable energy sector equally takes place in the developed world (330 thousand employed in the renewable energy sector in Germany, 200 thousand in Spain, 600 thousand in the USA) as well as in other countries (million employees in the sector of renewable energy in China).

Unit impacts on society are evaluated on the basis of jobs created as a consequence of policy measures. Several studies tried to estimate a number of jobs created by investing in new capacities for energy production. Table 6-2 shows results from the study made by UNEP.

Table 6-2: Jobs creation per MW capacity installed in lifetime of technology. Source: [119]

[1/MW]	Production, instalation	Maintanace, fuel processing	Sum
Solar PV	5.76-6.21	1.20-4.80	6.96-11.01
Wind power plants	0.43-2.51	0.27	0.70-2.78
Biomass CHP	0.40	0.38-2.44	0.78-2.84
Coal power plants	0.27	0.74	1.01
Gas power plants	0.25	0.70	0.95

The overview of statistical estimation data for five consecutive years presented by [121] for the European Union in recent years gives average unit outputs for new jobs/MW installed power or PJ of energy produced. By compiling data from 2007 to 2011 based on statistical yearbooks, Figure 6-4 shows change of job creation over time. It is interesting to see how number of jobs per MW is decreasing especially for PV technology, as it is getting produced less and less labor intensively – either due to production in larger factories, either due to more import.



	2007	2008	2009	2010	2011
Wind power plants	3.54	3.26	3.33	2.99	2.88
Solar, PV	17.70	11.26	9.03	9.07	6.08
Hydropower plants	1.69	1.18	1.22	1.22	1.77
Solar thermal systems	2.74	2.62	2.38	1.97	1.70
Coal	1.01	1.01	1.01	1.01	1.01
Gas	0.95	0.95	0.95	0.95	0.95
Solid biomass		3.21	3.19	2.88	2.60

Figure 6-4 Average number of jobs per Megawatt installed capacity in EU-27. Source: [118]

Distribution of number of jobs created per MW installed also defer on the type of technology – for some technologies such as wind power plants, most of jobs are located in manufacturing of wind power plants and very few in installing and maintenance; while for some other technologies such as PV, more jobs are created in maintenance and installing together than in manufacturing (Figure 6-5).

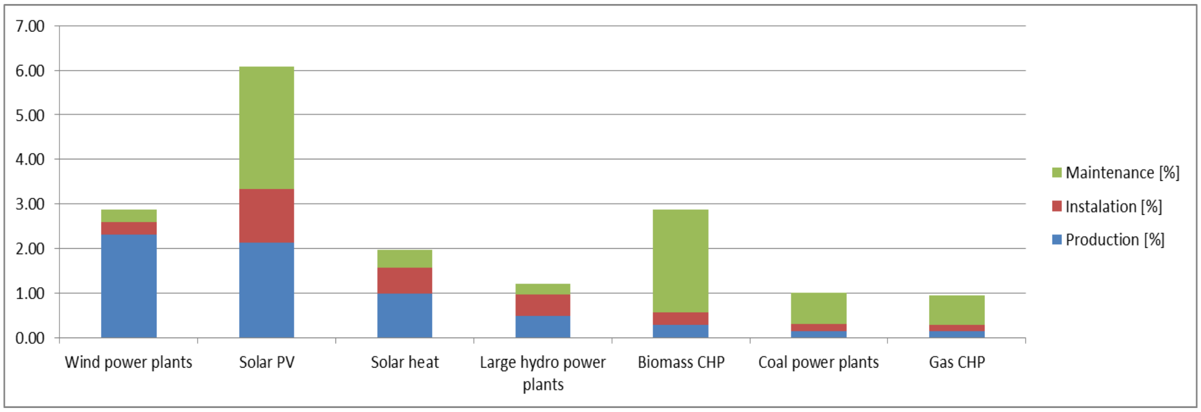


Figure 6-5 Division of jobs created per MW investments in new capacities for energy production. Source: [118]

6.1.6. Long term climate change impacts on renewable energy production

Following part of proposed methodology for assessing climate change impacts on long term power system planning could be applied for both low emission technologies and thermal power plants. It could be also applied to forecasting demand side (as energy consumption will be increased with hotter weather during the summer periods due to more energy needed for cooling; or less energy consumption in winter months due to expected warmer periods).

However, further focus in the proposed methodology will be only on generation from renewable energy sources – impact on energy demand will not be in focus, as an impact on other types of power plants other than renewable energy.

For the renewable energy sector as a whole, simple and reliable climate predictions are needed to accelerate technology deployment by reducing uncertainty of financial investments. When renewable energy sources and climate change are considered in the same context, the analysis is usually focused on the impacts that renewables might have on mitigation of climate change, with the aim to reduce emissions of greenhouse gases (GHGs). In this proposed methodology, the focus is on the adaptation side, to identify how future climate change might impact energy generation from renewables. Available analyses on this subject are currently very few, but a growing number of studies have initiated these questions, such as those given in overview in [122,123].

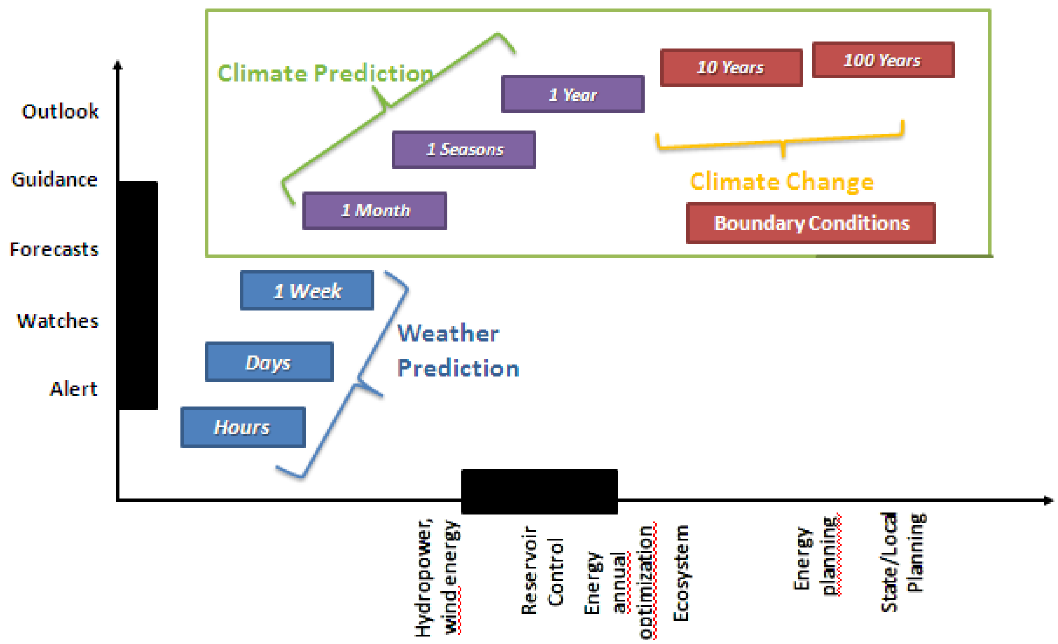


Figure 6-6: Graphical representation of meteorological data use in power system operation and planning

Power plants are facing a number of risks related to the long-term operation performances. The most significant sources of risk are related to the legislation, economy and resources. The resources related risks are especially important for the renewable energy sources. They are strongly influenced by weather and climate conditions which might change significantly in the future. Climate parameters vary from year to year, so for a reliable estimate of climate trends it is important to analyze data from long time periods. As no particular development of these GHGs concentrations could be possibly foreseen, various emission scenarios are developed based on different assumptions about variables that affect the GHGs emissions [124]. The most important influences are from variables associated with the growth of the world population, economic growth, energy production and consumption and land use.

Power system planning requires long-term approach due to the following reasons: the planning and construction processes of power plants take a long period of time, in most cases between 1-10 years; once built, power plants usually have long operation life time, from 25 years for wind, photovoltaics (PV) and gas power plants, to 60 years for nuclear and 80-100 years for hydro power plants, where the equipment is usually being changed after 30-50 years [125]. For such long time spans, it is important to somehow include the information about climate change in the power system planning process. On the liberalized energy markets, a decision to invest in the new power plant needs to be economically justified, because a loss of, for example, 5-10% of the future planned income can make a difference for an economically viable power plant project. In addition, the resource uncertainty due to potential climate change might increase the potential risk and might be detrimental for investors. The assessment of three different renewable sources is proposed within the methodology, solar, wind and hydro, because of their potentially high sensitivity to climate change.

Climate models are the only tools that enable understanding of how climate will change in the future. They model variables such as temperature, precipitation, humidity, wind speed, sea level rise, cloudiness and other relevant variables. Even though the climate modeling capabilities are developing continuously, climate models are only approximations of the atmosphere, oceans, and other components of climate system, and as such are unable to precisely predict the future state of that system. In order to alleviate uncertainties associated with climate modeling and to make climate predictions more reliable and applicable, it is necessary to take into account the results from different climate models. Climate models are broadly divided into global climate models (GCMs) and regional climate models (RCMs). A GCM can give an overview of climate and climate change of the whole planet, but, because of its relatively coarse horizontal resolution (between 150 and 300 km) GCMs are of little use when focusing on small areas. RCMs, on the other hand, with resolution of the order of 10 to 50 km are capable of resolving climate related processes at regional and local scales. While the advantages of RCMs are clear, they are dependent on GCMs for providing initial and lateral boundary conditions (forcing). The forcing of an RCM by a GCM, known as dynamical downscaling, is proposed in this methodology, whereby the results from one GCM are used for downscaling by the RCM [126,127]. Climate variables need to be modeled for the referenced scenario (from the past period) and for the future scenario representing the climate of the period in the planning focus.

Methodological approach for modeling climate change impacts on renewable energy sources is proposed here in two steps of different complexity levels. First proposed methodological step is simpler and uses results from climate models (forecasted climate information, like precipitation or wind speed for the future period) as an input to expert judgment to understand how it will impact energy production from renewable energy sources. In order to make good expert judgment it is important to understand correlation between climate and renewable energy output – for example, if wind speed increases 10% what does it mean in terms of increased energy produced from wind power plants.

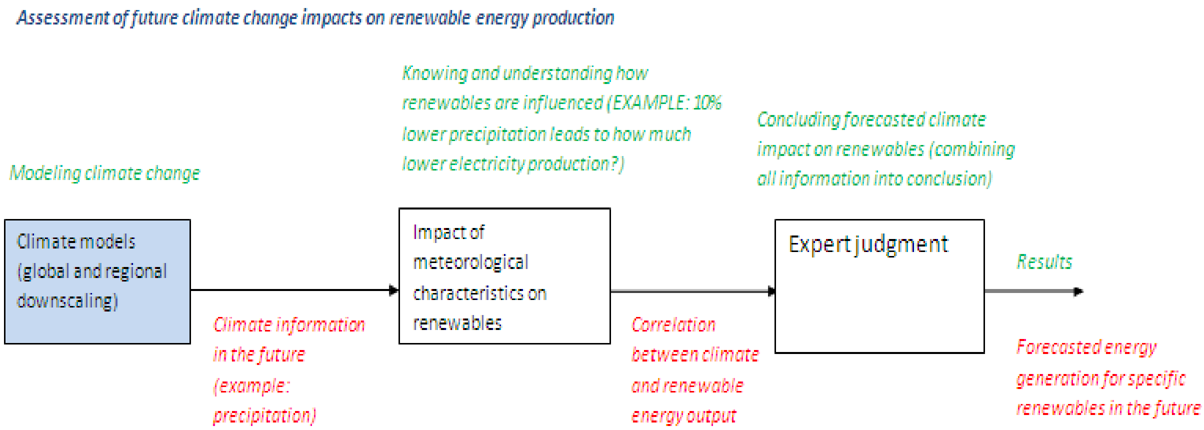


Figure 6-7: First step in methodological representation of climate change impacts on RES production. Author`s representation

Such representation of assessing climate change impacts on renewable energy production has some drawbacks – correlation is never linear and ideal. In ideal case 10% more precipitation would mean 10% more energy production from hydro power plant but in realistic conditions some of this water doesn't even get to the hydro power plant, another part goes to biological minimum for plant, some is lost in evaporation from accumulation lakes. Extensive use of historical hydro and meteorological data would help in creation of more correct correlation.

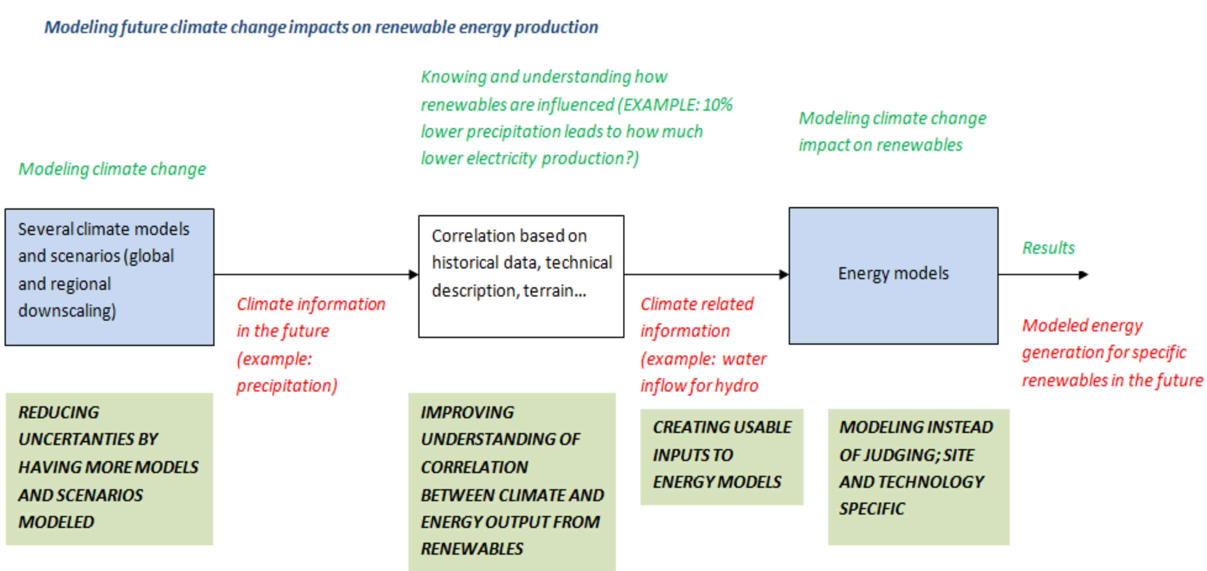


Figure 6-8: Second proposed methodological step in representation of climate change impacts on RES production. Author`s representation

Second proposed methodological step is more complex that the first one, and has several improvements from the first proposed step:

- Instead of using one climate model and/or one climate scenario only, it uses a range of climate scenarios and models in order to define a probabilistic range of forecasted climate information;
- It includes use of this historical data for understanding correlations between climate and renewable energy production, and in cases where it exist, also includes terrain specific information;
- Instead of expert judgment proposed in previous step, it uses energy models. Climate related information such as water inflow for hydro power plants is changed according to climate forecast and correlation; so it changes input to the energy model. Energy models used here can be either energy planning models (such as the one already used here for modeling long term power system planning), or can be technology specific such as model that enables modeling wind power plants. In both cases, input to the model can be modified according to the change of meteorological information (such as the change of average wind speed for wind power plant).

In case that long term power system model is used – the one that is already used in first step of overall methodology, created results based on climate change forecast could be used as an iteration for inputs to energy model. For example, if it is expected that due to climate change wind power plants produce 20% more energy than previously expected, inputs to energy planning model will be modify to model higher energy output from modeled wind power plants.

6.2. LRMC model

In this subchapter, a need for model that would enable comparation and definition of economical parameter of power plants is described. Further, proposed and developed model that satisfy these needs is described.

6.2.1. Theoretical background for model

The fact that emission price adds additional costs to fossil fuels and therefore changes its competitiveness can be analyzed by measuring its impact on LRMC and SRMC (Chapter 4). While decisions regarding merit order change are based on the SRMC (it also means decision on fuel switch for example), investment decisions in new plants are based on the LRMC. In order to analyze CO_2 price impact on LRMC and SRMC, a theoretical mathematical model is proposed and developed, based on the approach in IEA study [50] and [128]. Purpose of the model is to define LRMC and SRMC and how CO_2 price changes investment decisions for new power plants and change in merit order in existing plants. While the SRMC include fuel costs and variable costs, the LRMC of a plant include fuel costs, variable cost, fixed cost and costs of capital. In dependence of the CO_2 price, CO_2 costs are added in the model to the SRMC and LRMC. It main purpose in proposed model is to help identify LRMC for plant candidates – as impact of CO_2 price on different power generation technologies can be understood and compared much faster and easier in proposed mathematical model than through modeling it with power system model. Like this, modeler saves time and draws general conclusion much faster – which adds to simplicity but might not be enough for modeling more complex power system expansion, or when more input variables are changed.

Results from assessment performed by presented theoretical mathematical model within proposed methodology are taken as tool to:

- Explore simple emission trading impacts on power generation technologies (primarily on their LRMC and SRMC), and on investment decisions within power system;
- For easier defining and comparation of input data for new power plant candidates that will be modeled in PLEXOS model.

Mathematical model assumes that 100 per cent of the allowances are auctioned or sold to the companies, and should serve a reference case for other allocation methods. Amount of operation hours used in the analyses depends on the technology used and can be modified as an input (for example, 8000 h/annually for coal power plants, or 25% for wind power plants of time is assumed in full load hours (2200 h/annually). Input data sheet is presented in the table below. Since total investment costs in recent nuclear projects proved to be higher than expected [129], this sensitivity was analyzed within the model by adding additional variable – Nuclear HIGH, with significantly higher investment costs than variable Nuclear. Also, due to very fast development in technology and capacity installed, a case with economically more favorable wind power plant is considered (Wind LOW), with lower investment costs and lower fixed costs. Changed parameters in Wind LOW and Nuclear HIGH variables are emphasized with shade in the table cells. Even though Croatian Energy Strategy considers building of new CHP power plants, costs of electricity production from these plants are not included in the model. This is because price of heat is not defined yet in Croatia, and reasoning for building CHP plants is primary heat energy, not price of electricity that can be traded on the electricity market. Also, investment costs of CHP plants are in many cases combined with investment costs for district heating or heating stations.

Table 6-3: Economic parameters used to describe new power plants within scenarios (energy prices are defined according to oil prices of 84 USD/bbl while costs are according to average costs in USA from 2008. Sources: [129,130,131]

		Coal	CCGT	Wind	Wind LOW	Nuclear	Nuclear HIGH
Fuel price	€/GJ	3,12	8,57			1,00	1,00
Thermal coefficient	%	43,50	55,00			40,00	40,00
Heat Rate	GJ/MWh	8,28	6,55			9,00	9,00
Fuel price (MWh)	€/MWh	25,82	56,09			9,00	9,00
Variable costs	€/MWh	3,48	1,52			0,37	0,37
Emission coefficient	tCO_2/MWh	0,814	0,367	0,000	0,000	0,000	0,000
Annual fixed costs	€/kWyear	40,00	20,00	30,00	15,00	100,00	100,00
Fixed costs	€/MWh	3,98	1,25	13,69	6,85	6,55	6,55
Investment costs	€/kW	1600	800	1400	1000	2400	4000
Expected life	year	30	20	25	25	40	40
Interest	%	8,5	8,5	8,5	8,5	8,5	8,5
Investment costs	€/MWh	18,60	10,57	62,48	42,61	26,50	44,19
LRMC	€/MWh	51,88	69,43	76,17	51,46	42,42	60,11

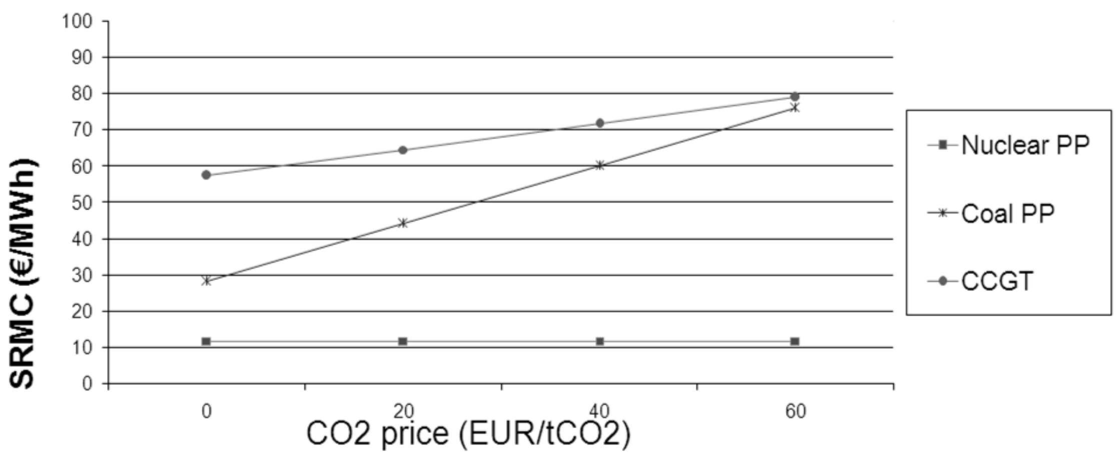


Figure 6-9: Impacts of emission allowances price on rise of SRMC for different electricity generation technologies (example). At prices of CO_2 higher than 62 €/tCO_2, CCGT becomes more competitive than coal

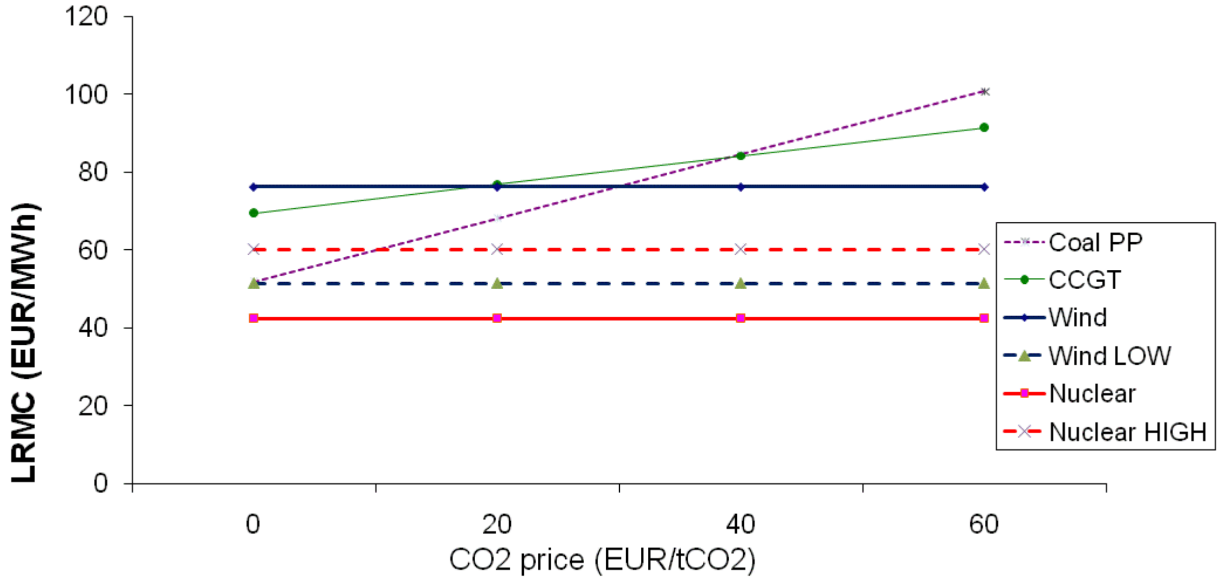


Figure 6-10: Impacts of emission allowances price on rise of LRMC for different electricity generation technologies, with oil price 84 USD/bbl

From the Figure 6-10, it can be seen that with CO_2 prices higher than 40 €/tCO_2, CCGT becomes more competitive than coal for investors (based on LRMC), while at prices of CO_2 higher than 31 €/tCO_2, wind power plants are more competitive than coal and CCGT. Sensitivity analyses shows that lower wind investment costs (expected with economy of scale in wind power plant production) mean that wind becomes more competitive technology for investment than coal or CCGT, regardless of the CO_2 price. Another sensitivity analysis for nuclear power plants` investment costs shows that even with the highest recorded investment costs nuclear power plant remains more competitive technology than CCGT, but is more competitive than coal only with CO_2 prices higher than 10 €/tCO_2.

A sensitivity analysis was also done for higher oil price – 126 USD/bbl instead 84 USD/bbl in the referent case (

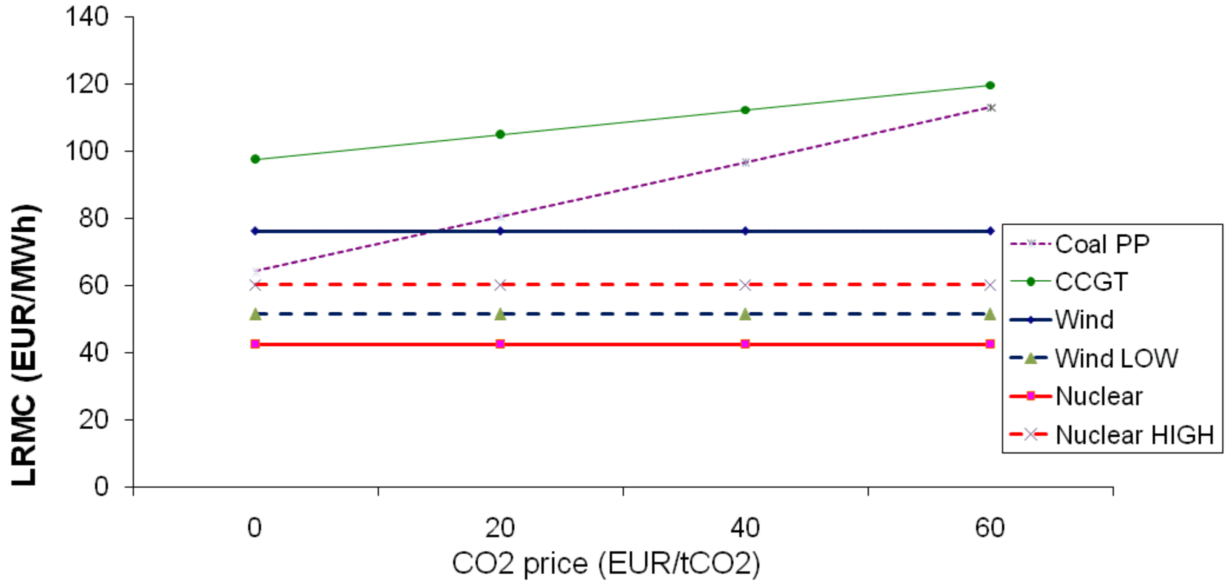


Figure 6-11).

Price of natural gas and coal are influenced by the price of oil [130] so price of natural gas in this case is 12.86 €/GJ instead of 8.57 €/GJ, and price of coal is 4.6 €/GJ instead of 3.12 €/GJ. The difference from the 84 USD/bbl case is seen from the figure bellow, where coal is always more competitive technology than CCGT regardless the CO_2 price, while wind becomes more competitive technology than coal with prices higher than 15 €/tCO_2.

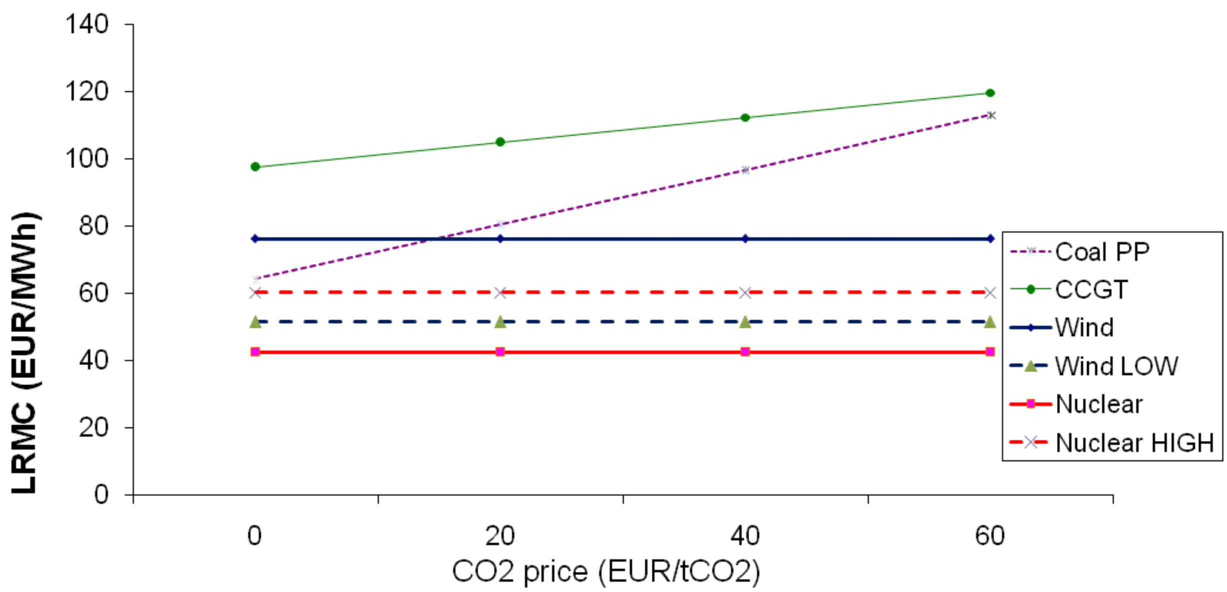


Figure 6-11: Impacts of emission allowances price on rise of LRMC for different electricity generation technologies, with oil price 126 USD/bbl

In case where lower fuel prices are applied (42 USD/bbl, Figure 6-12), according to the used pricing model coal price is 1.81 €/GJ and natural gas price is 4.28 €/GJ. In this case, CCGT is more competitive than coal regardless the CO_2 price. Wind is more competitive than coal only after 45 €/tCO_2, and even with its lower investment costs it is the most competitive after 28 €/tCO_2.

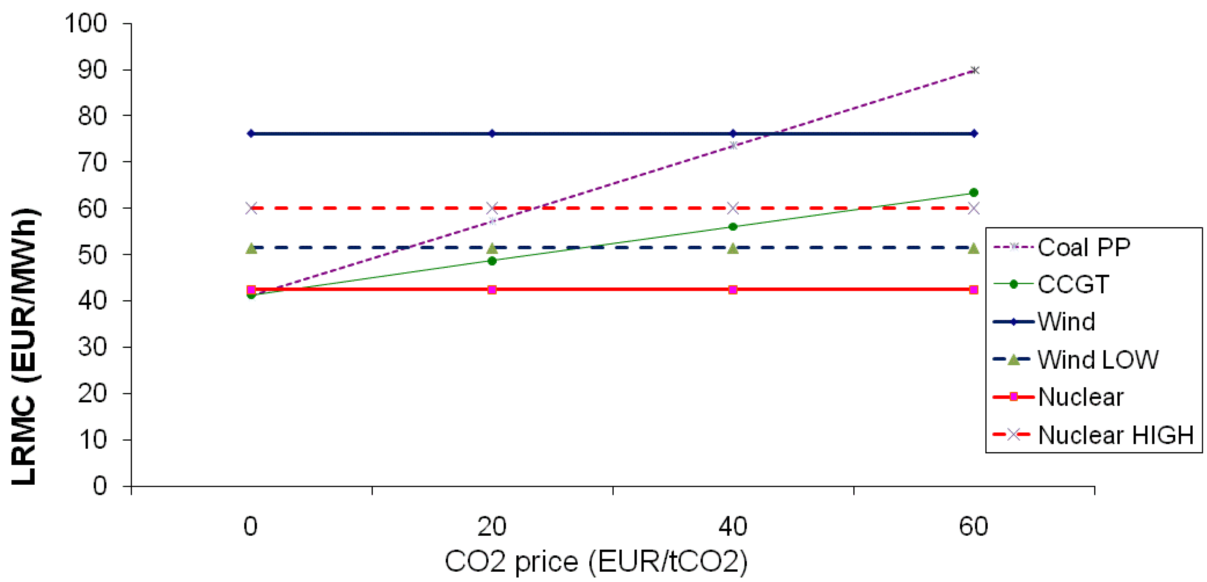


Figure 6-12: Impacts of emission allowances price on rise of LRMC for different electricity generation technologies, with oil price 42 USD/bbl

Results from this simple model show how uncertainties regarding definition of relevant parameters describing generation costs in power plants could have huge impacts on results. Like this, input data for power system model can be pre-checked before it is put in power system model and can save modeling time.

6.3. Model for estimation of sustainable development impacts

In order to measure how researched changes in power system (both climate change impact on renewable energy generation and impact of emission trading on generation price) would lead to measurable improvement towards sustainable development, it was necessary to design and develop a model that would enable quantification of agreed sustainable development indicators; and comparation between different scenario results. There was a need for model to model required measurable indicators in relation to inputs (which would be actually outputs from a power system model). So that would enable quantification of sustainable development indicators based on results from modeling long term power system planning. Such model was first constructed as a prototype according to the methodological description (as described earlier in this chapter), and then it was developed as an Excel based document, with working name “Model for estimation of sustainable development impacts”.

6.3.1. Inputs to model

Outputs from the power system model serve as inputs for this model developed to enable estimation of sustainable development indicators. By including emission price in the variable generation costs due to emission trading, there was a change in long term power system planning. With rise of CO_2 price, fossil based power plants from the list of power plant candidates are getting less competitive while low emission technologies are becoming more competitive, and more investments are happening in the direction of low emission technologies.

Several scenarios with different CO_2 price could be developed to model emission trading impact with power system model (based on different estimations of future CO_2 prices, future energy prices, investments costs and other uncertainties defined). Modeling these scenarios leads to several sets of power system modeling results.

Further, these results are compared and used as inputs into “Model for estimation of sustainable development impacts”. Like this, a range of more *break even points* can be assessed – under which CO_2 prices, emission trading impact on a power system results in fuel change (short time, based on SRMC) and investment decisions (long time, based on LRMC) in favor of low emission technologies. Upon the chosen low emission technologies and measures, this model calculates their impact on the desired set of indicators representing social, economic or technical aspects (such as number of jobs created, emissions reduction, size of investment etc).

Measure	2010			2020		
Basic	GDP 2010. [M€]	45.033,56	eihp	Expected rise of el.en. demand year [%]	2,00	
	El. energy consumption 2010. [GWh]	18.869,44	eihp	Expected rise of thermal energy demand		
	Thermal energy consumption 2010.					
Wind	Installed [MW]	78,95	eihp	Energy strategy [MW]	1200	e
	Energy produced [GWh/year]	139,10	eihp	Installed [MW]	1200	
	Percentage of el. en. consumption [%]	0,74		Average percentage of domestic manufacturing [%]	50	
				Average percentage of domestic installing [%]	90	
				Average percentage of domestic operation and maintenance [%]	90	
Solar PV	Installed [MW]	0,16	eihp	Energy strategy [MW]	45	e
	Energy produced [GWh/year]	0,12	eihp	Installed [MW]	45	
	Percentage of el. en. consumption [%]	0,00		Average percentage of domestic manufacturing [%]	40	
				Average percentage of domestic installing [%]	90	
				Average percentage of domestic service and maintenance [%]	90	
Small hydro (<10 MW)	Installed [MW]	31,05	eihp	Energy strategy [MW]	100	
	Energy produced [GWh/year]	124,10	eihp	Installed [MW]	100	
	Percentage of el. en. consumption [%]	0,66		Average percentage of domestic manufacturing [%]	90	
				Average percentage of domestic installing [%]	90	
				Average percentage of domestic service and maintenance [%]	90	
Solid biomass CHP	Installed el.power [MW]	9,37	eihp	Energy strategy [MW]	120	8
	Installed th.power [MWt]	15,55	50%t	Installed [MW]	120	
	El. energy produced [GWh/year]	33,00	eihp	Average thermal power installed [MWt]	200,00	
	Th. Energy produced [GWht/year]	124,43		Average percentage of domestic manufacturing [%]	90	

Inputs / Outputs / Coeffs / Wind / SolarPV / Hydro / SBMCHP / GTCHP / WasteCHP / BiogasCHP / SolarThermal / SBThermal / HeatPump / EEhouse / EEnonres / Biofuel

Figure 6-13: Input sheet for "Model for estimation of sustainable development impacts" (yellow cells are changed upon results from long term power system planning)

Data input starts on "Inputs" sheet, where for various low emission technologies (all possible renewable energy technologies and energy efficiency in buildings sector) technical and economical characteristics are described (Figure 6-13). Most of them are based on outputs from PLEXOS model. Yellow cells in "Inputs" sheet are those cells where input values can be entered, and model allows entering a set of inputs for different periods/years (2020, 2030, 2040, 2050). In order to provide more realistic estimations on a social perspective, model enables choosing the share of domestic manufacture as an input (depending on the share of installed technology produced domestically), the share of domestic installation and share of domestic operation and maintenance. It is up to modeler to set up various scenarios that would describe level of imported and level of domestically produced low emission technologies.

Each low emission technology that is modeled has its own sheet with all the calculated indicators (Figure 6-14), and for a specific year a cost – benefit analysis is done that includes the following benefits:

- Value of GHG reduction (based on total amount of CO_2 emissions, CO_2 price can be set in the model);
- Value of new jobs created (value of new created job can be set in the model);
- Value of energy produced/saved;
- Cost of support of new energy produced.

		Wind	Solar PV	Hydro	Solid biomas CHP	Geothermal CHP	Waste CHP	Biogas CHP	Solar thermal
Energy	Situation in 2020. compared to planned in Strategy [%]	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00
	New el.energy produced 2020. [GWh/year]	2.466,31	58,29	241,33	885,04	160,00	320,00	85,04	
	New electrical power installed per year [MW/year]	112,11	4,48	6,90	11,06	2,00	4,00	1,06	
	New thermal energy installed per year [MWt/year]								83,75
	New thermal energy produced/saved 2020. [GWht/year]				1.475,57	266,67	533,33	142,23	676,87
	New biofuel energy produced 2020. [GWh/year]								
	Average new electrical energy per year produced [GWh/ye	1.233,16	29,14	120,66	442,52	80,00	160,00	42,52	
	Average new thermal energy produced/saved per year [GWht/year]				675,57	133,33	266,67	8,90	338,43
	Average biofuel energy per year produced [GWh/year]								
	Percentage of el. en. consumption 2020. [%]	10,72	0,25	1,05	3,85	0,70	1,39	0,37	
	Percentage of th. En consumption 2020 [%]								
Environment	GHG saved 2010. [t/year]	39.323,57	21,44	36.398,53	41.338,64	0,00	0,00	53.543,93	13.032,90
	New GHG saved 2020. [t/year]	697.225,84	10.415,85	70.780,62	624.644,49	111.365,47	219.530,94	61.021,54	169.217,10
	New GHG emissions for construction and running 2020. [t/y	98.652,40	8.393,30	7.094,96	44.606,02	9.600,00	22.400,00	3.401,60	6.768,68
	New GHG saved in the period [t]	3.486.129,19	52.079,26	353.903,11	3.123.222,44	556.827,36	1.097.654,72	305.107,72	846.085,50
Social (jobs)	Nuber of jobs created 2020 in manufacturing [jobs/year]	117,71	11,82	24,45	8,36	1,14	3,02	0,80	93,69
	Numbers of jobs created 2020 in instalation [jobs/year]	24,21	9,30	18,18	5,68	0,82	2,05	0,55	28,83
	Numbers of jobs created 2020 in maintenance [jobs/year]	262,33	53,27	16,75	239,96	9,72	38,52	17,89	216,21
	Number of jobs in 2020 [jobs/year]	404,25	74,39	59,39	254,00	11,68	43,60	19,24	338,73

Inputs | Outputs | Coeffs | Wind | SolarPV | Hydro | SBMCHP | GTCHP | WasteCHP | BiogasCHP | SolarThermal | SBThermal | HeatPump | EEhouse | EEnonres | Bio

Figure 6-14: Result values of indicators from "Model for estimation of sustainable development impacts" for different low emission solutions

6.3.2. Description of support mechanisms

As technologies for renewable energy sources have higher investment costs than conventional power plants, and to ensure emission reduction target and targets on share of renewable energy sources are met, support mechanisms can be set in the model. They are designed to describe existing supporting mechanisms in Croatia: guaranteed incentive purchase price (feed in tariff) or partial subsidy of the investment from the government. Overview of modeled support mechanisms is given in

Table 6-4.

Table 6-4: Support mechanisms to reach energy targets [1]

[1] The rate used was 1 EUR = 7.5 HRK

ENERGY SOURCE	TECHNOLOGY	Guaranteed incentive purchase price			Subvention of investment
		Comment	€/kWh	€/l	%
Wind Energy	Wind power plants	Installed power over 1 MW	0.096		
Solar energy	Solar PV	Instalirane snage od 10 kW do 30 kW	0.297		
	Solar heat				20
Water energy	Large hydro power plants	*Partner in investment			50*
	Small hydro power plants	Yearly production 500 MWh - 1000 MWh	0.107		
Biomass	Biomass CHP	1 MW - 2 MW installed electrical power	0.160		
	Biomass heat				20
	Waste CHP		0.071		
	Biofuel	Biodiesel - Bioethanol		0.461-0.233	10
Geothermal energy	Geothermal CHP	Installed power over 1 MW	0.189		
	Heat pump				20

6.3.3. Description of impacts on energy production

Among the technological and economical characteristics described in the model, each low emission technology has its features energy production-wise. Some of differences are the possibility of power regulation, system regulation, dependence on inconstant energy sources etc. Because of these differences, there is a pressing need for establishing a balanced and flexible energy system.

Table 6-5: Comparison of technologies by load factor

ENERGY SOURCE	TECHNOLOGY	Load factor [%]
Wind Energy	Wind power plants	25
Solar energy	Solar PV	15
	Solar heat	27
Water energy	Large hydro power plants	63
	Small hydro power plants	40
Biomass	Biomass CHP	86
	Biomass heat	46
	Waste CHP	86
Geothermal energy	Geothermal CHP	86
Coal	Coal power plants	91
Natural gas	Gas CHP	68

In this model, one of the key features of energy technologies is the load factor. Table 6-5 represents modeled values of load factors. Fossil fuels-fired power plants have an advantage considering the load factor compared to technologies using renewable energy resources except technologies using biomass, geothermal and waste energy.

6.3.4. Description of impacts on GHG emissions

As more than 66% of world's greenhouse gas emissions come from the energy sector [1], key effects on the environment are greenhouse gas emissions from new energy facilities. In this model, effects on the environment are evaluated by the amount of GHG emitted or saved. Value chosen for energy production from different technologies is from lifetime of technology (Life Cycle Assessment).

Table 6-6: Emissions during energy generation in lifetime of technology. Source: [132]

Technology	Emissions [kgCO2/GWhe]
Coal power plants	960
Gas power plants	440
Wind power plants	10
Solar, PV	23
Hydropower plants	13
Biomass CHP	14
Geothermal CHP	28
Average emissions in Croatian EES	330

Different emission factors (tCO_2/MWh) can be set in the model for energy mix average, for heat generation emission factor etc.

In the model, jobs are divided by phases into production, installation and maintenance of technologies. It is possible to vary these factors and a percentage of a share of domestic component in production, installation and maintenance of technologies. Average number of jobs per MW installed capacity in EU-27 for each technology are based on already presented numbers from [118].

Unit outputs for new jobs in energy efficiency projects in households were modeled as 0.25 job-years for energy efficient refurbishment of an average house/flat, based on the experiences from UNDP projects for energy efficiency in Croatia [133].

Table 6-7: Division of jobs created by investments in new capacities for energy production used in model. Source: [118]

ENERGY SOURCE	TECHNOLOGY	New jobs		Share during lifetime of technology		
		Per power installed [1/MW]	Per energy produced [1/PJ]	Production [%]	Instalation [%]	Maintenance [%]
Wind Energy	Wind power plants	2.88	419.2	80	10	10
Solar energy	Solar PV	6.08	1944.8	35	20	45
	Solar heat	1.97	315.3	50	30	20
Water energy	Large hydro power plants	1.22	153.0	40	40	20
Biomass	Biomass CHP	2.87	112.6	10	10	80
	Waste CHP		73.2	30	30	40
	Biofuel		186.5	10	5	85
Geothermal energy	Geothermal CHP and heat pump		368.4	15	45	40
Coal	Coal power plants	1.01	52.1	15	15	70
Natural gas	Gas CHP	0.95	50.5	15	15	70

6.3.5. Model outputs

Sustainable development indicators which are modeled in presented model are divided in three categories (Figure 6-15):

- Environment - so far focused only on GHG emissions as emission trading and climate change are in main focus; but this could be easily expanded. There is a possibility given to calculate only GHG emissions during construction and running, but also saved emissions because low emission technology has been used instead of average energy mix;
- Social – so far only created jobs are modeled, but there is a given distribution to number of created jobs in a) manufacturing, b) installation and c) maintenance;
- Economy – a wide set of characteristics can be seen from modeling results, such as calculated costs and benefits.

Also, there is a list of indicators / results presented in correlation to energy (saved or produced energy, new installed capacity or consumption, etc).

Energy	Situation in 2020. compared to planned in Strategy [%]
	New el.energy produced 2020. [GWh/year]
	New electrical power installed per year [MW/year]
	New thermal energy installed per year [MWt/year]
	New thermal energy produced/saved 2020. [GWht/year]
	New biofuel energy produced 2020. [GWh/year]
	Average new electrical energy per year produced [GWh/year]
	Average new thermal energy produced/saved per year [GWht/year]
	Average biofuel energy per year produced [GWh/year]
	Percentage of el. en. consumption 2020. [%]
	Percentage of th. En consumption 2020 [%]
Environment	GHG saved 2010. [t/year]
	New GHG saved 2020. [t/year]
	New GHG emissions for construction and running 2020. [t/year]
	New GHG saved in the period [t]
Social (jobs)	Nuber of jobs created 2020 in manufacturing [jobs/year]
	Numbers of jobs created 2020 in instalation [jobs/year]
	Numbers of jobs created 2020 in maintenance [jobs/year]
	Number of jobs in 2020 [jobs/year]
Economy	Average investment per year [M€/year]
	Investment in period 2010. - 2020. [M€]
	Investment of the state in 2020. [M€]
	Investment of the state in period 2010. - 2020. [M€]
	Cost of support for new el.en. Produced 2020. [M€/year]
	Worth of th.en. Produced/saved 2020. [M€/year]
	Worth of new energy produced/saved 2020. [M€/year]
	Cost of new running in 2020. [M€/year]
	Worth of new GHG saved in 2020. [M€/year]
	Worth of new jobs opened in 2020. [M€/jear]
	Income of investors in 2020. [M€/year]
	Amortization on investors in 2020. [M€/year]
	Earnings before taxes of investors in 2020[M€/year]
	Taxes in 2020 [M€/year]
	Neto cash flow of investors in 2020. [M€/year]
	Earnings, no support, yes amortization [M€/year]
	Taxes then [M€/year]
	NCF then [M€]
	Earnings when amortization expired [M€/year]
	Taxes after amortization expired [M€/year]
	NCF then [M€]
	VAT in 2020. [M€/year]
	Benefit/cost of the project 2020. [M€/year]
	Benefit/cost of the project 2020. with GHG[M€/year]

Figure 6-15: Outputs from the model are sustainable development indicators for energy, environment, social and economy (for analyzed scenario with set end year is 2020): Source: print screen from model.

Outputs from the model are put in several sheets – general model results are found in "Outputs" sheet such as in Figure 6-16, while each of the modeled low emission technologies has its own sheet (Figure 6-17), and the graphical distribution over year of the following values can be found:

- Energy produced and consumed by year (GWh/year);
- GHG emissions per year (t/year);
- Jobs created per year (jobs/year);
- Direct costs and benefits.

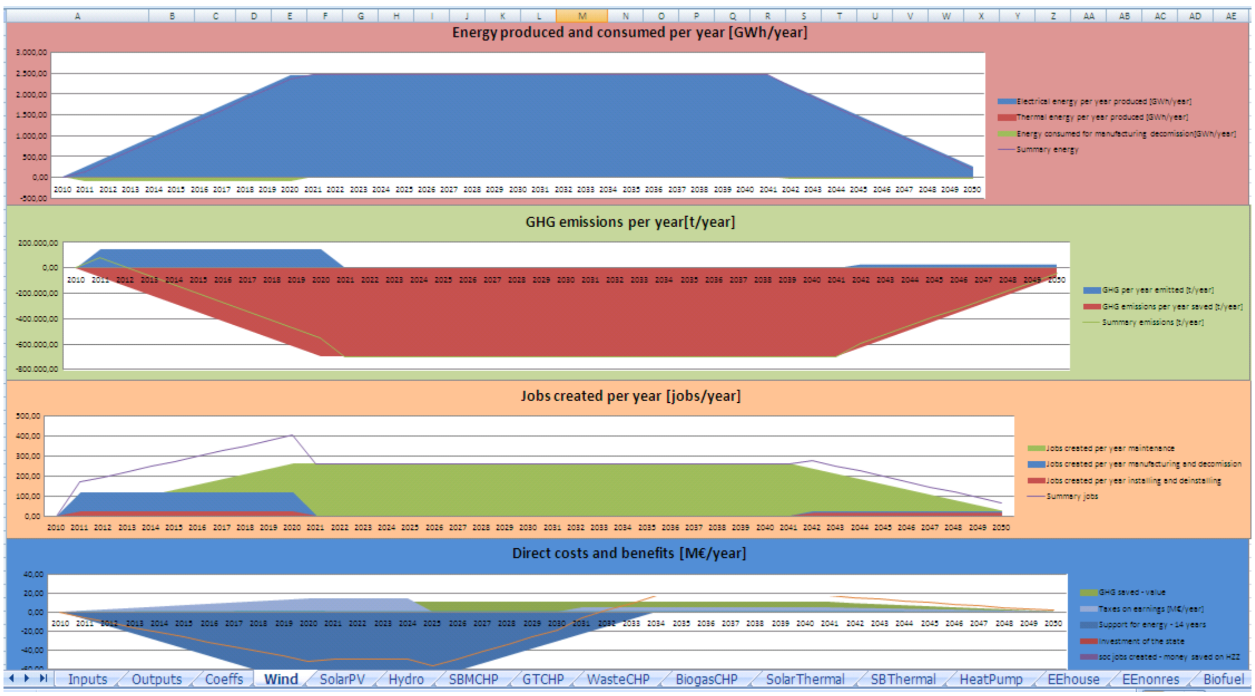


Figure 6-16: Result values on a time line from the "Model for estimation of sustainable development impacts"

Source: print screen from model.

	A	B	C	D	E	F	G	H	I	J	K	L
1	Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
2	Electrical energy per year produced [GWh/year]	0,00	246,63	493,26	739,89	986,52	1.233,16	1.479,79	1.726,42	1.973,05	2.219,68	2.466,31
3	Thermal energy per year produced [GWh/year]	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
4	Energy consumed for manufacturing decomission[GWh/year]	0,00	-20,72	-20,72	-20,72	-20,72	-20,72	-20,72	-20,72	-20,72	-20,72	-20,72
5	Summary energy [GWh/year]	0,00	225,91	472,54	719,18	965,81	1.212,44	1.459,07	1.705,70	1.952,33	2.198,96	2.445,59
6												
7	GHG per year emitted [t/year]	0,00	29.595,72	29.595,72	29.595,72	29.595,72	29.595,72	29.595,72	29.595,72	29.595,72	29.595,72	29.595,72
8	GHG emissions per year saved [t/year]	0,00	-71.522,99	-143.045,98	-214.568,97	-286.091,96	-357.614,95	-429.137,94	-500.660,93	-572.183,92	-643.706,91	-715.229,90
9	Summary emissions [t/year]	0,00	-41.927,27	-113.450,26	-184.973,25	-256.496,24	-328.019,23	-399.542,22	-471.065,21	-542.588,20	-614.111,19	-685.634,18
10												
11	Jobs created per year manufacturing and decomission	0,00	23,54	23,54	23,54	23,54	23,54	23,54	23,54	23,54	23,54	23,54
12	Jobs created per year installing and deinstalling	0,00	5,38	5,38	5,38	5,38	5,38	5,38	5,38	5,38	5,38	5,38
13	Jobs created per year maintenance	0,00	11,66	23,32	34,98	46,64	58,29	69,95	81,61	93,27	104,93	116,59
14	Summary jobs	0,00	40,58	52,24	63,90	75,56	87,22	98,88	110,54	122,19	133,85	145,51
15												
16	Support for energy - 14 years	0,00	-6,27	-12,54	-18,81	-25,08	-31,35	-37,62	-43,89	-50,15	-56,42	-62,69
17	Investment of the state	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
18	GHG saved - value	0,00	0,21	0,57	0,92	1,28	1,64	2,00	2,36	2,71	3,07	3,43
19	Social benefits	0,00	0,41	0,52	0,64	0,76	0,87	0,99	1,11	1,22	1,34	1,46
20	Taxes on earnings	0,00	0,60	1,20	1,80	2,39	2,99	3,59	4,19	4,79	5,39	5,99
21	VAT [M€/year]	0,00	3,92	3,92	3,92	3,92	3,92	3,92	3,92	3,92	3,92	3,92
22	Summary economy	0,00	-1,13	-6,33	-11,52	-16,72	-21,92	-27,11	-32,31	-37,51	-42,70	-47,90
23	Without GHG	0,00	-1,34	-6,90	-12,45	-18,00	-23,56	-29,11	-34,67	-40,22	-45,78	-51,33
24	NPV										full	-327
25												
26												

Inputs / Coeffs / Outputs / Comparition / MCAC calc / MCAC color / Summary / **Wind** / SolarPV / Hydro / SBMCHP / GTCHP / WasteCHP / BiogasCHP / SolarThermal / SBThermal

Figure 6-17: Example for result sheet for wind technology from the "Model for estimation of sustainable development impacts" Source: print screen from model.

6.3.6. Marginal Abatement Cost curve calculation

MAC model – enables Marginal Abatement Cost curve calculation method for the evaluated low emission solutions arriving as results from power system modeling in PLEXOS, along with more familiar financial instruments such as payback, net present value (NPV) or internal rate of return (IRR). The marginal abatement cost is plotted on the y-axis, and the projects ranked against this metric from lowest to highest, such as in Figure 6-18. The width of the column is equal to the amount of emission reduction from the calculated low emission solution, and the area of each column equal to the cost or benefit of the project. Negative MAC values indicate that the project is self-financing, whereas positive MAC values require judgment against the cost of inaction - in this case the cost of the purchase of emission allowances on the market. NPV is used from the previous model which calculates it based on the inputs above. Alternatively, a different financial indicator might be used, such as already mentioned IRR or non-discounted cash flow instead. Most important inputs for model include:

- The marginal investment costs of low emission solutions – either the total cost of the whole project if new projects are considered or just additional costs if it is just an additional investment (the cost can equate to the difference in cost between an energy-efficient replacement and a standard equivalent)

- The net annual costs and benefits of the project
- The net annual CO_2 savings
- Discount rate for return on investments

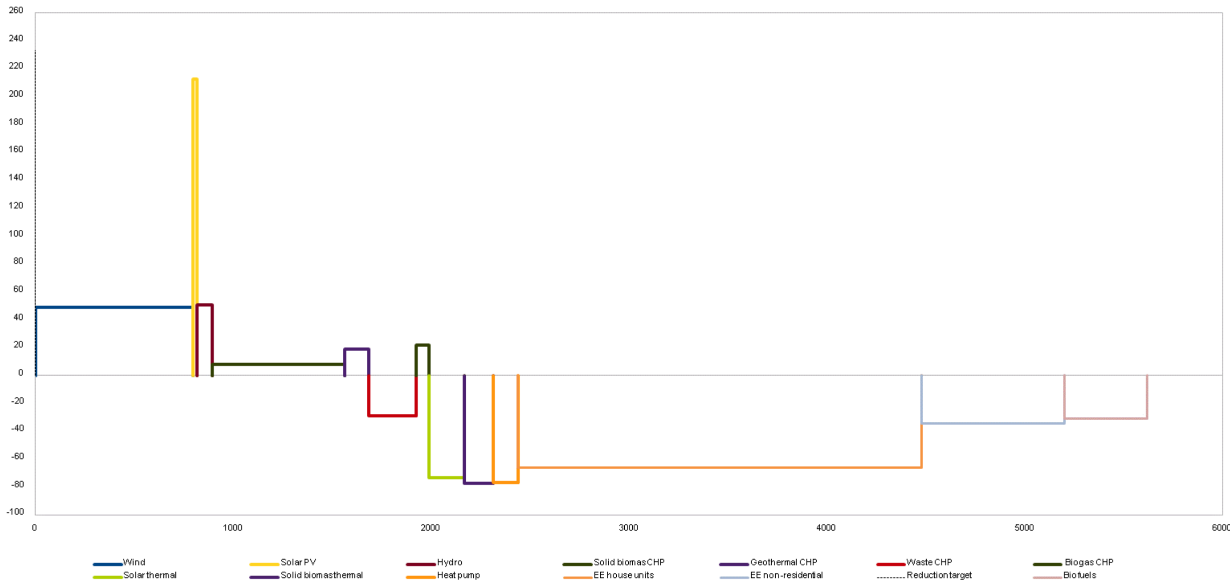


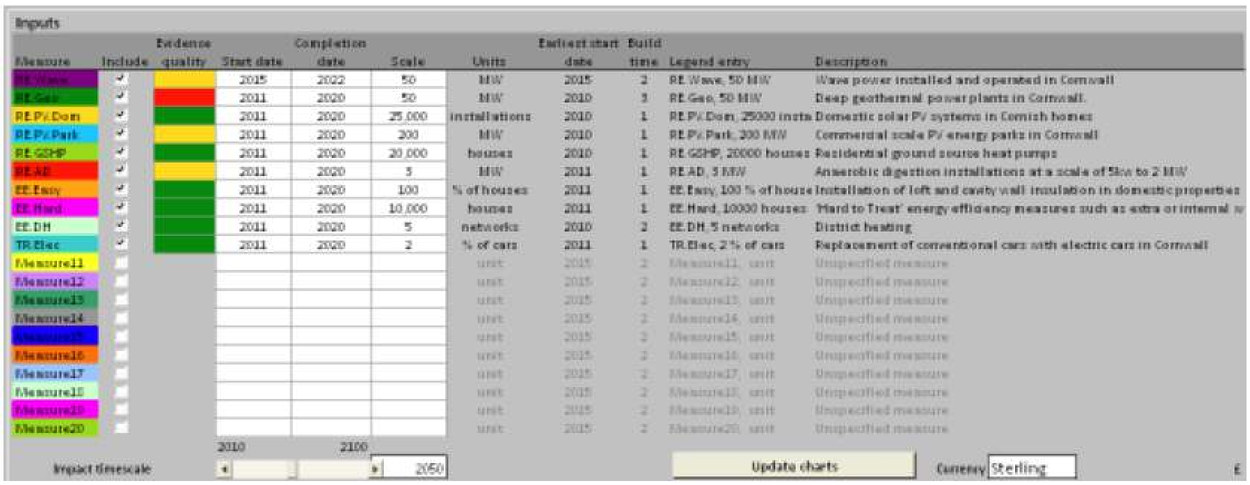
Figure 6-18: MAC example (author`s own test calculation for Croatia by 2020). Source: print screen from model.

6.3.7. PACE model

The model PACE (Prioritization of Actions for a Low Carbon Economy) was built as a part of the project "*Analysis of the Carbon Emissions-related Aspects of the Economies of Three Regions*" [134] in order to easier compare regional impact of various mechanisms to move to a low carbon economy. Within the project, it was used in three regions - Cornwall (UK), Marche (Italy) and Burgenland (Austria).

Model code is open so it is not complicated to use it for comparation of low emission solutions in some other regions. The tool is designed to compare a whole range of carbon mitigation measures that might be considered, from renewable energy (large, small and micro scale, electricity and heat), energy efficiency (in the domestic, public and business sector), and transport (modal shift and the introduction of low carbon vehicles). It can also be easily upgraded to include some other low emission solutions. It is design to allow comparison across three simplest indicators - cost, emission reduction and jobs; but this approach can easily be expanded to visualize and compare other sustainable development indicators in the same manner. Each measure's impact is always calculated in comparison to a reference case (what would occur if the measure was not implemented), i.e. the cost of installing a solar thermal system has to be compared to the cost of not fitting one, meaning higher electricity consumption and higher electricity costs.

The starting point for any analysis using the PACE tool is the 'Dashboard' tab as in Figure 6-20, which is designed to allow the user to choose and configure the measures to display. Within the proposed methodology, dashboard automatically contains as an input data, indicators from *"Model for estimation of sustainable development impacts"*. Here, for desired low emission solutions, one can select and deselect which measure to include in their analysis, change the scale of the measures included in the analysis, vary the time periods associated with the measures, and vary the results timescale.


Inputs

Measure	Include	Evidence quality	Start date	Completion date	Scale	Units	Earliest start date	Build time	Legend entry	Description
RE.Wave	✓		2015	2022	50	MW	2015	2	RE.Wave, 50 MW	Wave power installed and operated in Cornwall
RE.Geo	✓		2011	2020	50	MW	2010	3	RE.Geo, 50 MW	Deep geothermal power plants in Cornwall.
RE.PV.Dom	✓		2011	2020	25,000	installations	2010	1	RE.PV.Dom, 25000 insta	Domestic solar PV systems in Cornish homes
RE.PV.Park	✓		2011	2020	200	MW	2010	1	RE.PV.Park, 200 MW	Commercial scale PV energy parks in Cornwall
RE.GSHP	✓		2011	2020	20,000	houses	2010	1	RE.GSHP, 20000 houses	Residential ground source heat pumps
RE.AD	✓		2011	2020	5	MW	2011	1	RE.AD, 5 MW	Anaerobic digestion installations at a scale of 5kw to 2 MW
EE.Easy	✓		2011	2020	100	% of houses	2011	1	EE.Easy, 100 % of house	Installation of loft and cavity wall insulation in domestic properties
EE.Hard	✓		2011	2020	10,000	houses	2011	1	EE.Hard, 10000 houses	'Hard to Treat' energy efficiency measures such as extra or internal
EE.DH	✓		2011	2020	5	networks	2010	2	EE.DH, 5 networks	District heating
TR.Elec	✓		2011	2020	2	% of cars	2011	1	TR.Elec, 2 % of cars	Replacement of conventional cars with electric cars in Cornwall
Measure11						unit	2015	2	Measure11, unit	Unspecified measure
Measure12						unit	2015	2	Measure12, unit	Unspecified measure
Measure13						unit	2015	2	Measure13, unit	Unspecified measure
Measure14						unit	2015	2	Measure14, unit	Unspecified measure
Measure15						unit	2015	2	Measure15, unit	Unspecified measure
Measure16						unit	2015	2	Measure16, unit	Unspecified measure
Measure17						unit	2015	2	Measure17, unit	Unspecified measure
Measure18						unit	2015	2	Measure18, unit	Unspecified measure
Measure19						unit	2015	2	Measure19, unit	Unspecified measure
Measure20						unit	2015	2	Measure20, unit	Unspecified measure

Figure 6-19: Input parameters (results from the "Model for estimation of sustainable development impacts")

One of the carts coming out from this model, which is found very valuable, is so called "bubble chart". What is so specific is that it enables using three different indicators all on one chart. For illustration, graph bellow combines employment, emission reduction and cost impacts on one chart. The X coordinate of the bubble is the net cost to the region of the measure under the timescale in question (to 2050 in the example shown). High cost measures lie to the right of the chart, low or negative cost measures lie to the left. The Y coordinate of the bubble is the net regional employment impact of the measure under the timescale in question (to 2050 in the example shown). Measures contributing to high employment growth lie to the top of the chart; measures with low or negative employment impact lie to the bottom. The area of the bubble is proportional to the regional carbon impact of the measure under the period in question: measures with a large bubble have a relatively large carbon impact (either positive or negative); measures with a small bubble have a relatively small carbon impact. Measures with a negative carbon impact i.e. measures that increases in carbon emissions are represented by bubbles with a thick black border – e.g. RE.Geo is associated with a large increase in carbon emissions.

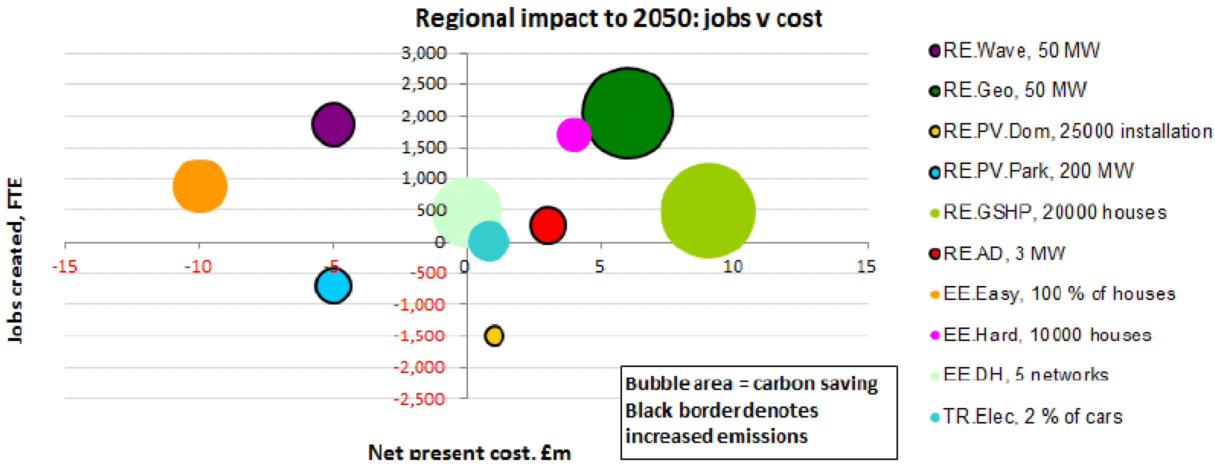


Figure 6-20: Illustration of "bubble graph", representing three different indicators on the same graph – correlation between numbers of jobs created costs of low emission solution and emission reduction

The best measures to implement from a regional perspective are represented by large (nonnegative) bubbles in the top-left quadrant of the chart: these are measures that create jobs, save carbon whilst overall saving money. However, many measures are likely to lie elsewhere in the chart, reflecting a trade-off between cost, jobs and carbon. This type of visualization can easily represent some other indicators that serve as an output from the previous models. Different scenarios modeled (different emission price, different coefficients or presumptions in calculation of chosen indicators) create different scenarios in PACE model.

6.4. Algorithm for emission trading developed for power system model

As power system model PLEXOS that will be used for verification of proposed methodology was not able to allow modeling emission trading impact on a power system, there was a need to develop an algorithm and to propose it to the model developers to include it in the model. There were available three options for modeling emissions in the model:

1) "Emission Hard Constraint", constraint for modeling physical emission limits that cannot be breached
2) "Emission Soft Constraint", constraint with one or more bands of penalty price
3) "Emission Price", that is treated as the 'accounting price' for emissions, and is used to compute cost assigned to generators for their emissions.

However, none of these two features was able to include the value of emission in the bidding process and to reflect enhanced production costs for each generator. Simulation of impacts that emission trading schemes have in electricity sector should be able to add additional costs to SRMC from each generator. This problem was recognized within research project [78] program "Simulator Development for Analysis of Emission Trading Impacts on Electricity Market". The solution that was proposed within this thesis was to include shadow emission price which would increase SRMC on the basis of defined emission price and emission production coefficient (tCO_2/MWh for each generator).

This was designed to fit the existing way of power system optimization in used power system model. In a communication with model developers need for this algorithm was described, and several solutions were tested and one solution how to include it was proposed. So it was added as a new function in PLEXOS model and makes it now possible to model emission trading impact on a power system. New algorithm for calculation of generation costs for each generation unit now is presented as:

Generation Cost = (Fuel Offtake * Fuel Price) +
(Generation * Variable Operation and Maintenance Cost) + (6.1)
(Generation * Emission Coefficient * Emission Shadow Price)

Table 6-8: Overview of emission modeling possibilities within PLEXOS with proposed and developed algorithm (Emission Shadow Price). Source: [97]

Emission Price	Emission Shadow Price (developed and proposed by author)	Emission Constraints	Emission dispatch	Emission accounting
YES	NO	NO	-	Emission Price
NO	YES	NO	Emission Shadow Price	Emission Shadow Price
YES	YES	NO	Emission Shadow Price	Emission Price
NO	NO	NO	-	-
YES	NO	YES	Constraint shadow price	Emission Price
NO	YES	YES	Constraint shadow price	Constraint shadow price + Emission Shadow Price

YES	YES	YES	Constraint shadow price	Emission Price
NO	NO	YES	Constraint shadow price	Constraint shadow price

If bidding strategy is based only on SRMC, generation cost is enlarged proportionally to Emission Coefficient (tCO_2/kWh) and Emission Price (€/tCO_2). In other bidding strategies such as LRMC Revenue Recovery or Nash-Cournot competition, emission prices directly influences generation costs and indirectly influences proposed market price from each generation unit.

6.5. Formulation of long term capacity expansion problem in model PLEXOS

The capacity expansion problem in model PLEXOS is formulated in the simulator as a Mixed-Integer Linear Program (MILP or MIP for short). The following simplified problem formulation presented in this chapter serves for illustration on how long term power system planning is modeled – it includes build decision but the same formulation can be used for retirement decision making.

In order to enable model to include emission trading in capacity expansion simulation, emission price is added in SRMC of generators (please see table with definition of parameters for problem formulation below).

Table 6-9: Definition of variables for problem formulation. Source: [97]

Variable	Description	Type
$\text{GenBuild}_{(\boldsymbol{g},\boldsymbol{y})}$	Number of generating units build in year $\boldsymbol{y}$ for Generator $\boldsymbol{g}$	integer
$\text{GenLoad}_{(\boldsymbol{g},\boldsymbol{t})}$	Dispatch level of generating unit $\boldsymbol{g}$ in period $\boldsymbol{t}$	continuous
$\boldsymbol{USE_t}$	Unserved energy in dispatch period $\boldsymbol{t}$	continuous
$\text{CapShort}_{\boldsymbol{y}}$	Capacity shortage in year $\boldsymbol{y}$	continuous

Table 6-10: Definition of parameters for problem formulation. Source: [97]

Element	Description	Unit
$\boldsymbol{D}$	Discount rate. We then derive $\boldsymbol{DF_y} = 1/(1 + \boldsymbol{D})^y$ which is the discount factor applied to year, and $\boldsymbol{DF_t}$ which is the discount factor applied to dispatch period $\boldsymbol{t}$	

$\boldsymbol{L_t}$	Duration of dispatch period $\boldsymbol{t}$	Hours
$\text{BuildCost}_{\boldsymbol{g}}$	Overnight build cost of generator $\boldsymbol{g}$	$
$\text{MaxUnitsBuilt}_{(\boldsymbol{g},\boldsymbol{y})}$	Maximum number of units of generator $\boldsymbol{g}$ allowed to be built by the end of year $\boldsymbol{y}$	
$\text{PMAX}_{\boldsymbol{g}}$	Maximum generating capacity of each unit of generator $\boldsymbol{g}$	MW
$\text{Units}_{\boldsymbol{g}}$	Number of installed generating units of generator $\boldsymbol{g}$	
VoLL	Value of lost load (energy shortage price)	$/MWh
$\text{SRMC}_{\boldsymbol{g}}$	Short-run marginal cost of generator $\boldsymbol{g}$ which is composed of Heat Rate × Fuel Price + VO&M Charge	$/MWh
$\text{FOMCharge}_{\boldsymbol{g}}$	Fixed operations and maintenance charge of generator $\boldsymbol{g}$	$
$\boldsymbol{Load_t}$	Average power demand in dispatch period $\boldsymbol{t}$	MW
$\text{PeakLoad}_{\boldsymbol{y}}$	System peak power demand in year $\boldsymbol{y}$	MW
$\text{ReserveMargin}_{\boldsymbol{y}}$	Margin required over maximum power demand in year $\boldsymbol{y}$	MW
CapShortPrice	Capacity shortage price	$/MW

The objective function of LT Plan seeks to minimize the net present value of build costs plus fixed operations and maintenance costs plus production costs. The core formulation for LT Plan is thus (based on [97]):

Minimize (6.2)

$$\sum_{(y)} \sum_{(g)} DF_y \times (\text{BuildCost}_{\boldsymbol{g}} \times \text{GenBuild}_{(\boldsymbol{g},\boldsymbol{y})})$$

$$+\sum_{(y)} DF_y \, X \left[\text{FOMCharge}_{\boldsymbol{g}} \times 1000 \times \text{PMAX}_{\boldsymbol{g}} \left(\text{Units}_{\boldsymbol{g}} + \sum_{\boldsymbol{i \leq y}} \text{GenBuild Units}_{\boldsymbol{g},\boldsymbol{i}} \right)\right]$$

$$+\sum_{(t)} DF_{t \in y} \times L_t \times \left[\text{VoLL} \times \boldsymbol{USE}_{\boldsymbol{t}} + \sum_{\boldsymbol{g}} (\text{SRMC}_{\boldsymbol{g}} \times \text{GenLoad}_{\boldsymbol{g},\boldsymbol{t}})\right]$$

subject to

Equation 1: Energy Balance

$$\sum_{(g)} \text{GenLoad}_{(\boldsymbol{g},\boldsymbol{y})} + \boldsymbol{USE_t} = \text{Demand}_{\boldsymbol{t}} \ \forall_{\boldsymbol{t}} \qquad (6.3)$$

Equation 2: Feasible Energy Dispatch

$$\text{GenLoad}_{(\boldsymbol{g},\boldsymbol{t})} \leq \text{PMAX} \left(\text{Units}_{\boldsymbol{g}} + \sum_{i \leq y} \text{GenBuild Units}_{\boldsymbol{g},\boldsymbol{i}} \right) \quad (6.4)$$

Equation 3: Feasible Builds

$$\sum_{i \leq y} \text{GenBuild}_{\boldsymbol{g},\boldsymbol{i}} \leq \text{MaxUnitsBuilt}_{\boldsymbol{g},\boldsymbol{y}} \quad (6.5)$$

Equation 4: Integrality

$$\text{GenBuild}_{(\boldsymbol{g},\boldsymbol{y})} \text{ integer} \quad (6.6)$$

Presented formulation of long term capacity planning in PLEXOS in this minimal format does not include constraints on capacity margin - but instead the natural trade-off between energy shortage and build costs will ensure that capacity is built if it is economic and that the energy price will exactly compensate the marginal build for its production and build costs. The resulting capacity reserve margin could take any value (including negative) and the amount of unserved energy could be any value up to the amount of load ***i.e.*** this 'natural' solution may or may not meet acceptable reliability standards. The reliability of the system can be measured by running PASA after LT Plan and reporting the LOLP and other reliability indices.

Equation 5: Annuity Calculation

In order to calculate (replace) build costs by the sum of the discounted annual charges, the weighted average cost of capital (WACC) is used in combination with Economic Life. WACC is the rate that a company is expected to pay to finance its assets; the minimum return that a company must earn on existing asset base to satisfy its creditors, owners, and other providers of capital. Companies raise money from a number of sources: common equity, preferred equity, straight debt, convertible debt, exchangeable debt, warrants, options, pension liabilities, executive stock options, governmental subsidies, and so on. Different securities are expected to generate different returns. WACC is calculated taking into account the relative weights of each component of the capital structure.

$$\text{BuildCost}_{\boldsymbol{g}} \times \text{PMAX}_{\boldsymbol{g}} \times (\text{WACC}_{\boldsymbol{g}} / \left(1 - \left[1 / (1 + \text{WACC}_{\boldsymbol{g}}) \right]^{\text{EconomicLife}} \right) \quad (6.7)$$

The build cost coefficient in the objective function (i.e. BuildCostg) is thus replaced by the sum of the discounted annual charges, starting from the given year y until the end of the economic life of the unit. The discount rate used is the system discount rate, whereas the Generator WACC (weighted average cost of capital) is project-specific.

7. VERIFICATION OF PROPOSED METHODOLOGY, MODELS AND ALGORITHM WITH USE OF CROATIAN DATA

Methodology proposed and described in the previous chapter is in this chapter applied with use of data from Croatia. Based on a Croatian power system, methodology will be applied in a long term power system planning environment by modeling how climate change and emission trading impacts competitiveness` increase for low emission technologies due to emission trading, and what is the impact on sustainable development.

This chapter consists of five subchapters. First one sets schematic representation of methodology, but this time with models that will be actually used for modeling Croatian power system. Next three subchapters are focused on verification of separate aspects of methodology – first one is on modeling emission trading impacts on Croatian power system; second one is on assessment of sustainable development indicators from power system development; and third one is assessing climate change impacts on generation from renewable energy sources.

Last, fifth subchapter is integrative – and it combines all previous chapter and modeling approaches in one methodology. For this purpose, development of Croatian power system until 2030 is modeled, with assessment if climate change impacts and measuring sustainable development indicators. With such integrative approach, goal is to assess emission trading and climate change impact on competitiveness of low emission technologies.

7.1. Models used for verification of proposed methodology - schematic description

As described in previous chapters, use of models that could fit the proposed methodology depends on the conditions studied. Models that are chosen to be used for testing the methodology are those that are applicable for modeling Croatian power system, regional climate, and sustainable development indicators in Croatia. All blue squares presented in the schematic representation bellow, indicate models, and are now represented with actual models.

Power system planning model used within the proposed methodology is model PLEXOS, which is described in more detail in the Chapter 4. Within the model PLEXOS, some technical details which are not important for this modeling were simplified or omitted (such as modeling transmission capacities is simplified by modeling only 400 kV lines and transmission losses are mainly simplified). Economic parameters of new power plant candidates are set in proposed and developed model (described in chapter 6.2.) that analyzes set emission price and fuel price scenarios on LRMC of new power plant candidates. Depending on these scenarios, power plant candidates are described in PLEXOS.

Modeling climate change impacts on renewable energy generations is done in two steps:

- In first case it is done with the use of two climate models: results from one Global Climate Model (ECHAM5-MPIOM) are used for downscaling to the regional level by the Regional Climate Model RegCM;
- In the second case, uncertainties from using only one scenario or only one model are minimized as results from 18 various climate models and climate scenarios are used, and a range of possibilities is created.

Model for estimation of sustainable development impacts was developed for use in this methodology (full description in given in chapter 6.3.). It was designed in order to be appropriately adjusted to the Croatian power and energy systems.

For the visualization and comparation of sustainable development indicators, two additional models are used that are based on results from Model for estimation of sustainable development indictors:

- Model PACE is used for multilevel visualization and comparation of chosen indicators;
- MAC model is used for visualization and comparation of marginal cost abatement curve.

Input data set that is used is adjusted for Croatia, for example a list of low emission solutions (technologies and/or measures) with defined technological and economical parameters is set according to existing potential in Croatia (renewable energy potential, economic and technical). The same thing is with a list of new power plant candidates, fossil fuel based, that will be used in long term modeling is defined separately and serves as an input to the power system model.

For modeling timeframe, lists of low emission technologies and new power plant candidates might differ during the different long term planning goals (2020, 2030, 2040, 2050), as economical and technical parameters from these technologies change over time (such as investment costs, efficiency, etc).

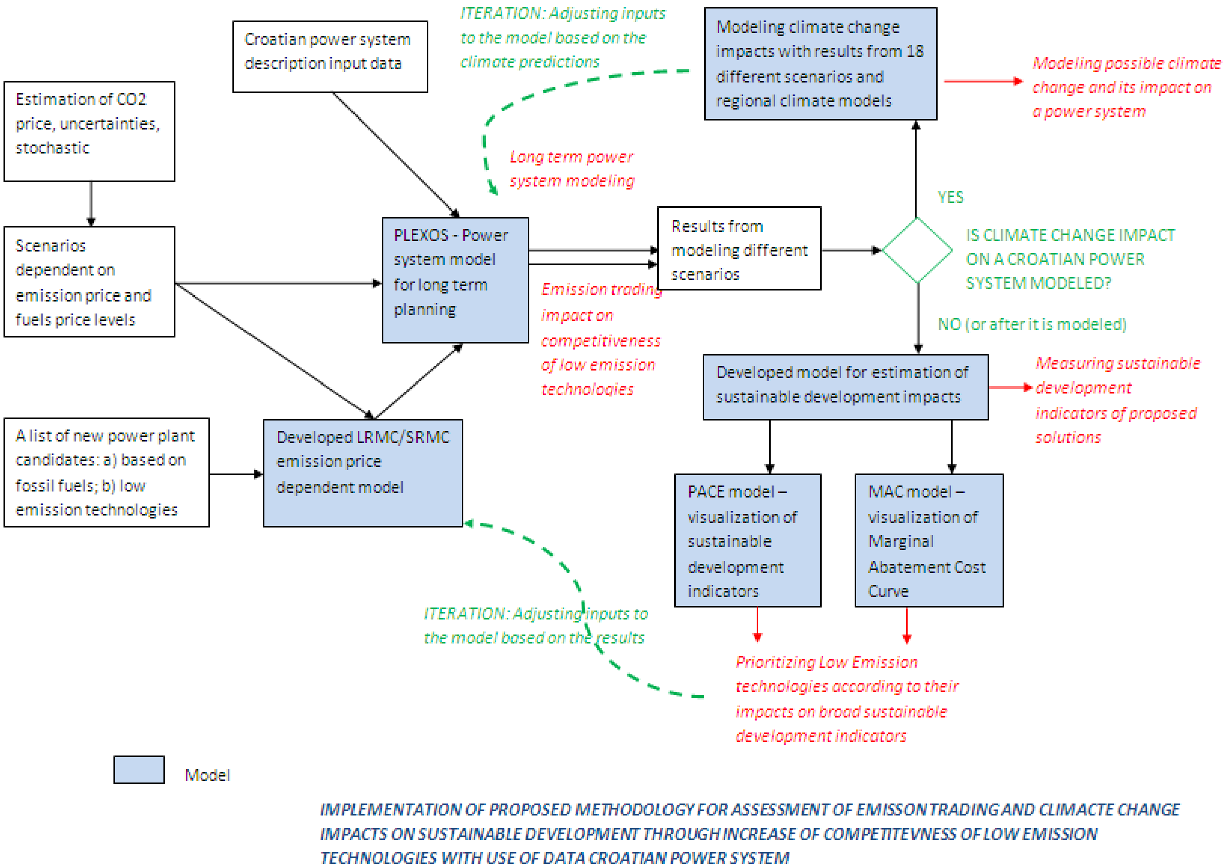


Figure 7-1: Schematic representation of proposed methodology with models chosen for verification of methodology, based on data from Croatia

7.2. Modeling power system with use of Croatian data

7.2.1. Description of power system in PLEXOS model with use of Croatian data

Croatian power system is modeled in PLEXOS based on data from available sources. Simulation model needs large amount of input data – technical and economical parameters of power plants, accumulation inflows, power system consumption and load factor, etc. Values for characteristics that were not available have been estimated based on similar existing values or based on expert judgment. Below in the text, main characteristics of individual model objects are presented. Basic object classes used in model are *Generator*, *Fuel*, *Emissions*, *Storage*, *Waterway*, *Physical Contracts*, *Market*, *Region*, and *Reserve*.

Generators

In modeled Croatian power system, a total of 83 generators are modeled (21 thermal, 60 hydro, one nuclear and one equivalent wind power plant). They were further added to a total of 33 power plants (8 thermal, 23 hydro, 1 nuclear and 1 equivalent wind power plant). Object class *Generator* in model PLEXOS describes characteristics of a specific generator, regardless of its type (thermal, hydro or wind).

For each generator, following characteristics were described in the model as basic characteristics (some generators have additional characteristics that were further described):

- Technical Generator Minimum (MW);
- Maximal Generator Power (MW);
- Fixed Operation and Maintenance Costs (€/kW/year);
- Variable Operation and Maintenance Costs (€/MWh);
- Own Fixed Consumption (MW);
- Variable Fixed Consumption (%);
- Max Ramp Up (MW/min);
- Max Ramp Down (MW/min);
- Heat Rate (GJ/MWh);
- Maintenance Rate (%);
- Forced Outage Rate (%);
- Minimal Generation Period (h);
- Start Costs (€/start);
- Generation Dependence on Inflow (MW/m^3/s).

Description between hydro and thermal generator differs according to the class of added object. Hydro generator have added class describing its accumulation (class *Storage*) that are connected with class describing water inflows (class *Waterway*); and thermal generators are further described with class *Fuel*.

Values for planned maintenance were gathered in consultations with HEP Trade; and this value was set for each generator separately – which means that power plants with more than one generator do not need to be in a total outage during the maintenance.

Total installed capacity of wind power plants in Croatia modeled was 200 MW (based on situation in 2012) and 2500 hours on nominal power were modeled. For easier modeling, all these wind power plants were modeled with a single equivalent wind power plant that works on a constant power of 58 MW (load factor 100%). Like this, amount of electricity generated within this equivalent power plant is the same as it would be for several wind power plants with total installed power 200 MW (0.5 TWh).

Some of thermal power plants work also produces thermal energy for heating – those are modeled based on real values - in such a way so their heating output satisfies real heat consumption in heating months.

As first modeling results have shown some distinction from real power system behavior, it was clear that some input data need to be improved or adjusted. First of all, calibration was needed for Heat Rate curve (impact of generator heat output based on fuel consumption), and for power dependence on water inflow at hydro power plants. During this calibration phase, model was enhanced.

Modeling hydro power plant accumulation

Water accumulation (class *Storage*) is described in the model with the following characteristics:

- Min Accumulation Volume (m^3);
- Max Accumulation Volume (m^3);
- Start Accumulation (m^3);
- Inflows (m^3/s);
- Min Flow (m^3/s).

In total, 33 accumulations are described in the model. This covered all cascade hydro power plant systems in Croatia. Min and Max Accumulation Volume defined according to the description of accumulation, while Start Accumulation can be defined according to the modeled situation (if neutral annual impact from existing water in accumulation is modeled, start volume (beginning of the year) can be set at the same value as the end volume at the end of the year. All accumulations are modeled as being on 50% of the usable volume.

Water inflows are modeled based on the real daily inflows (in Excel type document, as an input for PLEXOS model) for the period 2006-2011. Average daily water inflows are used (based on average values for several years).

Minimal water inflow is biological minimum, and is set only for some hydro power plants for which this value is known.

For modeling cascades of water accumulations, it was necessary to model auxiliary water accumulations that don't really exist. Like this, more realistic hydro model is achieved, with all relevant characteristics such as delays with water inflows (from one storage to another).

Fuels

In modeling class Fuels, only one characteristic is used – Fuel Price defined as €/GJ. Specific fuels are connected with thermal power plants that use these fuels for electricity and/or heat generation. Values used within the model are given in the table below:

Table 7-1: Fuel prices used in the model

Fuel	Price (€/GJ)
Coal	3
Natural gas	12
Heating oil	13
Extra light heating oil	15

In modeling fuels, it is possible to set constraints in terms of availability in specific time periods. Within the model, such constraints are set for description of Natural gas availability (minimal and maximal) on monthly and annual level.

Emissions

Emission factors are described in the model based on specific fuel types, and these values are attributed to description of fuels. Table below shows how much 1 GJ of used fuel emits kg CO_2 emissions. Plexus uses this value to calculate emission amount, from known amount of fuel used. These values are calculated by using IPCC methodology [135].

Table 7-2: Emission fuel factors used in the model. Source: [135]

Fuel	Emission fuel factor (kg/GJ)
Coal	92,69
Natural gas	55,8
Heating oil	76,58
Extra light heating oil	73,31

Modeling power system consumption

Power system consumption was modeling based on existing hourly values from 2005-2011. Modeled values represent total consumption on transmission network, including net consumption and transmission losses, but exclude power plant own consumption, and pumping energy (in reversible hydro power plants). Hourly consumption amounts for modeled 2013 are calculated by using linear regression of hourly values in period 2005-2011.

Power system consumption in the model is described under class Regions. Simulation tool PLEXOS enables creation of several interconnected regions with defined consumption for each one of them. In this case, only one region is modeled (Croatia), while the possibility for trade and energy exchange with other regions is made possible with defining object of class Market.

Modeling electricity and emission trading

As impact of emission trading on a power system planning is in focus of this thesis, special attention is on modeling emission and electricity markets in the model. In a simulation/optimization model, with assumption of ideal market, electricity import and export will depend on several issues such as electricity prices at external market and generation costs from domestic power plants. Like this, import and export is a result of optimization process, not an exogenous value in the model. In this model, external market is modeled (class *Market*) in a way to set electricity price for every hour in simulation period.

It is not possible to forecast market hourly prices for a year in advance, but there are several patterns to follow – patterns that can be followed throughout the day (depending on daily load curves that are different for working days / weekends and holidays), seasonal load curves etc. Except following these patterns, there are other factors such as expected energy price. Within this model, external market is modeled for year 2013 (forecast) in such a way that hourly prices were taken from HUPX-a[2] for year 2011, which are further corrected according to prices of *forward* contracts for 2013.

Even though in the model hydrological changes in Croatia do not have influence on spot prices on European market, changes in hydrology could be indicative for hydrology on a wider regional level (dry year in Croatia means also dry year regionally, and higher electricity prices in specific dry months).

[2] Hungarian Power Exchange, www.hupx.hu

Table 7-3: Constraints used for modeling import/export per months in MW

	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
Import	900	900	650	500	600	700	825	800	625	700	625	850
Export	975	925	950	650	725	825	925	1000	875	760	775	840

Export and import constraints are modeled in order to more realistically describe existing transmission lines and constraints. Monthly values that are modeled are set according to the real values from year 2012 (values are in Table 7-3).

Bilateral contracts

In the model, bilateral contracts are modeled with fixed value 250 MW, that on an annual level create energy equivalent 2.19 TWh. Forecasted price that is modeled for these contracts is 55 €/MWh.

Secondary reserve

In the model, 100 MW of secondary reserve is put. It is modeled that hydro power plants will provide this secondary reserve.

Transmission lines

Impacts of transmission are not of interest for this thesis, so it is not used and described in the model. Instead of transmission grid, model sets one reference node on which all power plants and all consumption are connected. Also, all import and export happens through this node. Consumption that is modeled also includes real transmission line losses.

7.2.2. Modeling year ahead emission price impact on power system

Description of Croatian power system in model PLEXOS (please see chapter 6) together with calibration phase performed with year ahead modeling in this subchapter, is a basis for further long term power system modeling. It enables applying first step of the proposed methodology – emission trading impact on a power system. Conclusions and lessons learned from this subchapter are therefore important for further power system modeling, and for improving existing power system description in the model.

Modeling impact of emission price on a power system depends on a number of parameters. This is in particular visible from results in modeling year ahead Croatian market – for year 2013, based on data from 2005 to 2011 (and some uncompleted data for 2012). Based on previously described technical and economic power system parameters (chapter 6), impact of three different emission prices on a power system is analyzed:

- Three different emission prices are simulated in three scenarios: 0 €/tCO_2, 7.5 €/tCO_2 i 14 €/tCO_2. As modeling is performed on a basis of one year ahead, uncertainties regarding emission price levels are not substantial so these three options are chosen for modeling;
- Zero emission price scenario is basically situation without emission price impact on a power system – a referent scenario to compare other scenarios;
- Scenario with 7.5 €/tCO_2 emission price is chosen as it was the average emission price for most of the year in 2012;
- When modeling year ahead emission price impact on a power system, it is unlikely to expect much larger emission price than in 2012 (unless there are signals it might happen), so high emission price scenario is modeled with 14 €/tCO_2, considering conservative emission price increase.

While modeling Croatian power system in 2013, it is set in the model that there will be no changes in technical parameters of a power system or existing generators, as this period is too short for investment decisions to take place. As for the energy prices in power plants, they are also set for whole year as a constant value, as it is considered that if there will be large change in energy prices it would also influence electricity prices from the external markets so that change will be in the end neutral between Croatian and external electricity markets. In further scenarios where modeling long term period is presented, real long term power system expansion modeling will be performed – with various scenarios of power system development where there are differences between scenarios on used technologies and installed capacities. Also, additional emission price range will need to be modeled as due to more uncertainties, CO_2 emission price could be much higher – especially if period after 2020 is modeled. More certainties also exist for energy prices, investment costs for low emission technologies etc.

7.2.3. Defining list of new power plant candidates for modeling long term development of Croatian power system until 2020

Input data for new candidate power plants are defined with use of proposed and developed mathematical model (chapter 6.2). As a baseline scenario until 2020, targets from Energy Development Strategy is used [136]. Strategy is the foundation document of the Energy Act that defines the energy policy and future plans for energy development for a ten-year period [137].

Strategy focuses on the period until 2020 to coincide with the period covered by all adopted EU energy strategies and provides a general forecast until the year 2030, as a “glimpse into the future”.

Modeling Energy Development Strategy provides final energy demand projections for both “Business as Usual Scenario” (BAU) - projection of final energy consumption according to market trends and consumers’ habits, without government interventions; and for the “Sustainable Energy Scenario” (SES) with enhanced energy efficiency measures.

Increase in demand was assessed for various sectors and subsectors of the so called Other Sectors which includes households, services, agriculture and construction, by using analogy modes (Croatia’s approach to EU-15 member states) and other econometric methods. In BAU scenario, the increase in electricity demand is rather steep – by an annual rate of 4.3 % in the period 2006-2020 (mostly due to low electricity-per-capita index compared with EU average). Within SES scenario, energy efficiency measures are applied according to EU Directive on energy efficiency [138], with goal of reducing 9% in final energy compared with BAU in year 2016. In all development scenarios SES scenario was used (with energy efficiency measures), and it resulted in lower increase in electricity demand – annual rate of 3.4 % in the period 2006-2020. In the electricity production sector, a high demand for new capacity is projected, due to growing consumption and the age of current substations and power plants. It is important to say that these growth rates modeled today seem too optimistic, but growth rates came as an analysis result in 2008 and 2009 when economic crises was not that visible, so it influenced results in a term of higher consumption expectations than those met afterwards. Nevertheless, modeling was performed under such assumptions.

Based on the expected electricity consumption and on the forecasted load factor of 0.7, expected peak load in 2020 is modeled to 4767 MW. Sufficient available reserves of installed capacity are needed in the power system in order to cover expected peak load. Necessary reserves in the system are determined on the basis of system features and the structure of production units in the system (taking in account large percentage of hydro generation which can provide less than one third of installed power during summer months). The outcome of analysis showed reserve margin of 30%, so the required capacity in the system amounts to 6200 MW.

Scheduled generation capacities in 2020 are described in PLEXOS with technical and economical characteristics: max capacity, scheduled maintenance, heat rate, min stable level, max ramp up/down, equity costs, debt costs, variable and fixed O&M costs, fuel price, start costs etc. Transmission capacities were modeled only for 400 kV lines and nodes, with two forecasted 'bypasses' planned until year 2020. First bypass considered is set through Bosnia and Herzegovina between nodes Mostar and Ugljevik and other connecting nodes Divača-Krško-Heviz-Pecs.

In order to exclude hydro meteorological uncertainties on generation planning, all hydro power plants are presented in the model as one power plant block, whose generated output equals P50 (50% probability of satisfying average level of annual output). Hydro generation is described in the model with hourly values, based on hydro generation from previous years. In order to exclude uncertainties from renewable energy sources, due to high share of wind generation which is of intermittent nature, all renewable generation was modeled as coming from one power plant block with fixed output. Electricity consumption is modeled according to hourly values and according to load share on different nodes. Sub-scenarios presented in this chapter don't assume electricity import or export, as one of the simulation goals was to examine self-sustainability of installed capacity and produced electricity. Retirement plan for existing power plants on which modeling was based, shows that 1130 MW of installed capacities will be retired until year 2020, and additional 260 MW until 2030 (Figure 7-2). Total installed capacity with demanded peak and required capacity, with a 30% reserve margin, is also shown on the same figure.

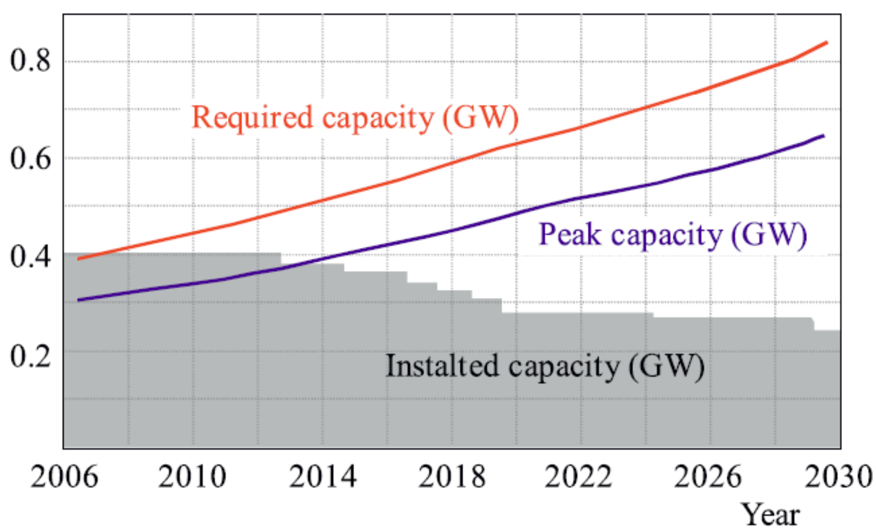


Figure 7-2: Decommission of existing power generation facilities and required installation capacities to satisfy projected demand (2006-2020), according to Energy Development Strategy until 2020. Source: [[139]]

Several scenarios of development opportunities to construct new power generation facilities were analyzed on the basis of the input data presented. In order to facilitate an easier handling of scenarios, they have been labeled according to color: Blue, Green and White. Reasoning behind the scenarios was on which combination of technologies to put strongest focus:

- White scenario focuses on coal and nuclear power plants;
- Green focuses on gas and nuclear; while
- Blue focuses on coal and gas.

If the focus would be put on only one technology (such as gas or coal), this would affect energy security issues too strongly, so a combination of two is used.

Targets set for 2020 are reaching 20% share of renewable energy in final consumption, improve energy efficiency by 10% based on average consumption in period 2001 – 2005, achieve 10% share of renewable energy in transport, achieve 35% share of renewable energy sources in final consumption of electrical energy. The Energy Strategy proposes measures listed in Table 7-4 to be implemented to reach set targets:

Table 7-4 Energy targets from 2010 until 2020[3]

ENERGY SOURCE	TECHNOLOGY	Transformed energy form			Production capacities 2010			Production capacities 2020			New production capacities from 2010 to 2020		
		Electricity	Heat	Liqud fuel	Electrical [MWe]	Heat [MWt]	Liquid fuel [t]	Electrical [MWe]	Heat [MWt]	Liquid fuel [t]	Electrical [MWe]	Heat [MWt]	Liquid fuel [t]
Wind Energy	Wind power plants	x			79.0			1,200			**1,121**		
Solar energy	Solar PV	x			0.2			45			**45**		
	Solar heat		x			64.1			900			**836**	
Water energy	Large hydro power plants	x			1,895.7			2,196			**300**		
	Small hydro power plants	x			31.1			100			**69**		
Biomass	Biomass CHP	x	x		9.4	15.6		140	234		**131**	**218**	
	Biomass heat		x			498.0			747			**249**	
	Waste CHP	x	x		0.0	0.0		40	67		**40**	**67**	
	Biofuel			x			64,000			180,000			**116,000**
Geothermal energy	Geothermal CHP	x	x		0.0	0.0		20	33		**20**	**33**	
	Heat pump		x			121.8			494			**372**	
Coal	Coal power plants	x			295.0			690			**500**		
Oil	Oil			x			720,000			576,000			**-144,000**
Natural gas	Gas CHP	x	x		1,028.0	1,318.0		1,233	1,475		**1,200**	**800**	
	Natural gas			x			1,908,900			1,336,230			**-572,670**

[3] A difference in the model from the Energy Strategy was the amount of new MW in coal power plants – 500 MW instead of 1200 MW because of a decline in electrical energy consumption leading to less need for new production power

7.2.4. Modeling impact of emission price on competitiveness of nuclear power plant within Croatian power system between 2020 and 2025

This chapter analyzes modeling impacts of CO_2 price on competitiveness of nuclear power plant within Croatian power system between 2020 and 2025, and is based on a paper [140]. Analyzes are focused on how nuclear power plant influences total emission from the power system regarding coal and gas prices, average electricity price regarding CO_2, coal and gas prices price.

For modeling Croatian power system situation by 2020, forecasted data from previous chapter (until 2020) was used - meaning that economic crises that appeared afterwards and that will influence electricity consumption by than is not taken in account. Forecasted peak load and energy consumption is given in Table 7-5.

Table 7-5: Forecasted peak load and energy consumption modeled in PLEXOS during 2020-2025

	2020	2021	2022	2023	2024	Annual increase
Peak load (MW)	4767	4838.5	4911.1	4984.7	5059.5	1.5 %
Energy consumption (PJ)	29.24	29.82	30.42	31.03	31.65	2 %

Two different scenarios of development opportunities to construct new power generation facilities are analyzed: White scenario (with nuclear power plant) and Blue scenario (without nuclear, but with additional coal and gas power plants).

The difference between White and Blue scenario is that instead of nuclear power plant in 2020, Blue scenario has an additional 600 MW coal-fired power plant scheduled for 2019 and 400 MW from TPP firing natural gas in 2020. All other details such as generation from renewables, hydro, cogeneration and old power plants remain the same.

New scheduled generation in the period 2020-2025 is in both scenarios:

- Additional 154 MW new renewable capacity annually (modeled as wind only with 25% working hours on nominal power) until 2025;
- Additional 30 MW cogeneration annually until 2025

Comparation of scenario without nuclear (Blue) and with nuclear power plant (White)

Two cases were modeled for each scenario, regarding CO_2 price. It means all together four cases were modeled and analyzed:

- Case 1: Blue scenario with 0 €/tCO_2;
- Case 2: Blue scenario with 40 €/tCO_2;

- Case 3: White scenario with 0 €/tCO_2;
- Case 4: White scenario with 40 €/tCO_2.

In modeling focus are several sets of results up which conclusions will be set on how expected emission price in the future has impact on nuclear power plant between 2020 and 2025:

- Generation of power plants in that period with and without nuclear power plant, depending on emission price level;
- Impact on total emission amount from power system in that period;
- Impact on electricity price during that period.

7.2.5. Modeling intermittent renewable energy sources in PLEXOS: wind power plant in Croatian power system

The production from wind and photovoltaic units is governed by the availability of the primary energy source. There is therefore often no correlation between the production and the local consumption as can be seen in Figure 7-3. Large amounts of variable generation from renewable sources are not fully forecastable and are causing increasing problems in electrical networks (both in local distribution networks and transmission networks including cross border networks). In some places, we can already observe an increase in the network stresses and needs for upgrades to provide greater capacity and flexibility to integrate the variable generation. It also increases the need for flexible, dispatch-able, fast-ramping generation for balancing variations in load, intermittent resources and contingencies such as the loss of transmission or generation assets. Similar problems can be seen at market: national and local balances between supply and demand are more complicated to manage with high levels of variable generation, which can increase total financial electricity costs. There are two tasks for integrating variable renewable generation, both locally and globally: integrating them into the electricity network and into the energy market. Wind power is expected to influence electricity market in two ways [141]:

- Wind power normally has a low marginal cost (zero fuel costs) and therefore enters near the bottom of the supply curve. This shifts the supply curve to the right (see Figure 7-4), resulting in a lower power price, depending on the price elasticity of the power demand. In the figure below, the price is reduced from Price A to Price B when wind power decreases during peak demand. In general, the price of power is expected to be lower during periods with high wind than in periods with low wind. This is called the “merit order effect”;

- There may be congestions in power transmission, especially during periods with high wind power generation.

Thus, if the available transmission capacity cannot cope with the required power export, the supply area is separated from the rest of the power market and constitutes its own pricing area. With an excess supply of power in this area, conventional power plants have to reduce their production, since it is generally not economically or environmentally desirable to limit the power production of wind. In most cases, this will lead to a lower power price in this sub-market.

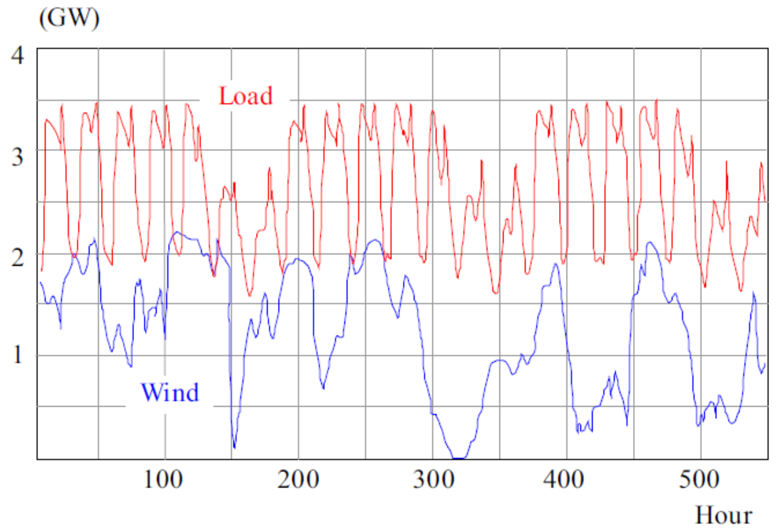


Figure 7-3: Wind power production (2400MW wind power) and load in Western Denmark. Source: [142]

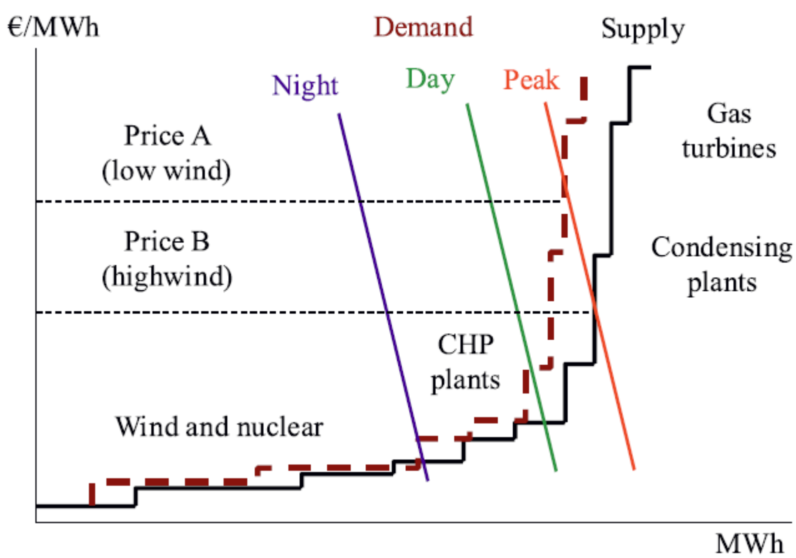


Figure 7-4: How wind power influences the power spot price at different times of day. Source: [143]

However, the impact of wind power depends on the time of the day. If there is plenty of wind power at midday, during the peak power demand, most of the available generation will be used. This implies that we are at the steep part of the supply curve and, consequently, wind power will have a strong impact, reducing the spot power price significantly (from Price A to Price B in Figure 7-4). But if there is plenty of wind-produced electricity during the night, when power demand is low and most power is produced on base load plants, we are at the float part of the supply curve and consequently the impact of wind power on the spot price is low. As an initial exercise, simulation of large amount of wind generation impacts on Croatian electricity sector has been performed by using PLEXOS model.

Within modeled power system in 2020, two scenarios were developed:

- Scenario A - that models wind generation linearly;
- One additional renewable energy scenario - A2 scenario, that includes 1140 MW of wind capacities with average capacity factor of 22%, on the basis of extrapolated real time hourly data of the first Croatian wind power plant Ravna 1 on island Pag (wind target from Croatian Energy Strategy is 1200 MW).

Main goal of this research was to assess how intermittent wind power energy could be modeled in PLEXOS model, and how it would impact results of power system modeling.

7.3. Modeling sustainable development indicators

In this chapter, model proposed in chapter 6.3. (Model for estimation of sustainable development impacts) will be tested on a study case, with data from Croatian power system.

7.3.1. Description of three different scenarios modeled for model testing and validation

Modeled case study is: modeling impacts of domestic production of technologies on job creation. Table below shows three various scenarios based on achieving from Croatian Energy Strategy until 2020 (in this case, targets are the same in all scenarios, but a path to achieve them is different). Modeled target for installed capacity of fossil based power plants is decreased from 1200 MW (Energy Strategy) to 500 MW due to lower consumption increase rate.

These scenarios modeled in proposed model to understand how share of domestic component is influencing sustainable development indicators. These three scenarios are proposed to embody three different approaches – starting from very low share of domestic component in Low scenario S1, to very high in High scenario S2 and Moderate scenario S3 in the middle of these two. For each scenario, also emission price differs – the reason for this is modeling scenarios holistically: Low scenario means that transition to low emission economy is not perceived seriously from policy makers so CO_2 price is low and importance of domestic component is also low. In contrary, High scenario presumes high importance provided by policy level, which results in high emission price and in high domestic share of technology production, maintenance and installation.

Some sustainable development indicators will remain the same (for example emission reduction with renewable energy production), but here differentiation will be regarding some other issues – like number of jobs created, cost – benefit assessment of feed-in- tariff etc.

Table 7-6: Proposed 3 scenarios with different share of domestic component in production of equipment, in installation and in maintenance; also difference for made in CO_2 price in each scenario

Scenarios	S1 - Low	S2 - High	S3 - Moderate
Share of domestic component in production [%]	10	90	50
Share of domestic component in installation [%]	20	90	60
Share of domestic component in maintenance [%]	40	100	80

Several other characteristics of Croatian energy and power system are defined in the model as follows in order to describe the energy situation as closer as possible, but in the same time not going too much in detail according to the thesis scope:

- Results from Croatian Bureau of Statistics 2011 Census show that an average flat/house area is 66 m2. Total flat/house area amounts 149.380.000 m2, are of commercial buildings 43.380.000, and area of public buildings is 9.580.000m2;
- The developed model accounts for these two support mechanisms: Feed in tariff for investors in renewable energy sources in Croatia is guaranteed for 14 years. Average production price for Croatia is 0.071 €/kWh. Up to additional 15% is added on the feed in tariff for the share of domestic component in investment (for example if wind turbine is made 100% domestically, feed in tariff is 15% higher);

- Investors with incentive purchase price are obliged to pay local community 0.01 HRK/kWh (cca. 0.00133 €/kWh) of electrical energy delivered to the grid. Support mechanisms for energy efficiency were modeled as a partial investment of the State by a 30% share in the private sector and a 50% share in the public sector;
- For comparation of saved emissions is used average amount of emissions in electrical energy production in the Croatian system from year 2006 to 2011 were 0.33 tons of CO_2 equivalent per megawatt hour of electricity produced [106].
- For the purpose of modeling heat energy generation, average unit emissions used in the model are 0.21 tons of CO_2 equivalent per GWh of heat energy produced. Unit emissions from fossil liquid fuels in the Croatian liquid fuel mix are modeled as 3.18 tons of CO_2 equivalent per ton of fossil fuel consumed. The use of biofuel is considered GHG-neutral when used in sustainable limits;
- The effect of energy efficiency measures in buildings on GHG reduction were modeled as a decrease in heat production in every house unit renewed from 175 kWh/m^2 to 75 kWh/m^2. Consequentially follows a decrease in gas consumption for heating.

7.3.2. Modeling monetary costs and benefits of policy measures of supporting low-carbon technologies in life-cycle of technologies

Monetary cost and benefit from energy production for the State and the society was evaluated as a difference from average generation cost in Croatia for each type of energy. The price of renewable energy production is higher during the period of incentive purchase price and is later considered as an average generation cost (after 14 years period of feed in tariffs).

Monetary cost and benefit for the society as a consequence of lowering or increasing GHG emissions was evaluated as emission price and its value varied in scenario analyses.

Monetary cost and benefit of new jobs was evaluated as 10,000 € per new job annually. This number was estimated as an average tax income from every employed person annually plus the cost for the State for social care of the unemployed plus cost of education of each person. This number can vary in the model.

Monetary cost of investment was modeled according to the Croatian tax-system as tax on earnings which investors achieve and as value added tax. Value added tax is proportional to the share of domestic component in production. In this model, the cost for the State and the cost for the society were considered equal. Model took as an input an average income tax rate of 10% for the first 10 years, and 20% for the further period. Value added tax used for modeling was 25% (as valid in 2013).

7.3.3. Model outputs

The goal of the holistic, low-carbon development is to optimize benefits for all three pillars of sustainable development – economic, social and environmental.

As explained in model description in chapter 6.3., outputs from the model are put in several sheets – general model results are found in "Outputs" Excel sheet with values distributed against years and calculated indicators, while each of the modeled low emission technologies has its own Excel sheet.

Outputs from "Model for estimation of sustainable development impacts" are further used as inputs for two other models, MAC model and PACE model. They are designed to allow prioritization of various low emission solutions (according to a number of indicators or only on investment costs). Another purpose is to enable visualization of results, in order to better communicate or compare them.

7.4. Assessment of climate change impacts on energy generation from renewable energy sources

7.4.1. Use of climate models in assessment of long term climate change impacts on renewable energy production – first proposed methodological step

Even though climate change has important impact on demand side (such as higher power demand on very hot days due to air conditioning or less energy needed for heating in warmer winters), climate change impacts on demand side are not part of research in proposed methodology or in this thesis. Only climate change impacts on generation side are researched, specifically on renewable energy sources.

Proposed methodology for climate change impact on renewable energy sources will be applied here on three technologies only: wind, solar and hydro energy production. Impact of climate change on biomass, biofuels and other renewable energy sources will not be researched.

The existing climatological data show that during the 20th century, most regions in Croatia experienced a decrease in precipitation and an increase in temperature in almost every season [144]. It is difficult to discriminate the causes of these changes between natural climate variation and anthropogenic climate change. But, climate models indicate that in the future Croatia is expected to be hotter and drier if the GHGs emissions continue to grow, in the so-called business-as-usual scenarios [145].

As already mentioned, climate models are the only tools that enable understanding of how climate will change in the future. The forcing of a Regional Climate Model by a Global Climate Model proposed in this methodology, is in first methodological step based on use ECHAM5-MPIOM as a GCM, and its outputs are used for downscaling by the RegCM RCM [126]. For this assessment, the results from various models were analyzed, all of them based on the IPCC A2 scenario. In this scenario, the climate system in the future is exposed to high forcing of the greenhouse gases (GHGs). The three different time periods were considered:

- P0: 1961-1990, reference climate (representing climate of the 20th century);
- P1: 2011-2040, near future climate;
- P2: 2041-2070, representing climate of the middle 21st century.

The assessment of three different renewable sources is proposed within the methodology, solar, wind and hydro, because of their potentially high sensitivity to climate change and because of their high impact on Croatian energy mix in the future.

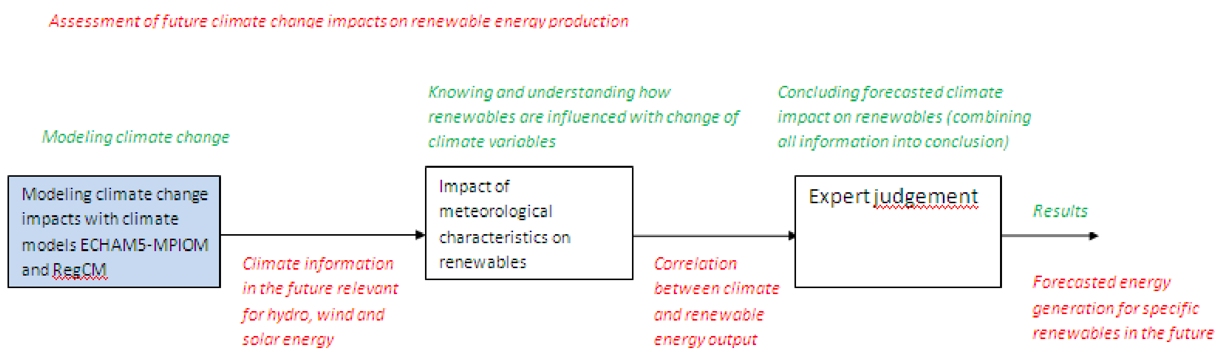


Figure 7-5: Schematic representation of first proposed methodological step for estimation of climate change impact on renewable energy sources

7.4.2. Assessment of climate change impact on photovoltaics

The geographical location of Croatia provides very good conditions for the use of solar energy. In the southern part of Croatia, where the Mediterranean climate prevails, these conditions are even more favourable than in the rest of country. The duration of mean annual insolation over the southern Croatian (Adriatic) coast is more than 2500 hours while in Dubrovnik and on some islands it even exceeds 2700 hours [146]. The Croatia's solar energy potential is best described by comparison with the European average. The Croatian southern coast has about the same average solar irradiation per day (5.1 kWh/m^{2}d) as southern Europe [147]. This is about 20% more than for the Croatian northern coastal region. For the continental Croatia, the average value is 3.8 kWh/m^{2}d which is about 20% more than in Central Europe. Clearly, irradiated solar energy in southern Croatia is up to 75% higher than in central and northern Europe, and it is only smaller than in the most southern parts of Spain, Portugal or Greece. The technical PV potential in Croatia is difficult to estimate without specific policy assumptions, as it is directly proportional to the land and roof area designated for this purposes.

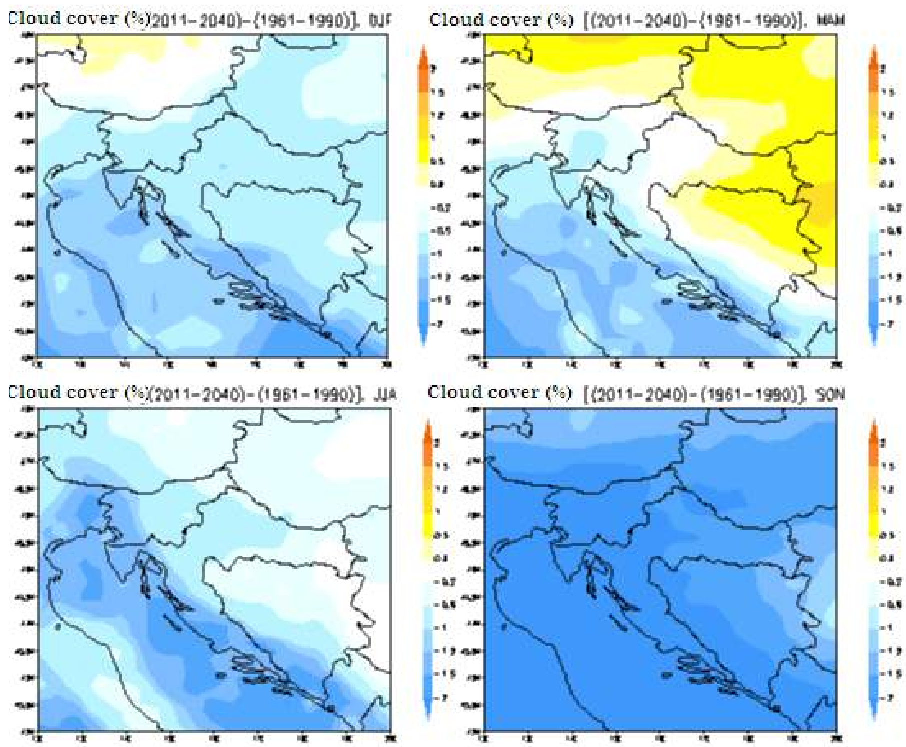


Figure 7-6: Cloud-cover change (in %) due to climate change in the period between 2011-2040 (P1) when compared to 1961-1990 (P0), for different seasons (DJF: December- February, MAM: March- May, etc), with A2 IPCC scenario. Source: [148]

The energy generation from PVs is directly proportional with global horizontal irradiance (GHI), the total amount of shortwave radiation received from above by a horizontal surface. GHI is in close relationship with cloud cover, where fewer clouds would imply more sun energy absorbed by PV modules. Based on the results from the regional climate model used at DHMZ for the period 2011-2040, a decrease in the mean cloud cover (and therefore a proportional increase in GHI) over the southern part of Croatia is between 1-3% depending on the season (Figure 7-6). Such an increase in GHI would have a directly proportional influence on electricity production from PV modules, corresponding approximately to an average rise of 2%.

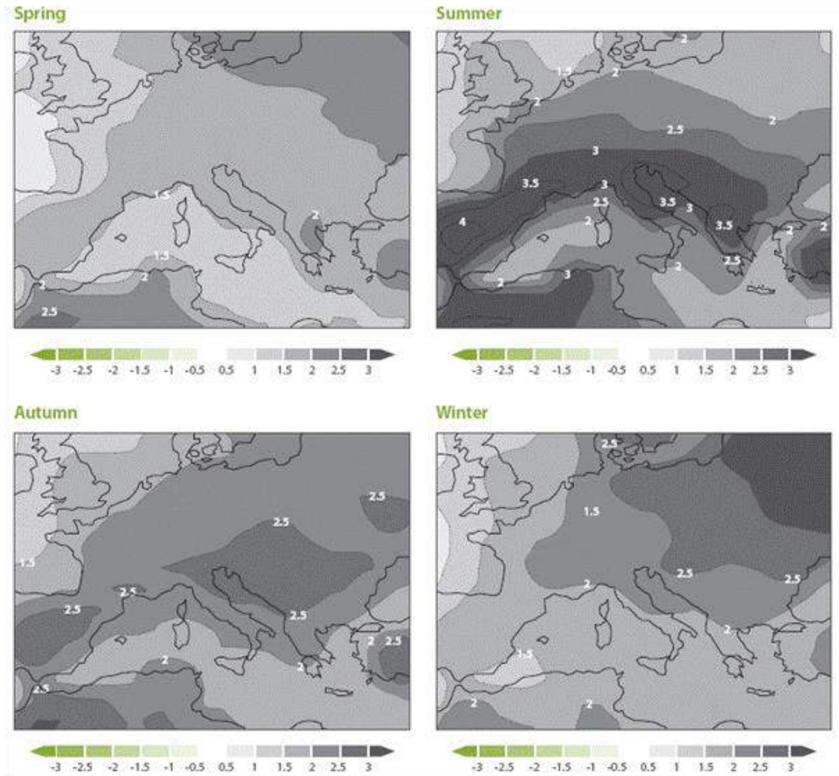


Figure 7-7: Comparison of the changes in an average temperature between the period 1961 – 1990 and period 2041 – 2070. Source: [145]

Energy production from PV depends on the following climate and weather conditions: change of temperature, snow cover, extreme weather and total irradiation. The results from climate modeling studies for Croatia made at DHMZ indicate that there would be a general increase in the mean air temperature in future climate, notably in the summer [127]. This temperature increase is projected to be smaller in the near-future climate period P1 (2011-2040) than in the next period P2, around the mid-21st century (2041-2070). Such an increase is not uniquely defined – it depends on the model and the IPCC scenario used but also on the area considered; for example, in most models, the increase is larger in the Mediterranean region than in central Europe. For the IPCC A2 scenario, the average increase in the mean air temperature for Croatia in the period 2041-2070 would be between 1.5°C in the spring and 3.5°C in summer (Figure 7-7).

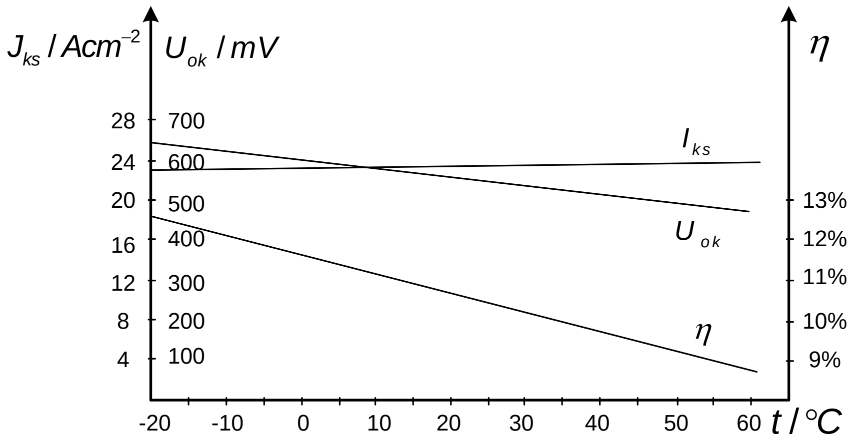


Figure 7-8: Decrease in PV`s electricity generation efficiency due to external temperature rise. Source: [149]

The rise of air temperature is manifested as a decrease in the PV efficiency, which is proportional to the so-called cell temperature coefficients for energy produced in a PV module (Figure 7-8). These characteristics depend on technology used. Based on estimates from Figure 3, it is assumed that for an increase of temperature by one degree Celsius, the PV efficiency decreases about 0.5% relatively to the referent value at 25°C. An important negative impact on electricity production from PVs is expected in summer when the projected largest increase in the mean temperature coincides with the largest electricity generation from PVs. This could reduce power production between 3 and 5 %.

The results from climate models indicate that snowfall is expected to generally decrease in the future [145]; in particular, in the western part of Croatia the reduction of, on average, two days with snowfall could be expected in the period P1 [126]. In addition, because of expected increase in the mean temperature, it might be assumed that snow that does fall stays on the ground for shorter periods of time. Both these effects would imply a lesser amount of cleaning of snow from the PV panels. However, this effect has little importance on energy production from PVs except in the mountain regions, since in the winter solar irradiance reaches its minimum.

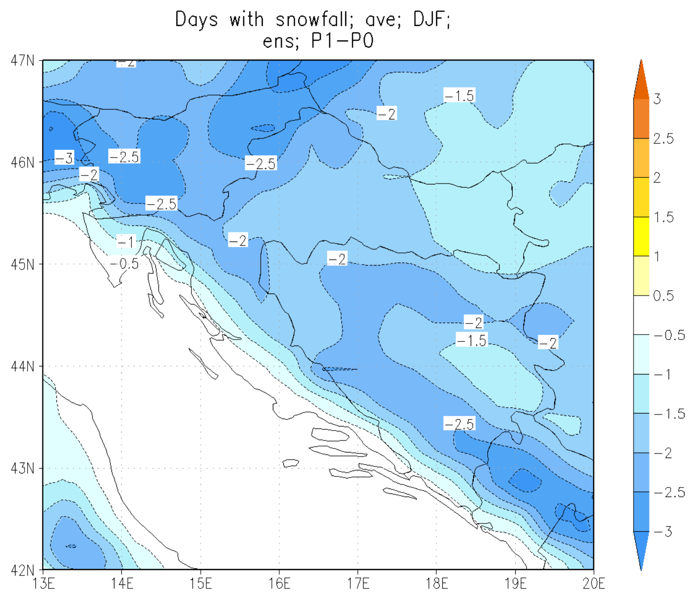


Figure 7-9: Change in number of days with snowfall due to climate change in the period between 2011-2040 (P1) when compared to 1961-1990 (P0), for December –February (DJF), with A2 IPCC scenario. Source: [148]

The climate change, including the projected increase in temperature and reduced precipitation in some seasons, would be also associated with a higher risk of severe weather and extreme conditions. For example, forest fires are expected to increase in strength and in frequency [150]. If a PV power plant is situated near forested area, it could be affected by an increased risk from forest fires (such fires are even now relatively frequent in the summer in the Mediterranean part of Croatia). This kind of risk is difficult to quantify, but it can be reduced by a careful choice of plant's location. In addition, the expected strengthening of storms in the future would inevitably result in increased wind speeds which could potentially cause damage to solar panels. Again, this risk could be alleviated by choosing those locations where the panels are least exposed to direct wind. Overall, this could be considered as having a small negative impact on energy production from PVs.

7.4.3. Assessment of climate change impact on wind energy production

Most of wind data (speed, direction, gustiness) across Croatia are available from continuous meteorological measurements performed by DHMZ at meteorological and climatological stations. Additional data are available from the *ad hoc* research and investors measurements at numerous specific locations. Technical wind potential, i.e., energy that might be produced at wind power plants, in the continental part of Croatia is estimated at 10 TWh and in the Mediterranean part of Croatia at 12 TWh [151]. According to the new energy strategy [136], the expected new wind capacity by 2020 would be 1200 MW (with assumed 2200 working hours annually these results in 2.64 TWh), and 2000 MW in 2030.

Several climatic factors can influence the energy generation from wind: wind speed and (prevailing) wind direction, variability of wind speed but also air temperature. Wind turbines can extract energy over a definite (limited) band of wind speeds, typically between 3 and 26 m/s [152]; at higher wind speeds their operation is interrupted in order to prevent damage that could be caused by high wind force. The impact of climate change on wind parameters would cause the following two main effects on wind power plants [153]: *(i)* change in wind speed - this affects the amount of electricity produced and the timing and duration of the plant operations, and *(ii)* increase in the maximum wind speed for which wind power plant is designed - this influences reliability and safety of the plant equipment.

A number of studies analyzed the changes in wind speed and its impacts on electricity production from wind power plants (for an overview see [153]). Electricity production from wind power plants is in the cubic relationship with wind speed, and it is proportional with air density [154]:

$$P = 1/2 \cdot c \cdot \rho \cdot A \cdot v^3 \cdot \qquad (6.1)$$

In the equation (1), P stands for electric power, c is the total efficiency of the wind power conversion (depends on wind speed), ρ is air density, A is surface area of the wind turbine rotor, and v is wind speed. The above power P is only nominal after a certain wind speed is reached (usually from 11 to 15 m/s). Due to the cubic relationship, the 10% change in the average wind speed could alter energy production by 13-25% [155].

For the purpose of this study, the results from the regional climate model, integrated at DHMZ with the IPCC A2 scenario, were used for both P1 and P2 time periods. They indicate that a relatively large change in the (climate) mean wind speed could be expected in the coastal and the adjacent mainland areas already in P1.Figure 7-10, shows that the largest change appears in the summer - when the wind speed is projected to increase between 15 and 25% (locally up to 35%). However, the Student two-tailed t-test yields that the changes shown are not statistically significant when compared to the reference climate P0. In other seasons, the projected increase in the mean wind speed in the above region is smaller than in summer; in the continental part of Croatia the future wind speed increase is mostly below 5%. In the P2 time period, the increase in the mean wind speed during summer would be even larger than in P1, amounting to between 35 and 60% in a large part of the coastal area. For the same period, the increase in the continental Croatia would be only 5%. In contrast to the P1 period, the changes in P2 are statistically significant.

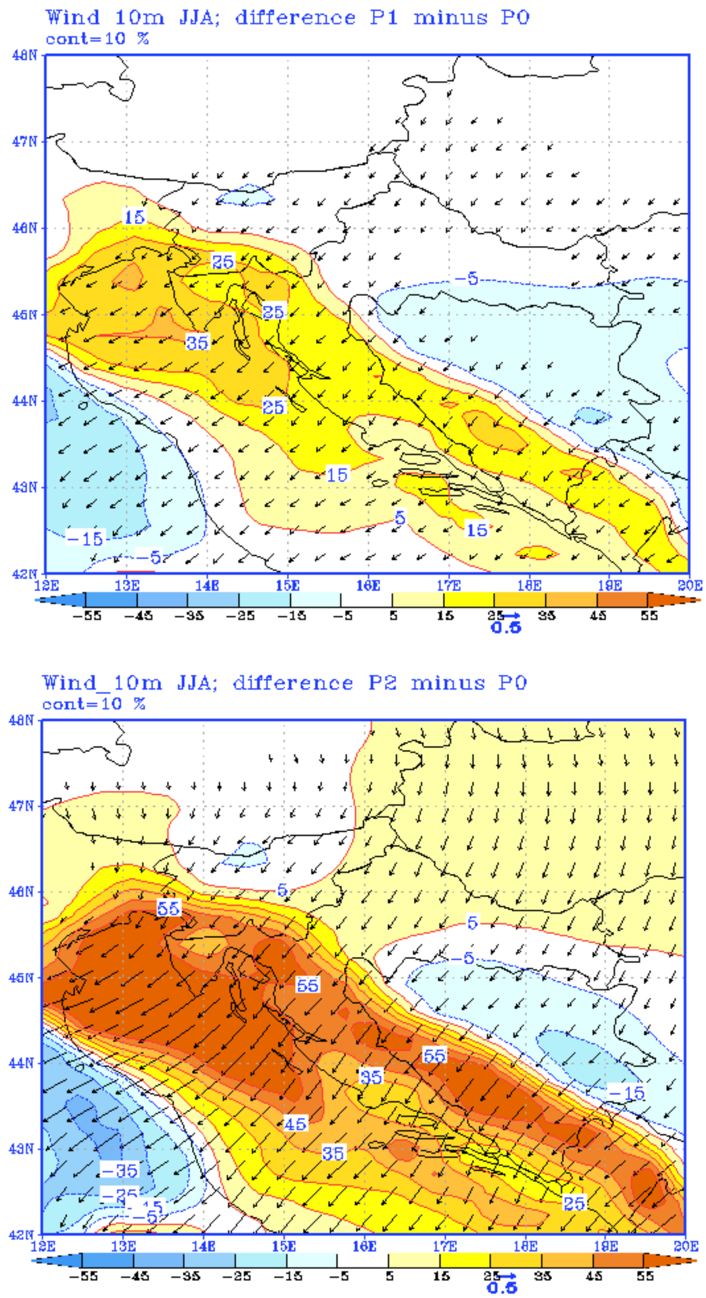


Figure 7-10: Changes in wind speed for the summer period (JJA: June, July, August), between 2011-2040 (P1, upper figure, panel a) and between 2041-2070 (P2) when compared to 1961-1990 (P0, lower figure, panel b) when compared to 1961-1990 (P0), with A2 IPCC scenario. Source: [148]

Such a projected increase of the mean wind speed in future climate could potentially have large impact on electricity production in southern Croatia. According to the above equation (1), the wind speed increase of, say, 25% would theoretically nearly double the electricity production from wind generators. Moreover, the increase of 50% (as modeled in the P2 period) would theoretically mean more than tripling electricity production as it was estimated for P0. However, the above results should only be seen as a projected trend in the future – they are susceptible to possibly large uncertainty margins because only one regional climate model forced by one global model and only one emission scenario were used in the DHMZ modeling study. Therefore it should be emphasized that more reliable results would be obtained by running more models forced by different emission scenarios.

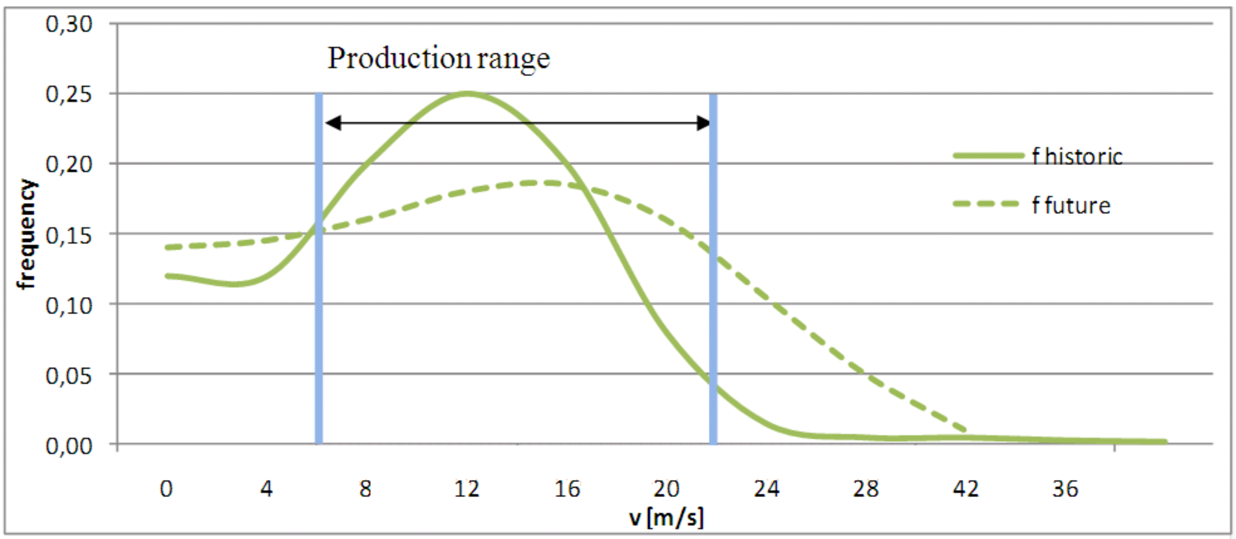


Figure 7-11: Possible changed of wind variability and wind power plant production range in the future, where part of the future wind speed frequency is out of the production range. Source: [148]

Variability of wind speed can have a significant impact on electricity production from wind power plants. This is seen in Figure 7, where, because of the projected climate change, the frequency of the higher wind speed is increased in the future [153]. However, a large part of this increase in the frequency of the higher wind speed could not be exploited because it lies outside of the upper limit of the effective wind speed level.

The change in prevailing wind direction can also impact energy generation from wind power plants. For example, if the (climatological) wind direction in the future climate is projected to be different from the one in the reference climate the terrain configuration at the plant's location could provide an obstacle for the new wind direction. Another impact of the changed wind direction might come from the layout of power generators which was based on the (original) dominant wind speed direction. With the change in the future wind direction some wind generators now may stand in the way and produce the wake effect which would reduce the utilization of the wind energy. However, without relevant data about wind prevailing direction variability and its change it is difficult to estimate a quantitative impact on electricity production.

As discussed, the results from climate modeling indicate an increase in the mean temperature in the future. Since the rise in temperature is associated with a reduction of air density, according to the equation (1) this would entail a reduction in wind generated power. Based on [153] the temperature increase of one degree Celsius affects a decrease of about 0.3% in the wind power electricity production. Clearly this influence is too small when compared with significant change of the mean wind speed. With projected temperature rise described in section 2.2, this would mean a reduction in electricity production by less than 1%.

7.4.4. Assessment of climate change impact on hydro energy production

The importance of electricity production from hydro power plants in Croatia is best judged from the fact that in the period 2000 – 2007 they generated about a half of the total electricity production [156]. In addition, about 50% of the total installed power capacities in Croatia are in hydro power. This is more than 2000 MW of the installed hydropower, and on average about 6 TWh/yr of electricity. Most hydro power plants are located in southern Croatia, with the water inflow depending on the river catchments in the neighboring Bosnia and Herzegovina.

The main climate change impacts on the hydro-energy production are the potential reduction in precipitation (especially in the regions where most of the hydro power plants are located) and the increased evaporation due to expected increase in the mean temperature. The latter acts as to reduce the water levels in the power plant reservoirs. In this assessment, only the reduction in precipitation will be discussed as it is more important and simpler to evaluate. The reduction in precipitation would cause less inflow to water reservoirs and hydro power plants. Several macro-scale hydrological models predict that the production of electricity from the south European hydropower stations will decrease between 20-50% by the 2070s [157]. The current experience from the new small hydro power plants in Bosnia and Herzegovina shows that electricity generation in many cases is already lower for 20-30% than expected [158]. Not all the above changes can be attributed to climate change, because in some places it is also related to the new water management (e.g. local irrigation). The current practice in Croatia is that the Croatian

Power Utility (HEP) forecasts the annual electricity production based on DHMZ data of aggregated water inflows into reservoirs. A linear relationship is assumed between the water inflow and the electricity production from hydropower plants.

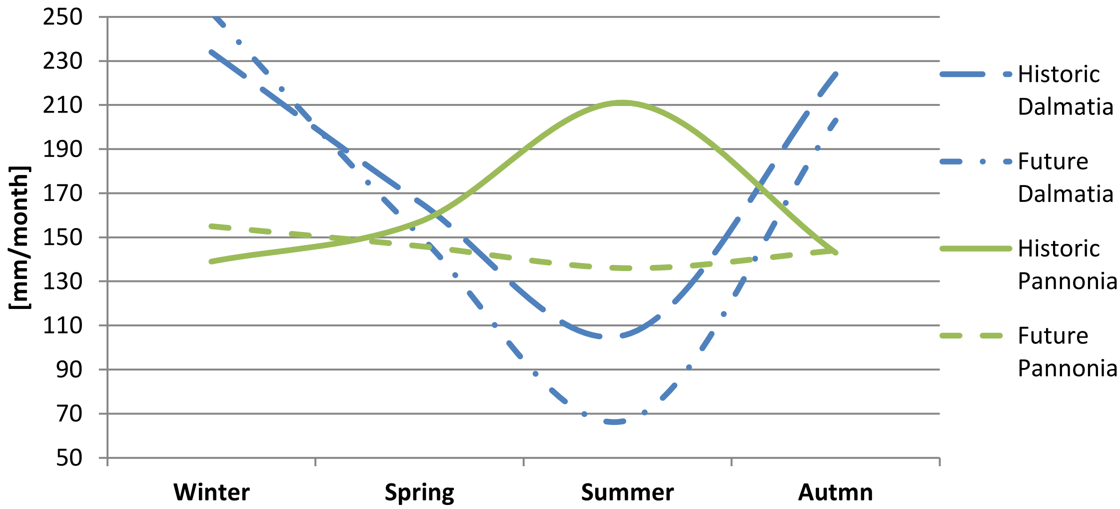


Figure 7-12: Historic (1961-1990) and future (2080-2100) average seasonal precipitation (mm/month) for northern (Pannonia) and southern regions in Croatia. Based on [145]

As seen in Figure 7-12 it is estimated that the future precipitation for major Croatian river basins is expected to be reduced by 35% in the summer in period 2080-2100 relative to the reference period 1961-1990, although in the eastern part of the country this change might be below 10% [145]. Hydro-power plants must also have defined a biological minimum water flow, below which the water flow for power production is not available. So, a reduction in water inflow (because of the projected reduced precipitation) would mean even less water for power generation, and the energy generation from hydro power plants is here expected to decrease by 15-35%. Most of the reduction in electricity generation from hydro-power plants is expected in the summer when the decrease in precipitation would be largest.

7.4.5. Use of climate and energy models in assessment of long term climate change impacts on renewable energy production – second proposed methodological step

As discussed in chapter "6.1. Description of proposed methodology", further improvement of methodology for assessment of climate change impact on renewable energy sources is proposed as "the second proposed methodological step". Improvements from the first proposed methodological step are the following:

- Using several different climate scenarios and models to define a probabilistic range of forecasted climate information (instead of only one such as was presented previously);
- Using historical data for understanding correlations between climate and renewable energy production, and in cases where it exist, also includes terrain specific information;
- Using energy models /power system models instead of expert judgment to understand climate change implications on specific renewable energy technology. These energy models / power system models used within methodology could be either energy planning models, or can be technology specific such as model that enables modeling wind power plants. In both cases, input to the model can be modified according to the change of meteorological information (such as the change of average wind speed for wind power plant).

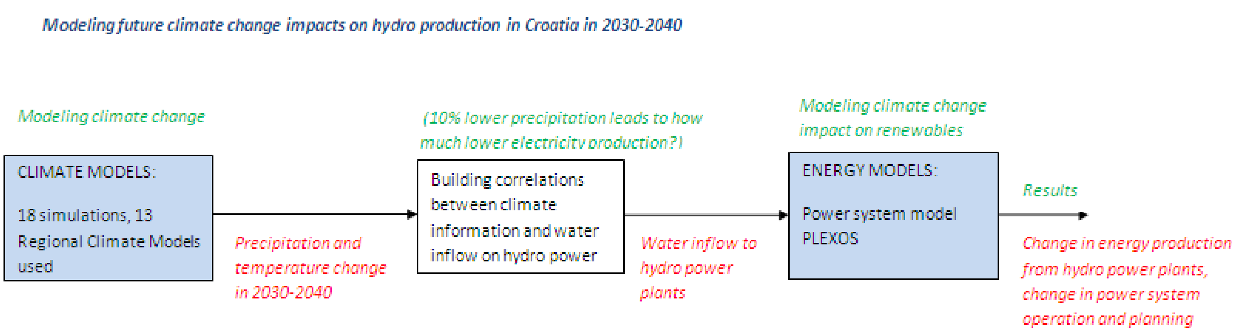


Figure 7-13: Schematic description of proposed methodology

For the verification of the proposed methodology, data was used from 18 simulations by 13 regional climate models (RCMs) which participated in the ENSEMBLES project [159]. Period for estimation of potential climate change over Croatia and the neighboring countries is chosen as 2011-2040. Climate changes for the shorter (10-year) periods are also discussed revealing that important variations within the given 30-year period may also exist. At the boundaries, the RCMs were forced by different global climate models under the IPCC A1B emission scenario. The RCMs horizontal resolution of 25 km enables a reasonably well-defined insight of future change of the seasonally-averaged precipitation climate patterns. In most downscaling studies, the spatial distribution of seasonal precipitation is well reproduced [127]; however, in the regions with high or complex orography, simulations of precipitation amounts might be less successful.

Table 7-7: Impact of hydrology on share of hydro power plants within Croatian power system between 2005 and 2007. Source: [106]

	2005.	2006.	2007.	2008.	2009.	2010.
	GWh					
Production	12458,9	12429,6	12245,1	12325,6	12777,1	14104,9
-hydro power plants	6438,6	6123,5	4400,2	5325,9	6814,4	8435,2

Due to high dependency of Croatian power system on hydro power plants (as seen in Table 7-7, difference between dry/wet years can be between 4.4 TWh and 8.4 TWh), it would be interesting to first test this methodology on hydro power plants in Croatian power system. Focus of implementation is put on the region of Dalmatia where many of Croatia's hydro power plants are located and some of them depend on the water inflow from the neighboring Bosnia and Herzegovina. A particular attention is given to the spread of the RCM results, and change is visible in Figure 7-14 and Figure 7-15. Assuming that the modeling errors are not too large, this measure of consistency indicates potential uncertainty in the climate change projections.

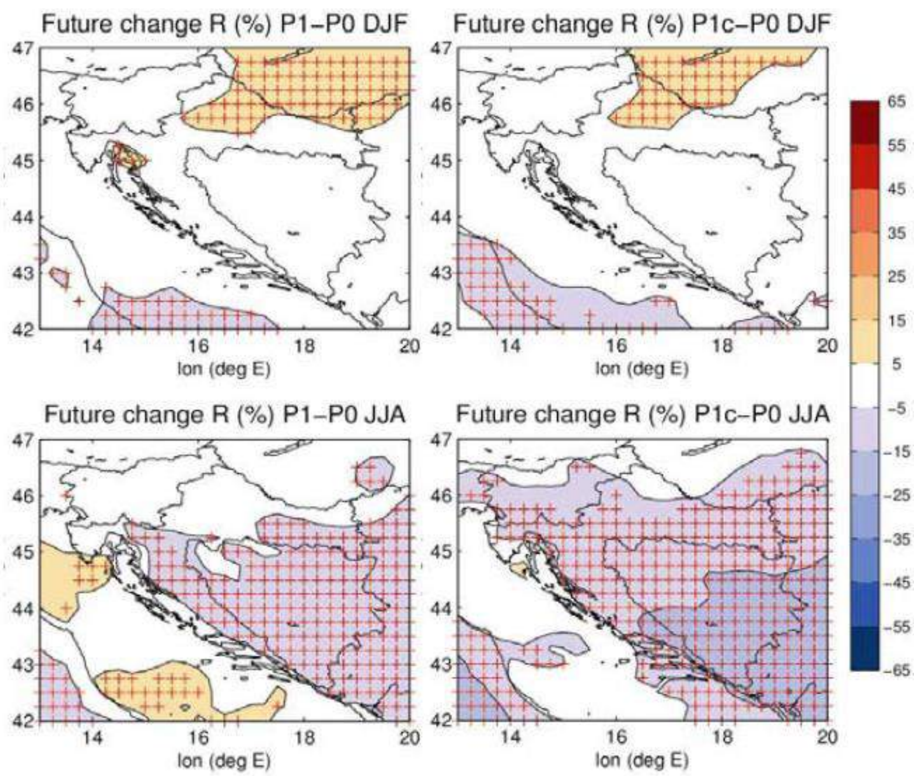


Figure 7-14: Relative change with respect to the reference period 1961-1990 (in %) of seasonal precipitation for winter (top panels) and summer (bottom) in the period 2011- 2040 (left) and 2031-2040 (right). Crosses indicate that 66% of the RCMs agree in the sign of change. Source: [160]

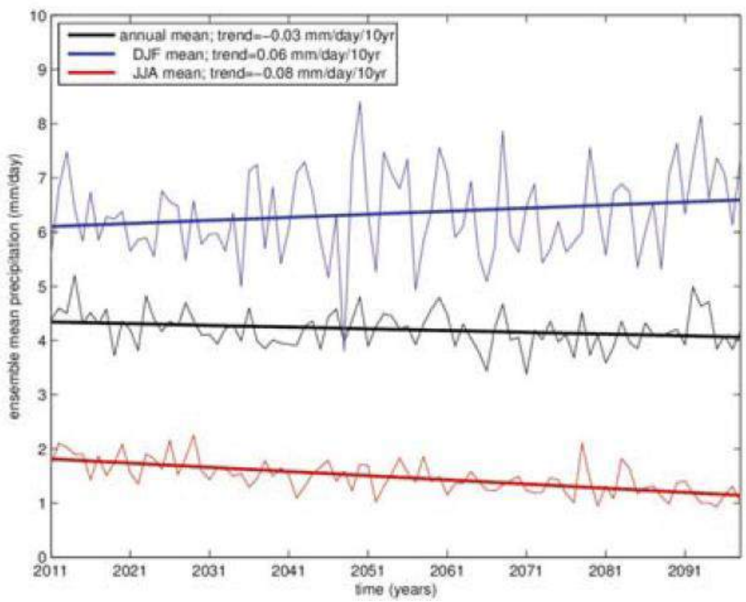


Figure 7-15: Trends in precipitation over Dalmatia for annual (black, -0.03 mm/day per 10 years), winter (blue, 0.06) and summer (red, -0.08) precipitation as projected for the 21st century. A slight increase in seasonal precipitation is seen only in winter. The interannual variation is only indicative and it remains similar to that of the present climate. Source: [160]

7.4.6. Use of energy models within the second methodological step proposed

There is a wide spectrum of energy models focused on specific renewable energy technologies (hydro, wind, solar) that can be used in proposed second methodological step. Some of them will be shortly presented here. Model types can be divided in three main groups [161]:

- Dimensioning or sizing models/tools perform dimensioning of the system (determining the optimal size of each of the different components of the system). Some of them tend to optimize minimization of life-cycle cost of the system; others may size the system in a way that would lead to a properly functioning system;
- Simulation tools specify the nature and size of each component and then model provides a detailed analysis of the behavior of the system. Simulations can also provide information concerning the financial and environmental characteristics of the system, such as the life-cycle cost and CO_2 emissions;
- Research models are used when a high level of flexibility in the interaction of the components is required. While traditional simulation tools can perform extensive sensitivity analyses, they generally do not permit the user to modify the algorithms that determine the behavior and interactions of the individual components.

Solar energy

Several models are identified according to their purpose (Figure 7-16).

(dim: dimensioning tool, des: mini-grid design tool, sim: simulation tool, res: research tool)

free tools

RETScreen	dim
HOMER	sim/dim
Hybrid2	sim
Vipor *	des
Jpélec *	des

* Mini grid design

commercial tools

Off Grid Pro	dim
PVsyst	sim/dim
PV*SOL	sim/dim
Solar Pro	sim

standard commercial system simulators

Simplorer (APL)	
PowerSim	res
MATLAB/Simulink	res
Dymola	res
PowerFactory	res

internal tools

Off Grid Sizer	dim	Conergy
Sunny Island Design	dim	SMA
PVS	sim/dim	ISE
TALCO	res	ISE
Dymola	res	ISE
MATLAB/Simulink PVToolbox	res	Canmet
MATLAB/Simulink Hysis	res	CIEMAT
MATLAB/Simulink N.N.	res	ISET
PowerFactory Tool box	res	ISET

Figure 7-16: Availability of models/tools for solar energy (PV). Source: [162]

Wind energy

Some of the proposed models for modeling impact of climate information on wind energy are the following:

RETSCREEN – Uses online wind resource mapping applications or non-interactive maps of wind resources[4]. In order to model climate change impact, these maps with wind resources would need to be modified so they can address forecasted wind change. This model is of poor quality for wind projects as shear and turbulence values are not available, it doesn't have available statistical distribution of wind speed, and has no site specific data. Typical energy estimate is around +/- 50%.

WAsP - stands for Wind Atlas Analysis and Application Program, and is used for wind farm production and efficiency, micro-siting of wind turbines, power production calculations and wind resource mapping. Time-series of wind data may be obtained from meteorological stations

[4] Samples of maps of wind resources: www.3tier.com; www.WindNavigator.com; www.windatlas.dk

or from other sources, and could be used to model climate change impacts if forecasted data are available.

WindPRO and WindPRO – models enables users to design wind farms, including wind turbine layout and electrical design. Technical characteristics such as energy production, turbine noise levels, turbine wake losses, and turbine suitability can be calculated. They use wind flow modeling inputs from WAsP software.

Hydro energy

Modeling climate change impacts on hydro energy is more complex than modeling impacts on solar and wind energy because of the following challenges in modeling hydro energy:

- Stochastic value of water inflow on a short time range (important for run-through hydro power plants) or medium and long term time range important for both storage and run-through hydro power plants;
- Definition of water value that is in energy storage (which can be spent immediately or saved for later use when its value might be higher);
- Water inflow that dependent on more than one meteorological variable (rain and snow, but also warm weather for melting snow and ice);
- Many technical concerns that needs to be taken in account for energy calculation from hydro power plants;
- Decrease in 20-30% of water inflow to hydro power plant might result in much larger energy outputs due to some restrictions such as biological minimum;
- Nature of energy generation from pump hydro power plants which is dependent on the whole energy system;
- Cascade hydro power plants where water output from one hydro power plant can be water inflow for the next one down the waterway.

Because of all these, it might be more appropriate to use power system models able to technically describe hydro power plants (such as model PLEXOS used within this verification of methodology).

7.5. Integrative modeling – verification of proposed methodology on modeling power system development with using data for Croatia in 2030

In this chapter, proposed methodology will be applied on modeling power system development with data for Croatia in 2030. In previous subchapters of Chapter 7, description of *modeling* power system development according to the proposed methodology is already presented, but in fragmented way:

- In subchapter 7.2. modeling power system with use of Croatian data is presented;
- In subchapter 7.3. use of proposed models and modeling sustainable development indicators is presented; while
- In subchapter 7.4., methodology is presented for assessment of climate change impact on renewable energy sources production.

Therefore, the purpose of chapter is to integrate all these modeling on one single case: modeling power system development with data for Croatia in 2030.

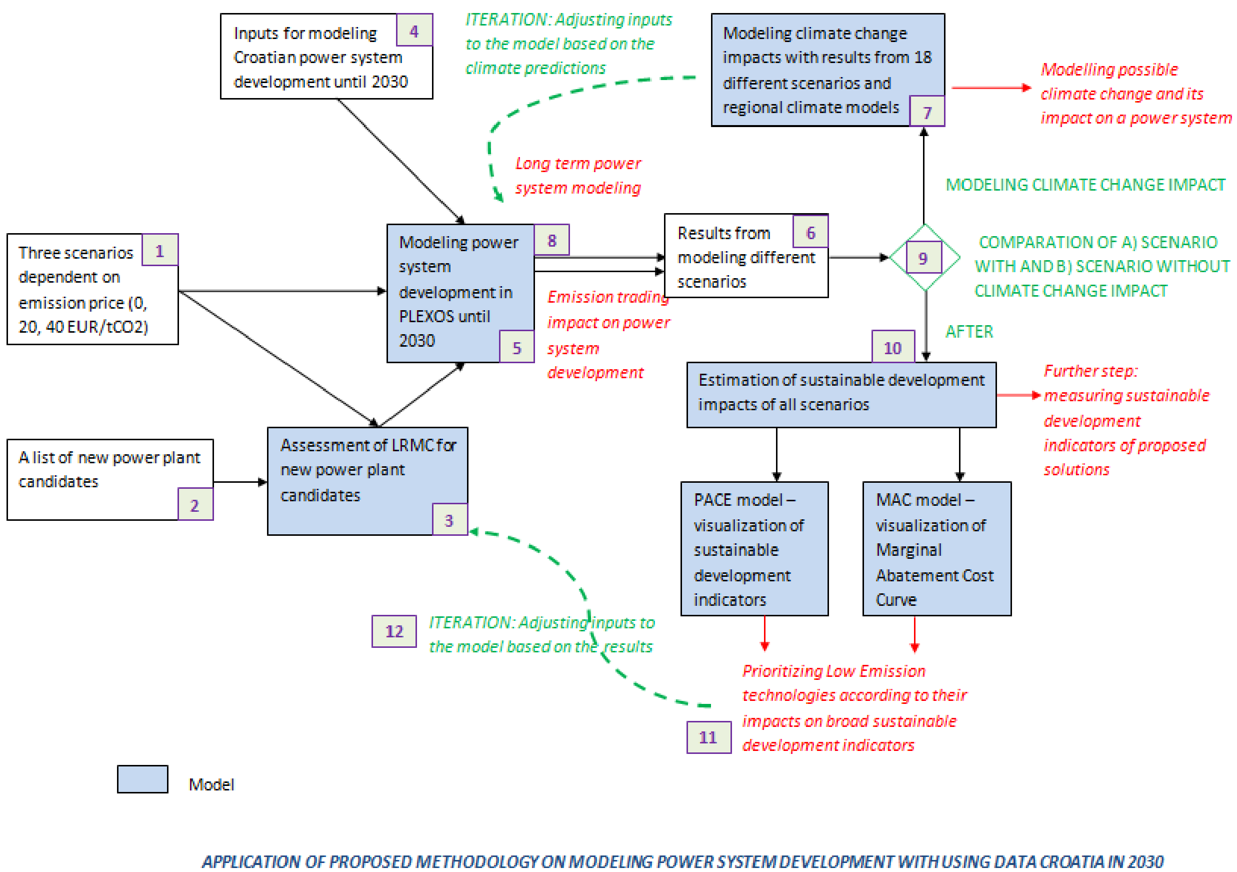


Figure 7-17: Schematic representation with numbered steps for application of proposed methodology on modeling power system development with using data for Croatia in 2030

In order to easier track use of models in methodology, description of modeling is presented in twelve steps in Figure 7-17 (upon which modeling results in chapter 8.4. will be also presented).

STEP 1: Defining emission price scenarios – use of methodology starts with defining emission price scenarios that will be used. Three different emission prices will be modeled: 0, 20 and 40 EUR/tCO_2

STEP 2: Defining list of new power plant candidates that will be used in modeling. Some of description data for power plants is given below, while more detailed description is in chapter 7.4.:

- **TPP Sisak blok C** - thermal power plant based on gas; Nominal power: 230 MW, Investment costs: 900 EUR/kWh;
- **TPP Plomin C** - thermal power plant based on coal:, Nominal power: 500 MW; Investment costs: 2166 EUR/kW; coal price: 4,16 EUR/GJ;
- **TPP Ploce** – has the same characteristics as TPP Plomin C, but it's possible commissioning date is set after 2020.
- **TPP Slavonia** - thermal power plant based on gas; Nominal power: 500 MW; Investment costs: 800 EUR/kW; gas price: 10 EUR/GJ;
- **WPP 1Best** - wind power plant based on best wind potentials; Investment costs: 1200 EUR/kW; Nominal power: 400 MW; Number of hours on nominal power: 3000 h/annually; Approximated nominal constant power used in modeling: 137 MW;
- **WPP 2Best** - wind power plant based on second best wind potentials; Investment costs: 1200 EUR/kW; Nominal power: 400 MW; Number of hours on nominal power: 2700 h/annually; Approximated nominal constant power used in modeling: 123 MW;
- **WPP 3Bbest** - wind power plant based on third best wind potentials; Investment costs: 1200 EUR/kW; Nominal power: 400 MW; Number of hours on nominal power: 2300 h/annually; Approximated nominal constant power used in modeling: 105 MW;
- **WPP 4Best** - wind power plant based on fourth best wind potentials; Investment costs: 1200 EUR/kW; Nominal power: 400 MW; Number of hours on nominal power: 2000 h/annually; Approximated nominal constant power used in modeling: 91 MW;

STEP 3: Assessment of LRMC for new power plant candidates – this step will be performed using proposed and developed “LRMC model” whose description is presented in chapter 6.2., new power plants presented in the previous step will be assessed with use of model according to the emission price level 0-60 EUR, and for three different referent oil prices (95, 125 and 140 USD/bbl).

STEP 4: Inputs for modeling long term power system development of Croatian power system in 2030. In this step, data for Croatian power system will be set as an inputs to the model PLEXOS. This part is necessary to define constraints under which modeling of power system development will take place (plan for closing existing power plants is in Table 7-8, while increase of energy consumption is given in Table 7-9 existing system capacity etc.).

Data on Croatian power system definition in model PLEXOS are based on data already presented in chapter 6.2. It means that one wind power plant already exists; as there is already 400 MW installed “WPP existing” power plant with 2700 numbers of hours on nominal power, described with approximated nominal constant power used in modeling: 123 MW. In order to limit the scope of modeling, this power plant represents existing wind power and other renewable energy sources.

Some other renewable energy sources are not modeled per se, but are represented as a part of energy efficiency measures in industry and households. Their contribution in number of jobs, CO_2 reduction and others will be calculated with Model for measuring sustainable development impacts. These are:

- Solar thermal systems – 2.5 million square meters, installed thermal power 2.45 GWh;
- CHP biomass – 120 MW electric power, 200 MW thermal power;
- Solid biomass thermal – 750 MWt installed power;
- Heat pumps – 40,000 units installed with total power installed 488 MW;
- PV – 200 MW;
- Energy efficiency measures in buildings (households) – 30% of houses to be renovated;
- Energy efficiency measures in public buildings – 75% of buildings to be renovated.

Thermal energy and energy efficiency in houses are modeled as supported by state with 20% of investment. Wind power plants are modeled without any subventions, while other electricity renewable energy sources are modeled with current subventions but not higher than 15 EUR cents per kWh. Coal and CCGT power plants are modeled to sell their electricity with profit 15 EUR/MWh, and wind power plants with profit of 10 EUR/MWh.

In order to enable that modeling results have less impact from electricity price in neighboring countries and external markets, further constraints are modeled on energy import/export (300 MW capacity limit set for both purchase and sales).

Table 7-8: Timelines for closures of existing power plants from 2013 to 2030 that serves as an input. Source: inputs to the model set by author, based on available data

Generator / power plant	Nominal power [MW]	Scheduled time for plant closure
EL-TO Zagreb blok A	13	2015.
TE Sisak blok A	210 (198)	2015.
TE Sisak blok B	210 (198)	2015.
TE Plomin blok A	105 (93)	2017.
TE-TO Osijek PTA A	25 (23,5)	2017.
TE-TO Osijek PTA B	25 (23,5)	2017.
KTE Jertovec KB A	42,5 (37)	2018.
KTE Jertovec KB B	42,5 (37)	2018.
TE-TO Zagreb blok C	110	2019.
TE-TO Osijek blok A	45 (42)	2020.
TE Rijeka	320 (303)	2020.
EL-TO Zagreb blok B	32 (26)	2022.
EL-TO Zagreb PTA A (blok H)	25,6	2025.
EL-TO Zagreb PTA B (blok J)	25,6	2025.

Table 7-9: Input for increase of energy consumption in the power system (GWh) and peak load from 2013 to 2020. Source: inputs to the model set by author, based on available data

Year	Energy consumed (GWh)	Increase rate (%)	Peak load (MW)	Increase rate (%)
2013	17002		3354	
2014	17172	1	3417	2
2015	17343	1	3483	2
2016	17517	1	3530	1

2017	17692	1	3580	1
2018	17869	1	3629	1
2019	18047	1	3680	1
2020	18228	1	3731	1
2021	18410	1	3783	1
2022	18594	1	3836	1
2023	18780	1	3890	1
2024	18967	1	3944	1
2025	19157	1	4000	1
2026	19349	1	4055	1
2027	19542	1	4112	1
2028	19738	1	4170	1
2029	19935	1	4228	1
2030	20134	1	4287	1

STEP 5: Modeling long term power system development - in this step, based on described inputs, power system expansion will be modeled until year 2030 with model PLEXOS for three defined emission scenarios. Capacity adequacy is first checked and based on the results from modeling one of the cases; input data are adjusted as necessary (calibration of model). Usually this input data calibration takes more adjustments in order to enable modeling reliable inputs.

STEP 6: Comparing results from modeled scenarios based on different emission prices – impact on emission price on competitiveness of low emission technologies is assessed (in this case wind power plants).

STEP 7: Modeling climate change impacts on hydro and wind power plants generation – due to time and scope restrictions, within this thesis climate change impacts on hydro and wind generation would be modeled only. As described in subchapter 7.4., climate change impacts on thermal power plants or on energy demand would not be modeled nor assessed here.

To assess climate change impacts on hydro energy production in Croatia, approach developed as second methodological step was used (as described in chapter 7.4).

Results from 18 different regional climate models and scenarios used are showing (Figure 7-18) that a reduction in precipitation between 5 to 15% is expected over most of southern Croatia in the summer during the period 2011-2040. In the last decade of this period (years 2031-2040), the projected summer reduction is up to 25% in the parts of southern Dalmatia. This indicates that the rate of change is not evenly distributed throughout the 30-year period, but the sign of change (reduction) is consistent in majority of models.

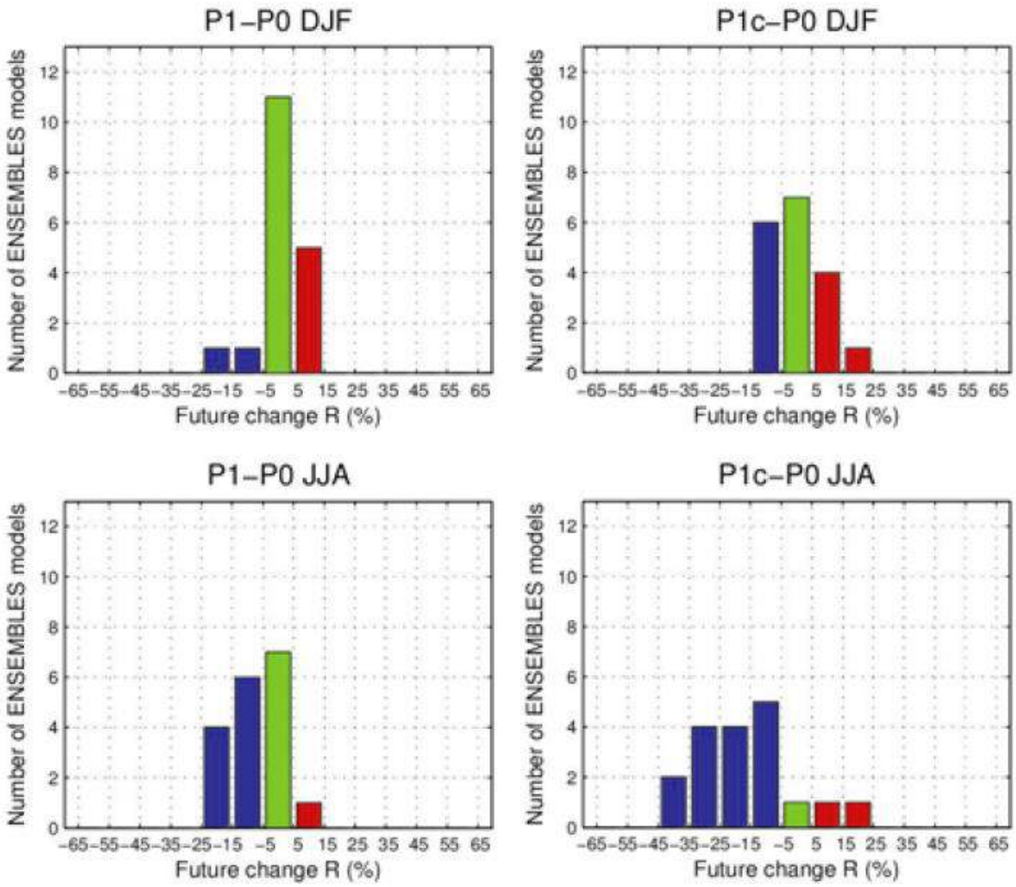


Figure 7-18: Bars denote the number of RCMs producing a given change in precipitation in winter (top) and summer (bottom) for the periods 2011-2040 (left) and 2031-2040 (right) for the area of Dalmatia where most of Croatia's hydro plants are located. Clearly, more models "predict" a larger reduction in precipitation in the 10-year period (bottom right panel). Source: [160]

These climate information would have effect on hydro production, and will be used as an input to the power system model PLEXOS. As an input to further modeling, hydro power plants located in Southern Croatia will be modeled as follows:

- With 10% lower generation in period 2020 – 2025 due to less precipitation expected;
- With 20% lower generation in the period 2025 – 2030 due to less precipitation expected.

Hydro power plants in Southern Croatia that will be modeled with climate change impacts are all except those described in model with HPP Sjever; HPP Zapad, Rijeka, Ozalj, Zeleni Vir, and HPP Zapad Gojak Lešće.

Wind power plants will be modeled with:

- With 5% higher generation in period 2020 – 2025 due to higher wind speed expected;
- With 10% higher generation in the period 2025 – 2030 due to higher wind speed expected.

STEP 8: Modeling "Climate scenario" in power system model

While other input data will remain the same, inputs for hydro and wind power plants would be changed as described in the previous step.

Hydro power plants located in Dalmatia are modeled with modified water inflow files, while wind power plants are modeled with the higher output.

STEP 9: Comparation of modeling results from "Climate scenario" to previous "Non-climate scenario"

Modeling results are compared and discussed across all three emission price levels, making in total 4 different scenarios (three scenarios with different emission price levels, and additional scenario without emission price but with climate change impacts).

STEP 10: Measuring sustainable development indicators for each of four result scenarios. Resulting indicators from all scenarios are then compared in PACE model, and visualized. Also, results are compared in MAC model.

In order to simulate importance of one of sustainable development indicators (green jobs), three different levels of domestic production of wind technology are modeled and discussed.

STEP 11: Prioritizing low emission technologies according to their impacts on sustainable development

Upon the results from modeling done in previous steps, impact of emission price and climate change on wind power plants` competitiveness would be analyzed and discussed. Also, impact of three different levels of domestic production of wind technology is taken in account.

In case that impacts on competitiveness of more low emission technologies is modeled (not only wind), they would be prioritized according to their impacts on sustainable development.

In case that importance of more than one sustainable development indicator would be modeled, (as in this modeling only importance of green jobs was assessed), multi criteria analysis could be performed for prioritization of their impacts on sustainable development. This was not part of this thesis but could be a field of further, follow up research.

STEP 12: Adjusting models inputs based on conclusions

Based on conclusions and recommendations from the previous step, model inputs are adjusted in a new iteration on modeling long term power system development.

8. RESULTS FROM VERIFICATION OF METHODOLOGY USING DATA FROM CROATIAN POWER SYSTEM

In this chapter, modeling results are presented based on verification of proposed methodology using data from Croatian power system. Modeling results presented are based on:

- Chapter 8.1. refers to results of modeling described in chapter 7.2. (modeling emission trading impacts on a Croatian power system);
- Chapter 8.2. refers to results of modeling described in chapter 7.3. (modeling and measuring sustainable development indicators, based on data from Croatian power system);
- Chapter 8.3. refers to results of modeling described in chapter 7.4. (modeling climate change impacts on generation from renewable energy sources);
- Chapter 8.4. refers to results of modeling described in chapter 7.5. (where integrative modeling approach was used and modeling was performed according to the proposed methodology).

8.1. Results from modeling emission trading impacts on a Croatian power system

Within this chapter, results from modeling emission trading impact will be presented based on chapter 7.2., showing results from several cases:

- Modeling year ahead emission price impact on a power system;
- Modeling impact of emission price on power system planning by 2020;
- Modeling impact of emission price on competitiveness of nuclear power plant within Croatian power system between 2020 and 2025;
- Modeling intermittent low emission technologies in PLEXOS: wind power plant in Croatian power system.

8.1.1. Results from modeling year ahead emission price impact on a power system

First application of modeling emission trading impacts on a Croatian power system is performed on modeling year-ahead emission price impact (as described in chapter 7.2.2. with three defined scenarios depending on three emission price levels).

In the following results of different emission price scenarios several characteristics are compared between scenarios, such as change in electricity import, generation from thermal power plants, daily emission amounts and daily electricity prices / costs per power plant. Orange line denotes scenario with higher CO_2 emission price

Base scenario with 0 €/tCO_2 emission price

Scenario with CO_2 zero emission price (0 €/tCO_2) is chosen as a base scenario for comparation of emission price impacts on a power system with CO_2 price rise. Results in graphical representation of hourly values can be seen in figures below.

Base scenario results:

- Total emissions [tCO_2]: 3.408.673
- Average electricity price [€/MWh]: 55,49
- Hydro power plants [GWh]: 5.819
- Thermal power plants [GWh]: 3.021
- TPP Plomin 2 [GWh]: 1.729
- NPP Krško [GWh]: 2.731
- Total generation costs for TPP [€]: 310.554.740
- Total generation costs TPP Plomin 2 [€]: 57.066.760
- Total generation costs NPP Krško [€]: 111.975.260
- Generation from wind power plants [GWh]: 508
- Net import [GWh]: 3.748

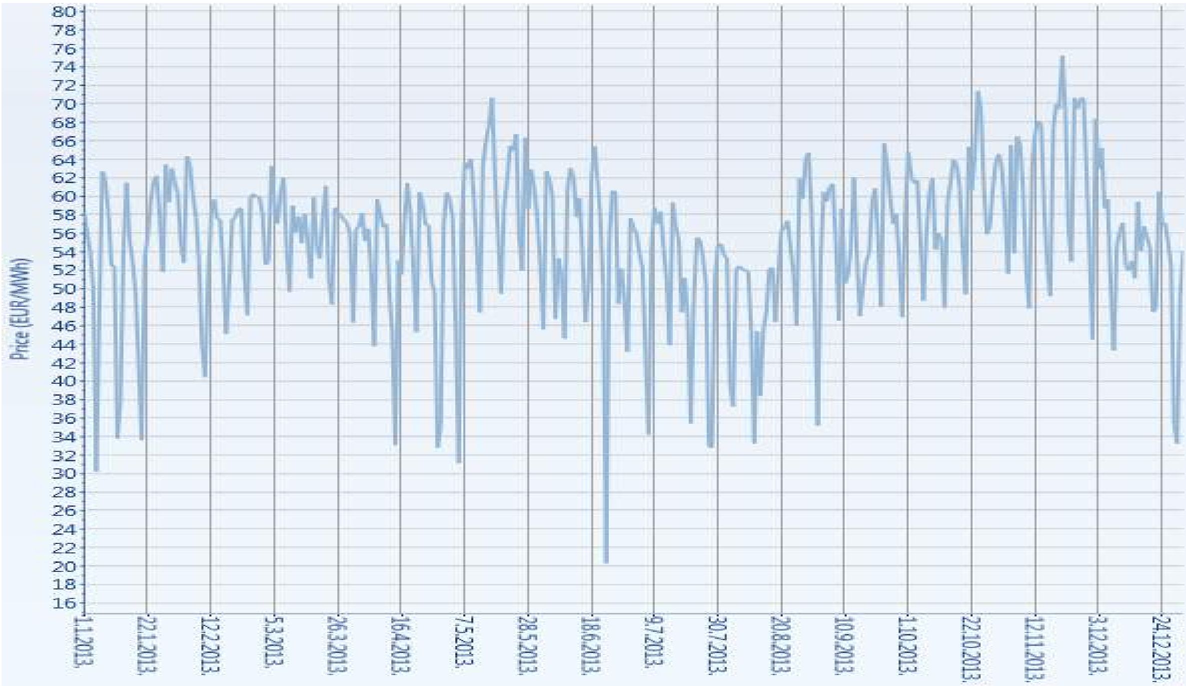


Figure 8-1: Daily average electricity price in the power system

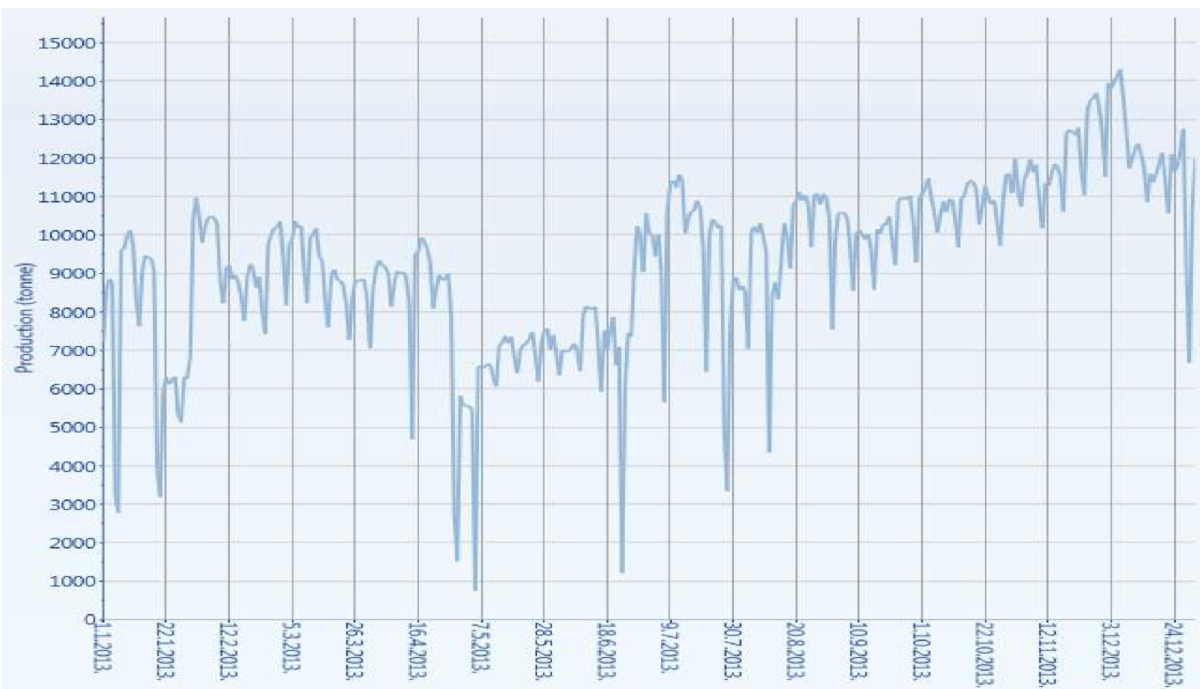


Figure 8-2: Daily amount of CO_2 emissions in the power system

Table 8-1: Annual generation costs for specific TPP in Croatian power system (in mill. EUR)

TE Rijeka	0	ELTO Zagreb blok A	6,334
TE Sisak	0	ELTO Zagreb blok B	11,030
TETO Osijek	11,871	ELTO Zagreb blok H	16,908
TETO Osijek PTA 1	0,022	ELTO Zagreb blok J	17,603
TETO Osijek PTA 2	0,048	KTE Jertovec GT 1	1,618
TETO Zagreb Blok L-GT	71,501	KTE Jertovec GT 2	3,398
TETO Zagreb Blok L-ST	0,908	KTE Jertovec ST 1	0,020
TETO Zagreb G3 (Blok C)	16,444	KTE Jertovec ST 2	0,056
TETO Zagreb G4 (Blok K-GT)	67,295	NE Krsko 1/2	111,975
TETO Zagreb G5 (Blok K-GT)	66,715	TE Plomin 1	18,148
TETO Zagreb G6 (Blok K-ST)	0,635	TE Plomin 2	57,067

Comparation of Base scenario (0 €/tCO_2) with scenario with medium emission price (7.5 €/tCO_2)

Figure 8-3: Comparation of daily net market sales – net electricity export (GWh) with lower (0 €/tCO_2, blue line) and higher (7.5 €/tCO_2, orange line) emission price

With increase of CO_2 price to 7.5 EUR/tCO_2, net electricity export represents a difference between electricity import and export, meaning that negative values on the figure present electricity import (Figure 8-3). The difference is very small.

Medium emission price scenario results (with comparation to the Base scenario – italic letters in brackets):

- Total emissions [tCO_2]: 3,312 *(0.972)*
- Average electricity price [€/MWh]: 55.79 *(1.005)*
- Hydro power plants [GWh]: 5,813 *(0.999)*
- Thermal power plants [GWh]: 3,002 *(0.994)*
- TPP Plomin 2 [GWh]: 1,647 *(0.950)*
- Total generation costs for TPP [€]: 323,633,000 *(1.042)*
- Total generation costs TPP Plomin 2 [€]: 65, 547,000 *(1.149)*
- Total generation costs NPP Krško [€]: 111,975,260 *(1)*
- Net import [GWh]: 3,854 *(1.028)*

Comparation of Base scenario (0 €/tCO_2) with scenario with highest emission price (14 €/tCO_2)

Figure 8-4: Comparation of daily net market sales – net electricity export (GWh) with lower (0 €/tCO_2, blue line) and higher (14 €/tCO_2, orange line) emission price

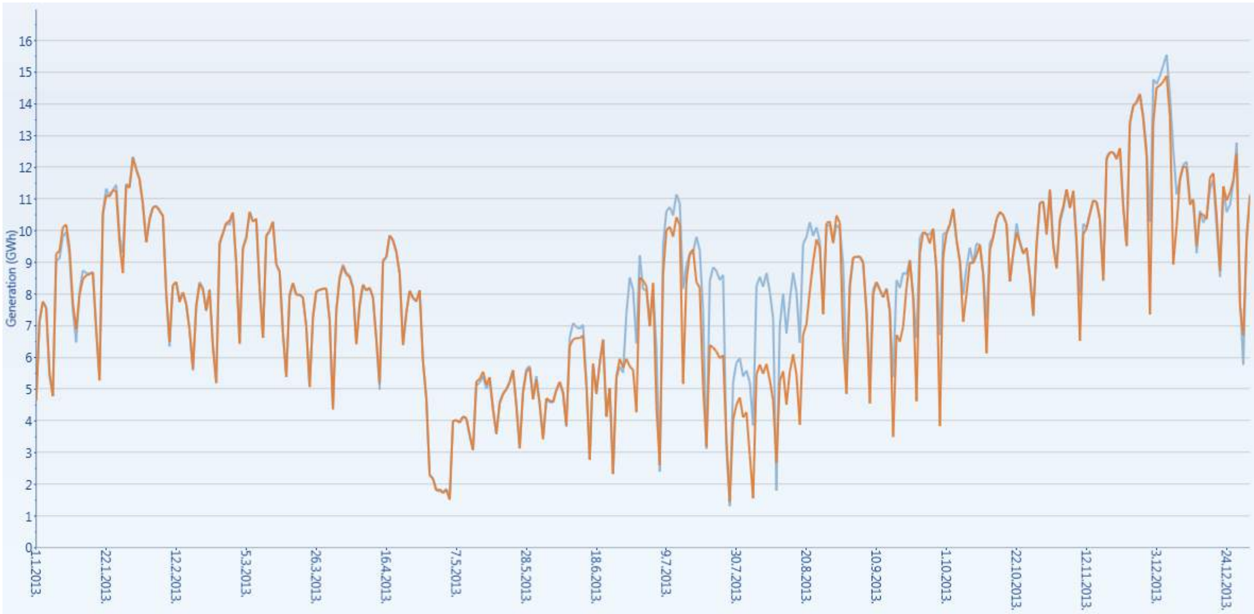


Figure 8-5: Comparation of daily generation from TPPs with lower (0 €/tCO_2, blue line) and higher (14 €/tCO_2, orange line) emission price

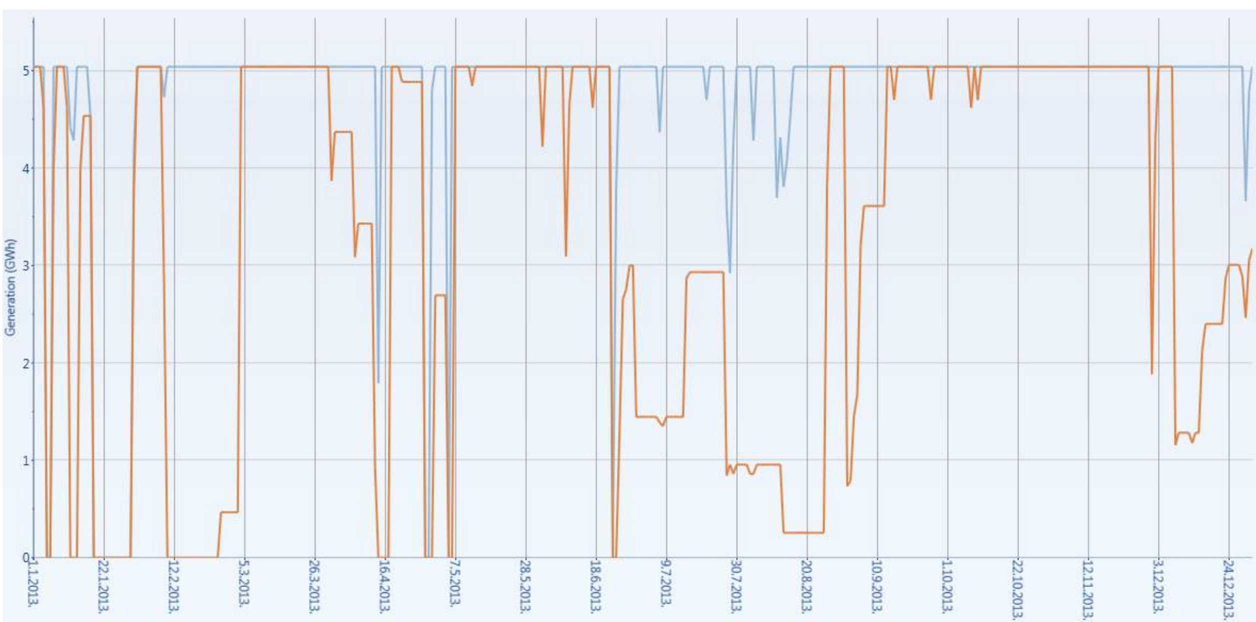


Figure 8-6: Comparation of daily generation from TPP Plomin 2 with lower (0 €/tCO_2, blue line) and higher (14 €/tCO_2, orange line) emission price

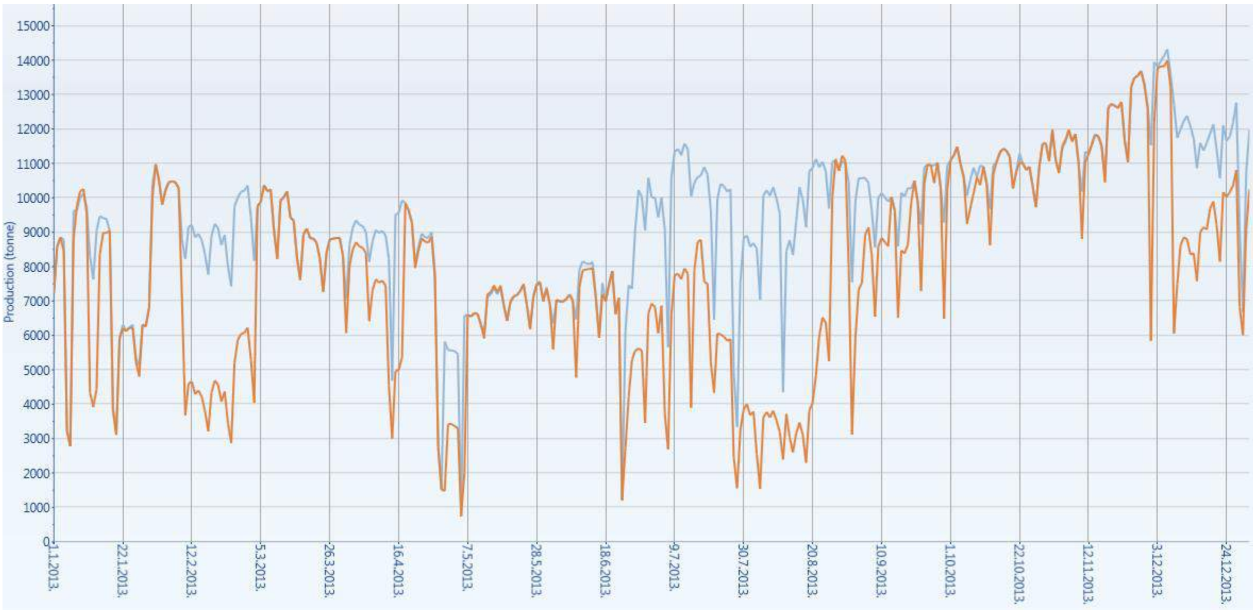


Figure 8-7: Comparation of daily amount of CO_2 emissions (in tons) with lower (0 €/tCO_2, blue line) and higher (14 €/tCO_2, orange line) emission price

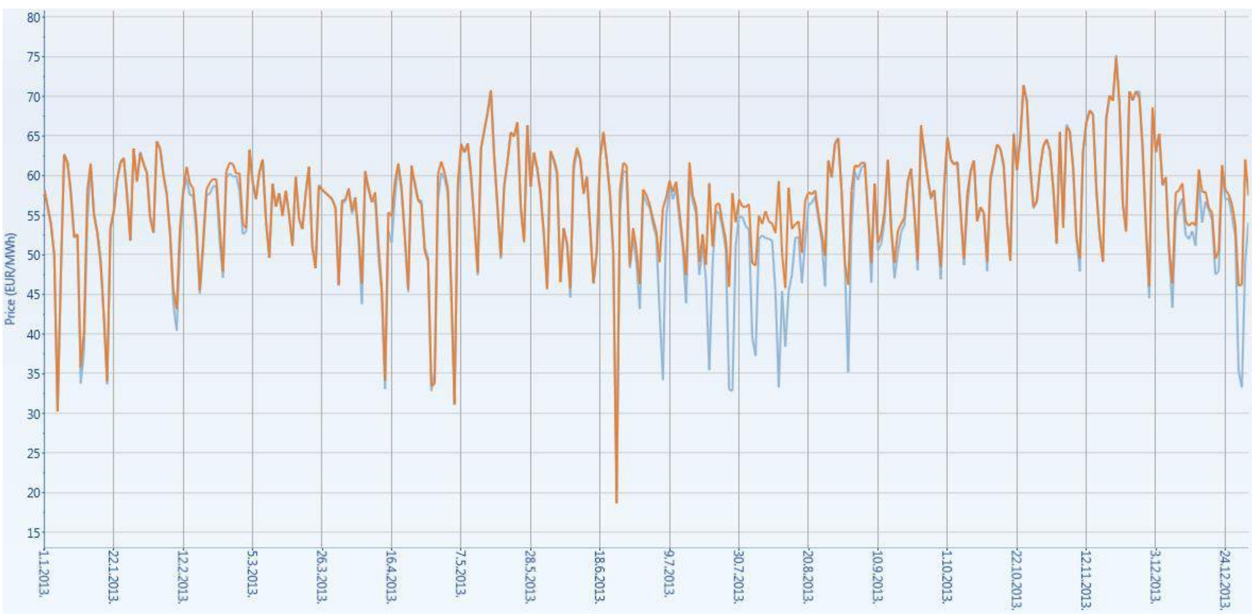


Figure 8-8: Comparation of daily average electricity price (€/MWh) with lower (0 €/tCO_2, blue line) and higher (14 €/tCO_2, orange line) emission price

One of the most important reasons for modest increase of electricity price (on the Figures above) is domination of external market – meaning that with emission price increase competitiveness of domestic thermal power plants is decreasing and they generate less electricity (which is offset by higher electricity import). Modeling results therefore indicate inflexibility (low competitiveness) of thermal power plants from Croatian power system on CO_2 emission price increase.

Higher emission price scenario results (with comparation to the Base scenario – italic letters in brackets):

- Total emissions [tCO_2]: 2,834 *(0.831)*
- Average electricity price [€/MWh]: 56.66 *(1.021)*
- Hydro power plants [GWh]: 5,814 *(0.999)*
- Thermal power plants [GWh]: 2,900 *(0.960)*
- TPP Plomin 2 [GWh]: 1,223 *(0.707)*
- Total generation costs for TPP [€]: 330,665,000 *(1.065)*
- Total generation costs TPP Plomin 2 [€]: 56, 310,000 *(0.987)*
- Total generation costs NPP Krško [€]: 111,975,260 *(1)*
- Net import [GWh]: 4,358 *(1.163)*

Conclusions on modeling emission price impacts on a Croatian power system in a year ahead period

Modeling emission price impact on a power system for a year ahead doesn't include investors' decisions as one year period is too short to have impact on a power system expansion. However, modeling results can be indicative for investors as they help in understanding competitiveness of existing power plants and how does it change with emission price increase. Once that model describes power system technical and economical characteristics, it can be also used for day ahead, weekly or medium term modeling (year ahead) – and in terms of modeling emission price impacts, it can help different groups (such as power system operator, power plant operator, electricity or emission allowance traders) to understand both short term, medium and long term implication of emission price increase on a power system.

Impacts of emission price increase on a power system and /or power plant cannot be analyzed separately but generation and trade should be optimized with price developments on other connected markets (external electricity markets, coal/gas/oil markets, technology markets…). Market of fossil fuels and its prices have direct, and emission markets and its prices have indirect impact on power plants` generation costs. Electricity markets have impact on electricity import and export, and therefore on power plant generation (but also emissions from power plants). These three markets are closely interlinked and should be analyzed together. Other important factors on a power system that need special attention then modeling emission price impacts are power system consumption (daily, weekly and annual load curves), hydrology impact on generation from hydro power plants, constraints with fuel (market and physical), transmission line capacities etc.

Description of Croatian power system in model PLEXOS is a basis for further long term power system modeling. It is designed and built to enable assessment of emission trading impact on a power system. Proposed model and model description along with set constraints enables modeling of various factors on short term and medium term optimization of a power system through describing following technical and economical parameters:

Initial accumulation volume – based on the real data on accumulations in hydro power plants. Important for short and medium term optimization;

Water inflows in hydro power plants – based on hydro meteorological predictions and forecasts helps in modeling short and medium term hydro production;

Fuel prices – can change on a monthly bases (gas) or upon delivery (coal), so describing these parameters influences both short and medium term planning;

Electricity price – based on “forward” contracts, highly predictable for short and medium term modeling of electricity price on the market;

Emission allowance price – similar as for electricity, based on “forward” contracts, highly predictable for short and medium term modeling;

Consumption – various predictions can help in modeling expected consumption change (and load curves) in short, term but also long term period (with high uncertainties);

Planned outages – maintenance outages for power plants can precisely describe in the model when some power plant would be out of work in short and medium term (or this can be optimized based on other data such as expected consumption). As for unexpected outages, probability of expectation and durance of maintenance can be also modeled;

Contracts for electricity purchase/sell – amount and price of traded electricity on an annual, monthly or day ahead basis can be inputted in the model which helps in realistic description of short and medium term power system optimization.

Mentioned parameters can be described in the model with high probability in a short term optimization that enables operative optimization of a power system concerning electricity trade, emissions, etc. With less probability it can help in precise power system description in medium term optimization (from one week to one year) and with even much lower probability for long term planning (longer than one year).

Emission allowances are initially purchased on an annual basis and then their quantity is modified on a shorter term basis according to difference between annual emission plan and real emissions. This enables defining average emission price, but also enables assessing impacts on generation costs of power plants on annual basis. It is therefore important to have medium term modeling on an annual basis.

But, investment decisions start from annual basis to longer period, and demand for modeling long term power system planning. Based on solid power system description and describing power plant candidates, it helps to understand possible emission trading impacts on power system development and how does it influence competitiveness of existing power plants, but even more new planned power plants - both those based on fossil fuels and low emission technologies.

8.1.2. Results from modeling impact of emission price on power system planning by year 2020

Results from power system modeling by 2020 presented in this subchapter are based on modeling inputs described in subchapter "7.2.3. Defining list of new power plant candidates for modeling long term development of Croatian power system until 2020".

As previously explained, three different scenarios were constructed based on combination of technologies to put strongest focus:

- White scenario focuses on coal and nuclear power plants;
- Green focuses on gas and nuclear; while
- Blue focuses on coal and gas.

Scenarios were constructed in such a way as if they rely only on one technology (nuclear, gas or coal) this would affect strongly energy security issues.

Table 8-2: Forecasted start up dates of new power generation units by 2020 according to the White Scenario. Source: [163]

FACILITY/UNIT / PART OF	NOMINAL POWER ON GENERATOR, MW	YEAR IN OPERATIO
TE-TO Zagreb unit L	100	2009
TPP Sisak unit C	250	2012
TPP GAS 1	400	2013
TPP COAL 1	600	2015
NUCLEAR 1	1000	2020
COGENERATION	Progressive yearly increasing by 30 MW, additional total 300 MW	2011-2020
HPP other	Progressive yearly increasing by 50 MW, total 300 MW (0,75 TWh new energy from HPP)	2015 – 2020
Renewable	1545 MW Renewables with production of 4000 GWh in 2020 - 154 MW progressive annual growth	2011 – 2020
Total GAS	1050	
Total COAL	600	
Total NUCL	1000	
HPP + REN	1845	

The difference between White scenario (Table 8-2: Forecasted start up dates of new power generation units by 2020 according to the White Scenario) and other scenarios is that instead of 600 MW coal-fired power plant scheduled for 2015 and 1000 MW nuclear power plant scheduled for 2020 they forecast these power plants and scheduled dates (all other details such as generation from renewables, hydro, cogeneration and old power plants remain the same):

- Blue scenario schedules 2 TPPs firing coal, 600 MW in 2015 and 600 MW in 2019, and 400 MW from TPP firing natural gas in 2020;
- Green scenario schedules 400 MW TPP firing natural gas in 2015, and one 1000 MW nuclear power plant in 2020.

Modeling results are presented in Figures below.

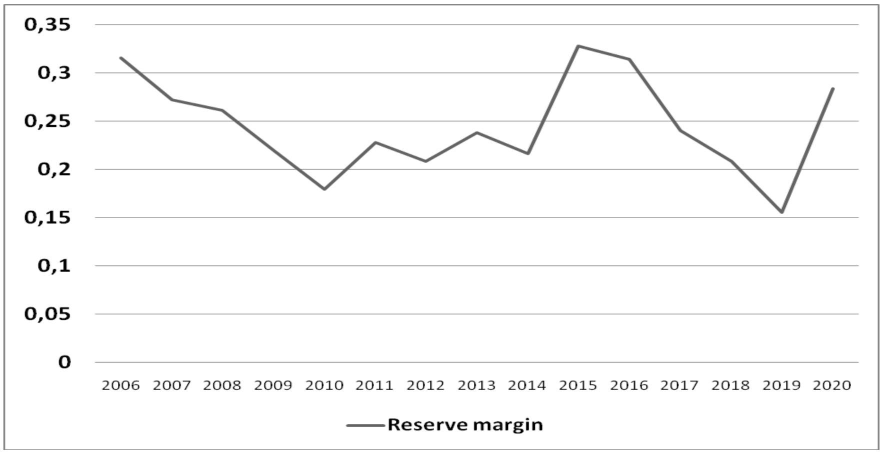


Figure 8-9: Reserve margin in White scenario fluctuates between 16% and 33% of installed capacity. Source: [163]

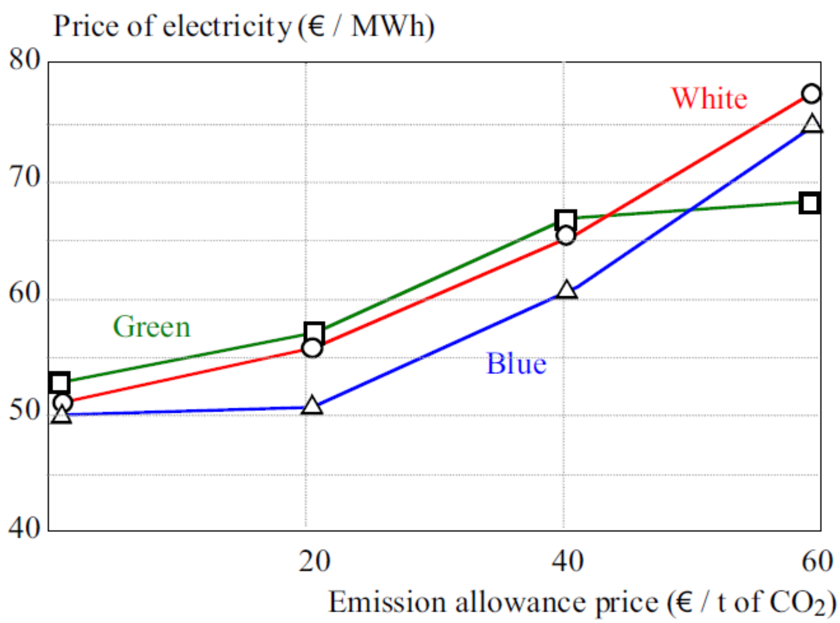


Figure 8-10: Impact of emission price on electricity price in three modeled scenarios (Green, Blue, White) in 2020

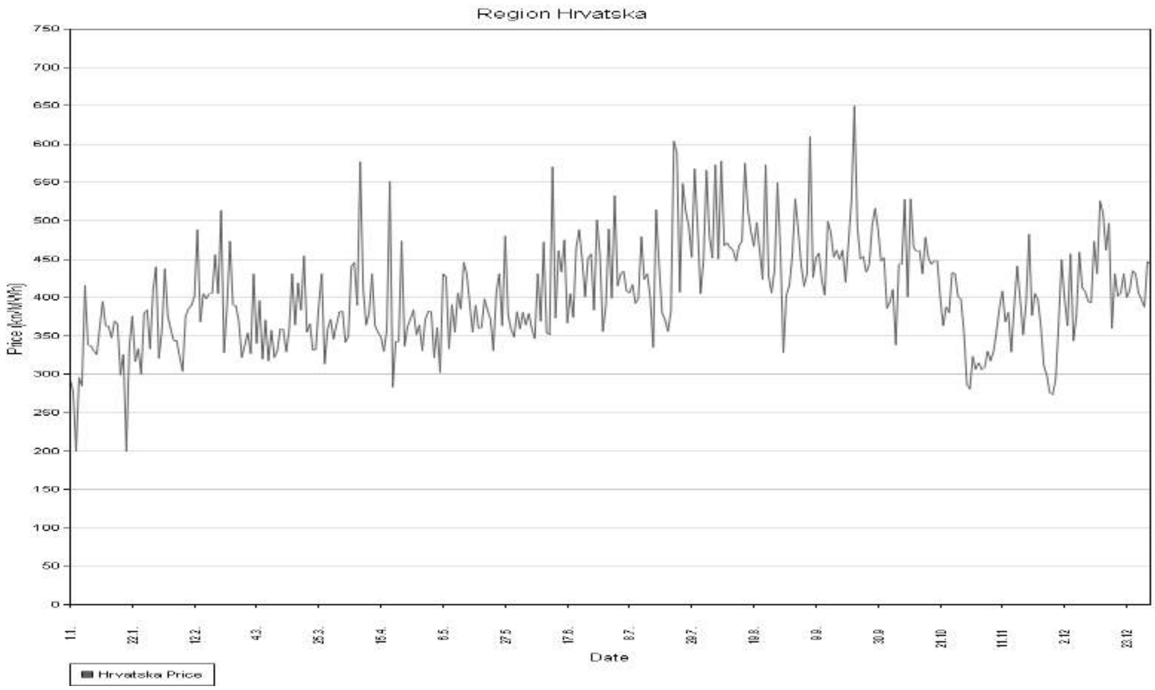


Figure 8-11: Daily amounts of electricity prices in White scenario in year 2020 – summer months have higher prices because of low production from hydro power plants

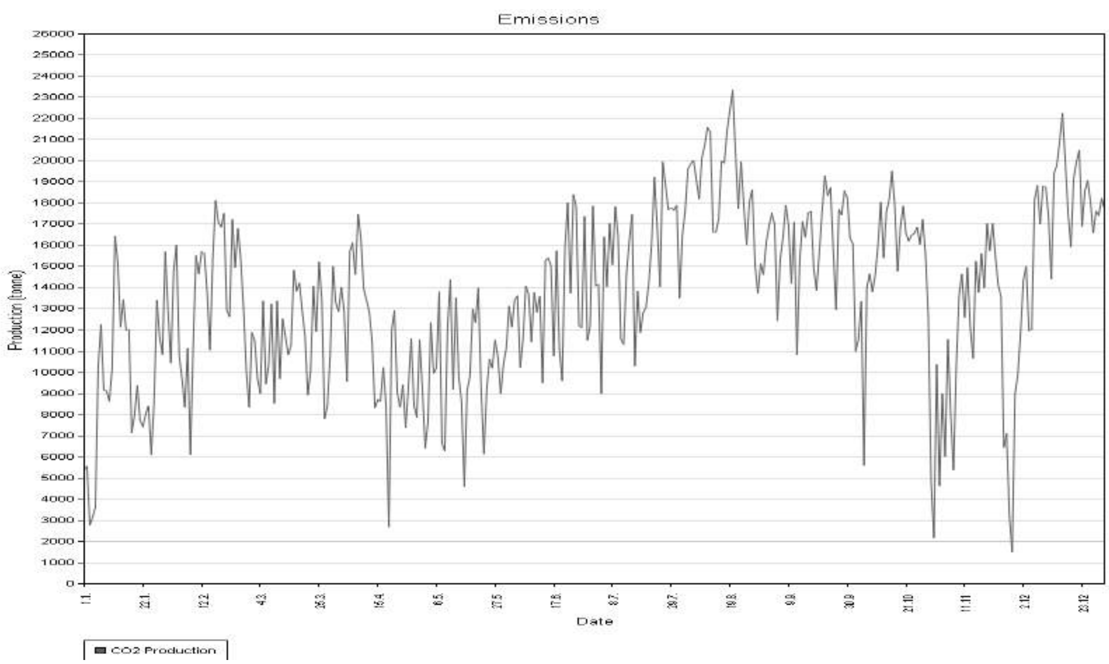


Figure 8-12: Daily CO_2 emission in White scenario in year 2020

As shown in the Figure 8-13, such power system development would mean that only Green scenario with inputs defined would meet the Kyoto obligations in both 2015 and 2020, and more effort would need to be put in energy efficiency and renewable energy sources - otherwise emission reduction would have to be met by purchase on emission trading markets.

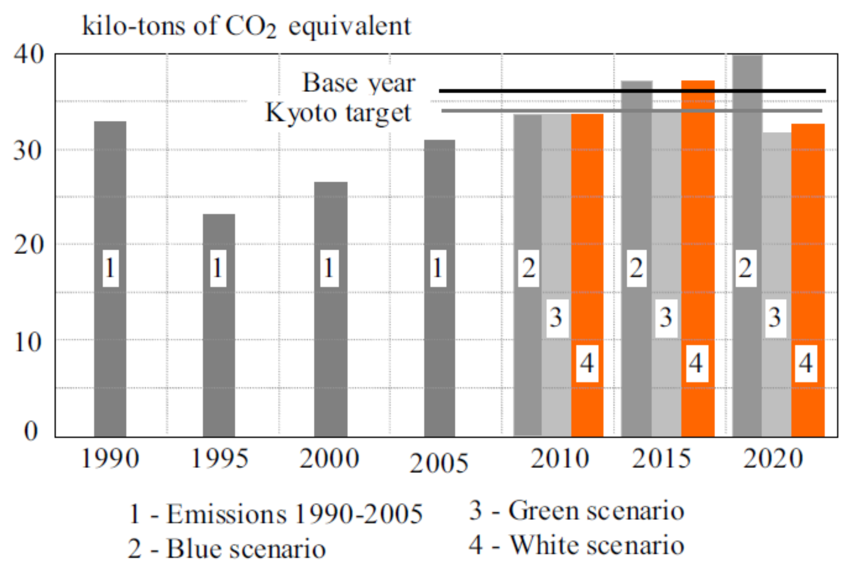


Figure 8-13. Influence of different scenarios on Croatian Kyoto targets (electricity sector added to total of other sectors) – in year 2015, only green scenario is meets target, while in 2020 white and green scenarios are under Croatian Kyoto obligation

Conclusions from modeling Croatian power system development until 2020

Dynamic CO_2 price impacts on three different scenarios in chapter were modeled for year 2020. Assessment made for emission price ranging from 0–60 E/tCO_2 has shown how electricity prices and total emission amount react responding to emission price.

Concluding, power system modeling in the long term period can provide help in understanding several aspects:

- Emission amount from the power system in the future;
- Expected emission trading impact on electricity price;
- Rise in generation costs from power plants based on fossil fuels.

Indirectly, modeling can help to analyze rise of competitiveness of low emission technologies, and rise in their investments in a power system.

8.1.3. Results from modeling impact of emission price on competitiveness of nuclear power plant within Croatian power system between 2020 and 2025

This subchapter presents results of modeling described in subchapter “7.2.4. Modeling impact of emission price on competitiveness of nuclear power plant within Croatian power system between 2020 and 2025”.

Results presented in this chapter are showing impacts of CO_2 price on competitiveness of nuclear power plant within Croatian power system between 2020 and 2025. Two different scenarios have been set to analyze it:

- Scenario without nuclear (Blue);
- Scenario with nuclear power plant (White).

  Two cases were modeled for each scenario, regarding CO_2 price. It means all together four cases were modeled and analyzed:

- Case 1: Blue scenario with 0 €/tCO_2;
- Case 2: Blue scenario with 40 €/tCO_2;
- Case 3: White scenario with 0 €/tCO_2;
- Case 4: White scenario with 40 €/tCO_2.

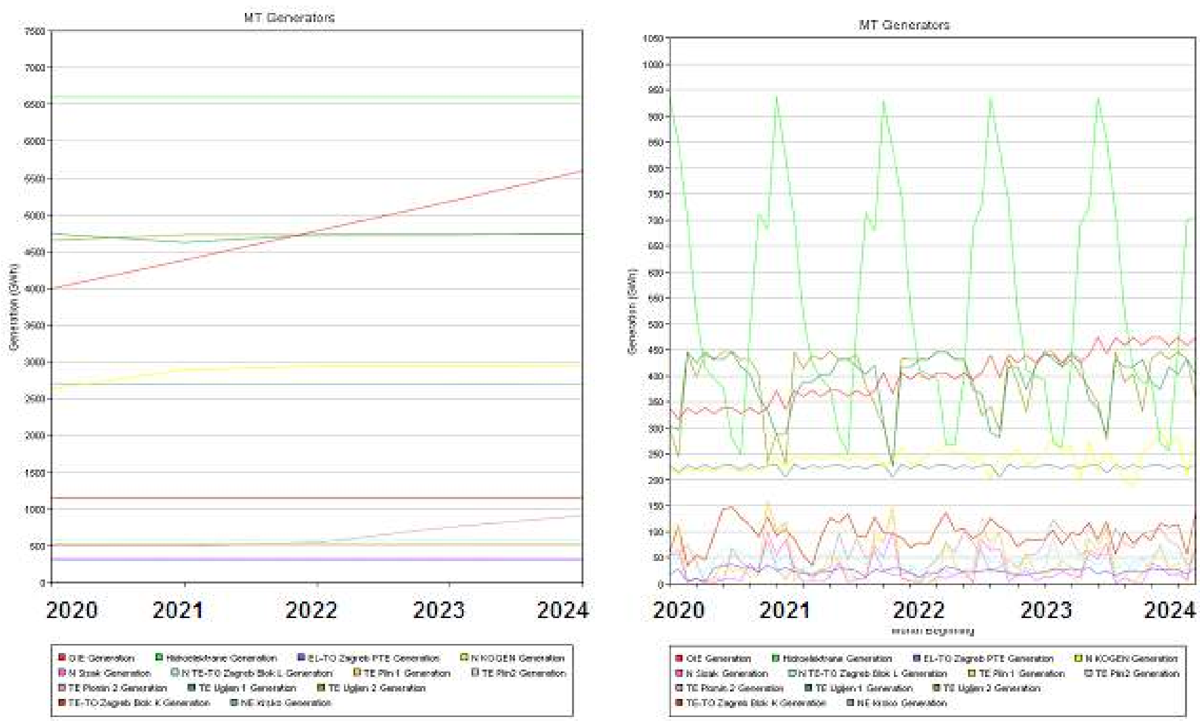


Figure 8-14: Generation of power plants in Blue scenario - annual and monthly values of generation during 2020-2025

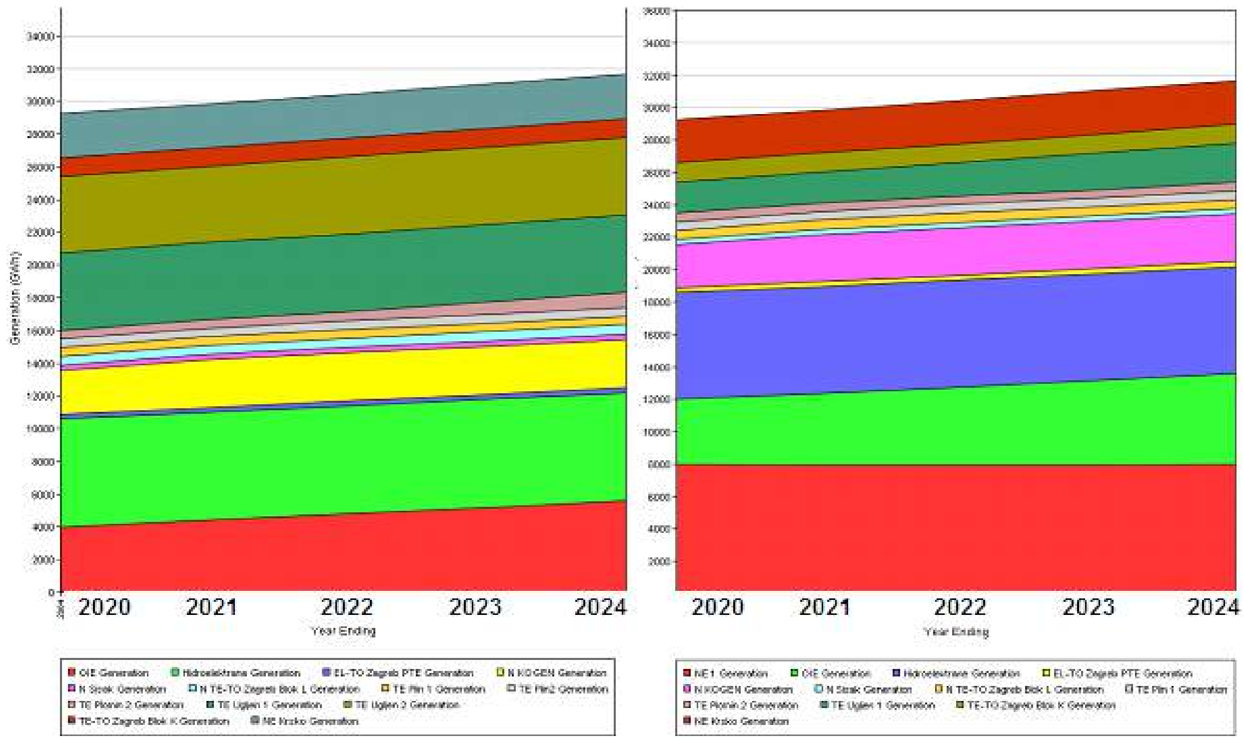


Figure 8-15: Annual generation of power plants within Blue and White scenarios during 2020-2025

In the Figure 8-15 above, for Blue scenario (on the left) red bar represents renewables and green represents hydro. Red bar in White scenario (right side) at the bottom represents new nuclear capacity which generates most of the energy in the system along with renewables (green bar) and hydro (blue bar).

Results in Figure 8-16 are indicating that the introduction of nuclear power plant in the scenario (1000 MW instead of one nuclear and one gas power plant) means nearly 6 MtCO_2 emissions less annually and gives possibility to achieve Kyoto target (for which Croatia was already missing by 2.6 MtCO_2 in 2007).

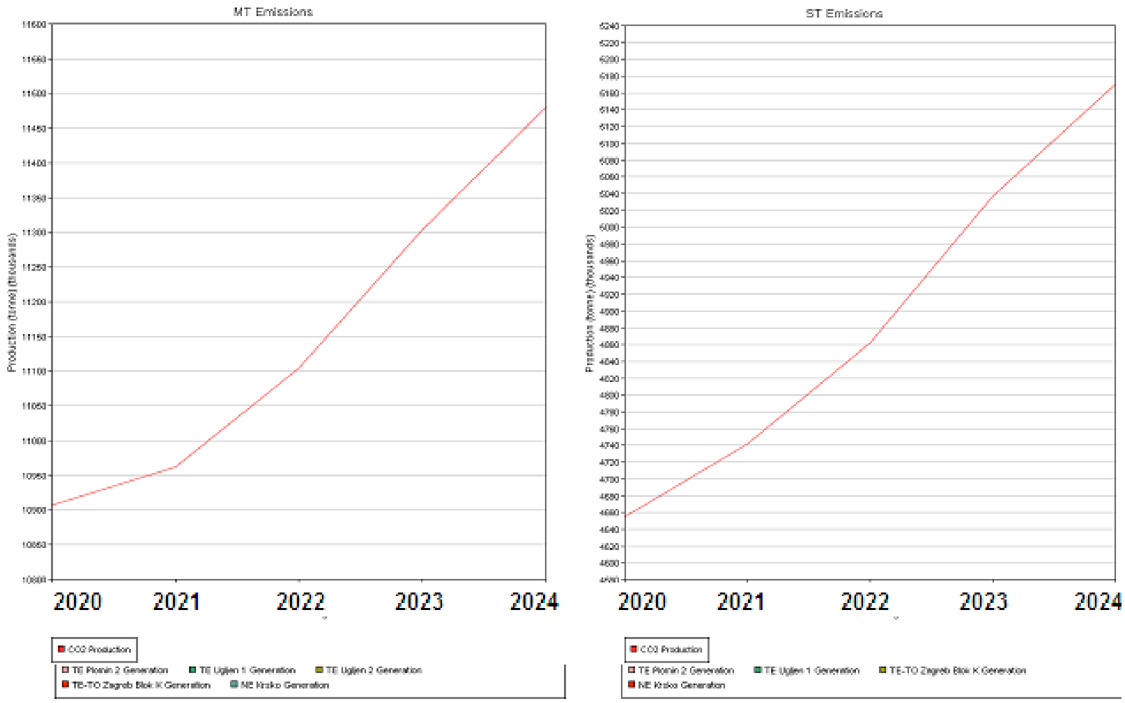


Figure 8-16. Annual rise in emissions within Blue and White scenarios during 2020-2025

The difference in emissions for two scenarios is seen from the figure above – emissions in Blue scenario (left side) start from 10.9 MtCO_2 in 2020 and grow up to 11.5 MtCO_2 in 2024. Emissions in White scenario are much lower – from 4.6 MtCO_2 in 2020 until 5.2 MtCO_2 in 2024. It means that nuclear scenario means approximately 6.5 MtCO_2 emissions which represents nearly 22 % of Croatian Kyoto target.

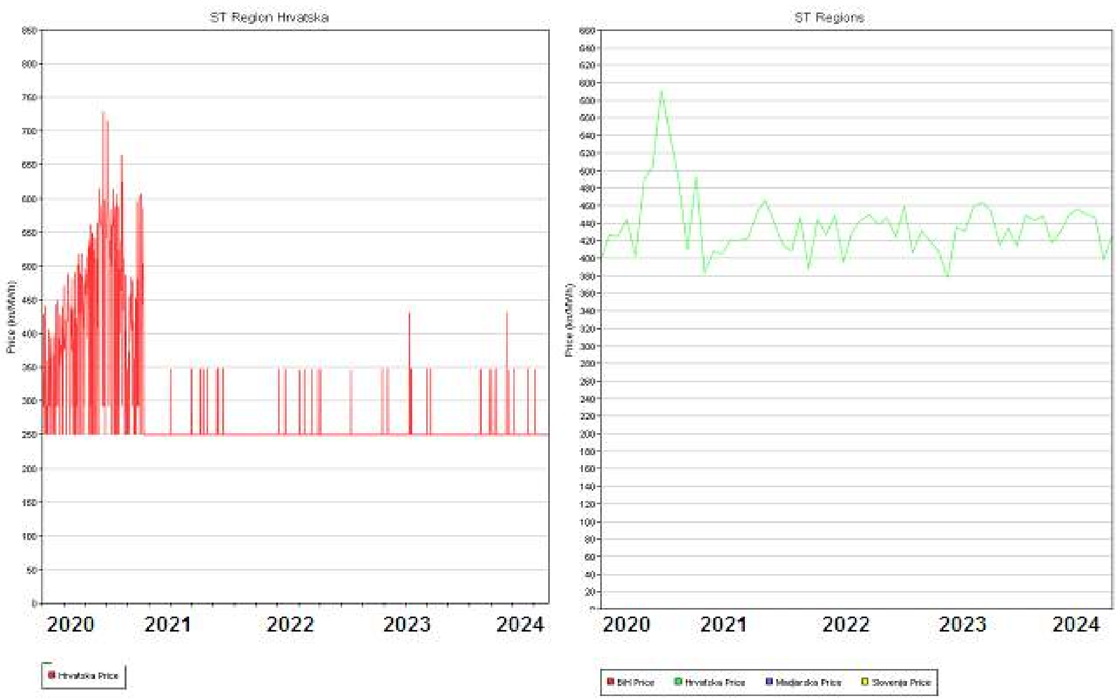


Figure 8-17: Short-term electricity price change (expressed in HRK: 1 € = 7.5 HRK) in White scenario during 2020-2025 for a case without emission price and with 40 €/tCO_2 (in first picture daily values for a case without CO_2 price are shown; in second monthly average values for a case with 40 €/tCO_2)

Conclusions from modeling impact of emission price on competitiveness of nuclear power plant within Croatian power system between 2020 and 2025

Goal of this modeling was to analyze emission price impact on rise of competitiveness of low emission technology in the future – nuclear power plant. Results are showing the following:

- Introduction of nuclear power plant in modeled scenario (1000 MW instead of power plants based on coal and gas) means nearly 6 MtCO_2 emissions less annually and gives more room to achieve emission reductions and emission targets in the future;
- Results are also showing how increase in CO_2 price is enhancing competitiveness of a nuclear power plant by increasing long term marginal costs of power plants that use fossil-based fuels. Even with higher investment costs, nuclear option is more competitive than any other with CO_2 price higher than 10 €/tCO_2.

8.1.4. Results from modeling intermittent low emission technologies in PLEXOS: wind power plant in Croatian power system

This subchapter presents results of modeling described in subchapter "7.2.5. Modeling intermittent low emission technologies in PLEXOS: wind power plant in Croatian power system", and are also presented in [139].

As previously explained, modeling was done within modeled power system in 2020 (described in subchapter 6.2.2.), and two scenarios were developed:

- scenario A (that models wind generation linearly),
- scenario A2 which includes 1140 MW of wind capacities with average capacity factor of 22%, on the basis of extrapolated real time hourly data of the first Croatian wind power plant Ravna 1 on island Pag (wind target from Croatian Energy Strategy is 1200 MW).

Some initial results of the correlation between the production and the consumption are shown in Figure 8-18, as well as the influence on electricity market price in Figure 8-19.

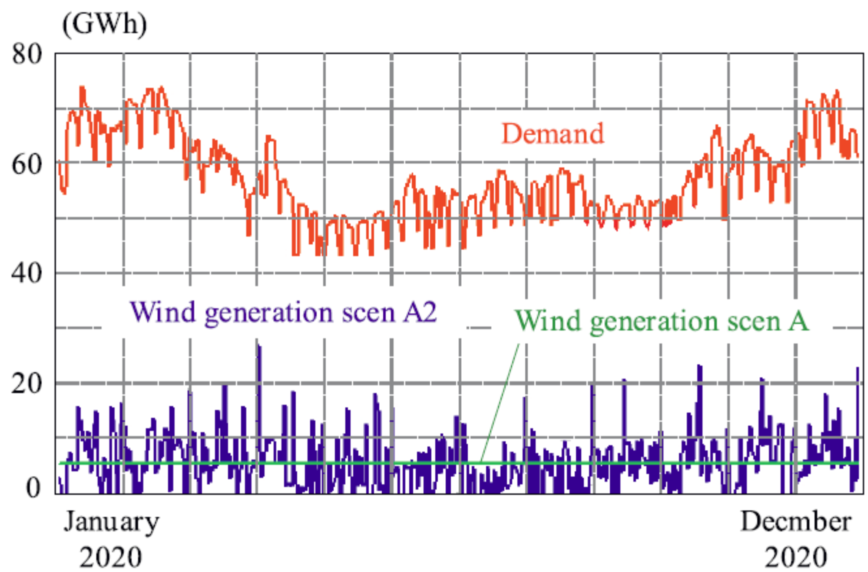


Figure 8-18: Initial results of simulation of daily wind power production and consumption in Croatian power system in 2020. Source: [139]

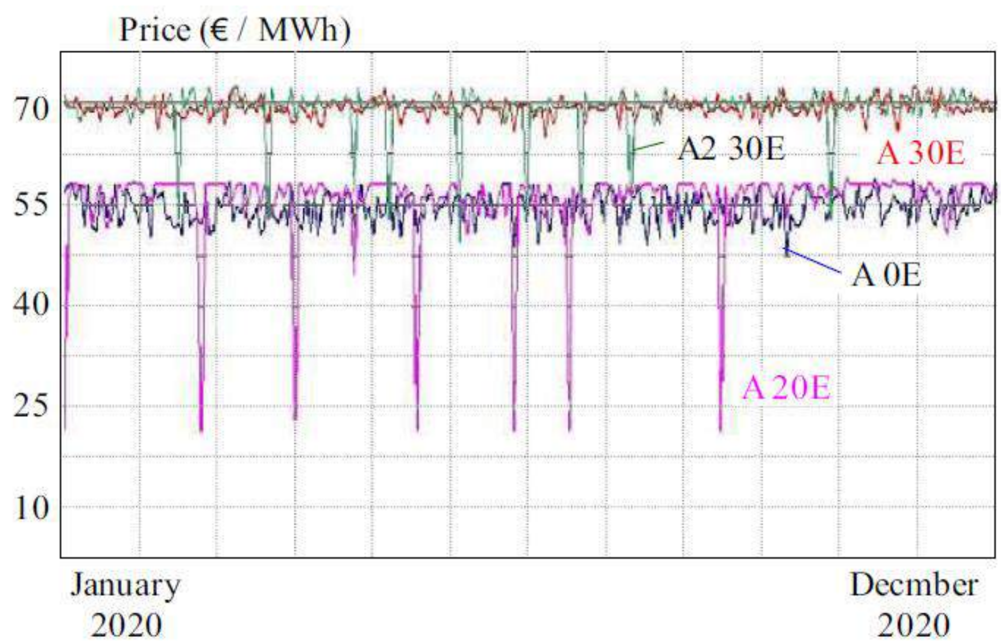


Figure 8-19: Initial results of simulation of the impact of wind power production on the prices in Croatian power system in 2020 on two simulated scenarios (A and A2) and with two emission prices (0 and 30 EUR/MWh). Source: [139]

Conclusions from modeling intermittent low emission technologies in PLEXOS: wind power plant in Croatian power system

As an intermittent source, wind power plants have large influence on power system. Therefore there is a demand for advanced planning models which might help to understand how power system can regulate large wind generation.

Results have shown that power market simulator PLEXOS can be used as tool to simulate and quantify how wind power influences the power spot price due to its low marginal cost as shown in Figures above. However, further research is needed in order to improve initial model of Croatian electrical system as well as wind generation input data by including wind power plants that have been recently put in operation.

8.2. Impacts on sustainable development indicators

In order to test developed model described in chapter “7.3. Model for estimation of sustainable development impacts”, it was applied on three scenarios proposed in chapter 7.3. Table below shows results - three various scenarios based on achieving from Croatian Energy Strategy until 2020 (in this case, targets are the same in all scenarios, but the role of domestic component to achieve them is different). Modeled target for installed capacity of fossil based power plants is decreased from 1200 MW (from scenario described in 7.2.) to 500 MW due to lower consumption increase rate.

These scenarios modeled in proposed model to understand how share of domestic component is influencing sustainable development indicators. These three scenarios are proposed to embody three different approaches – starting from very low share of domestic component in Low scenario S1, to very high in High scenario S2 and Moderate scenario S3 in the middle.

8.2.1. Energy produced and saved

Energy efficiency in buildings showed potential to increase energy efficiency by saving almost 16 PJ by 2020. In terms of energy production, planned coal and gas power plants have the highest production potential. Regarding low-carbon technologies, wind power plants can produce around 8.5 PJ, biomass CHP 7 PJ, followed by investments in biofuels, biomass heating, waste CHP, solar thermal and others as shown in Figure 8-20.

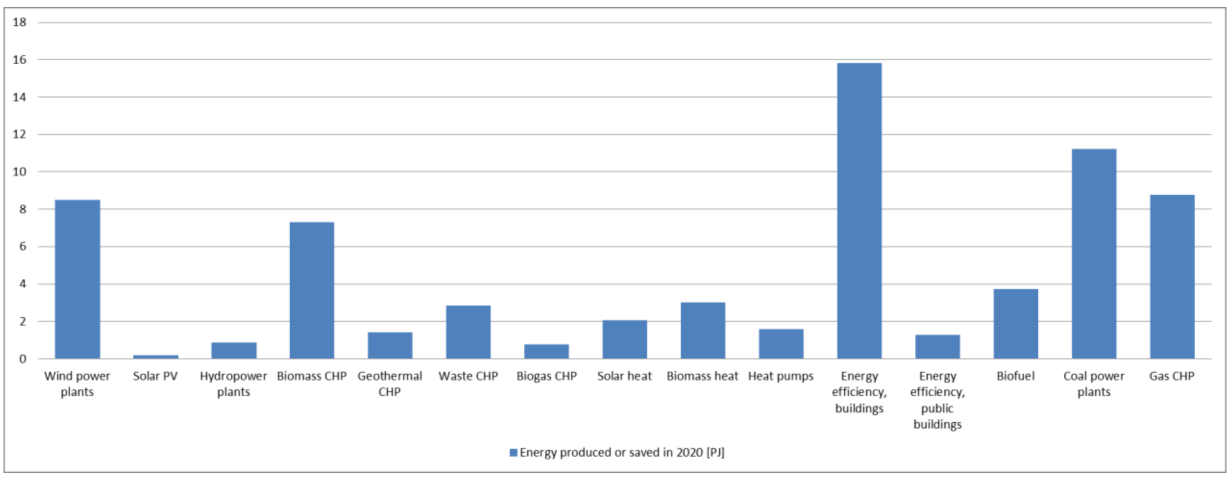


Figure 8-20. Results from modeling new energy produced or saved in 2020 [PJ], Scenario S3

In terms of the type of new energy produced or saved (Figure 8-21), most of it falls under heat energy and electrical energy. It is followed by a smaller amount on liquid biofuels.

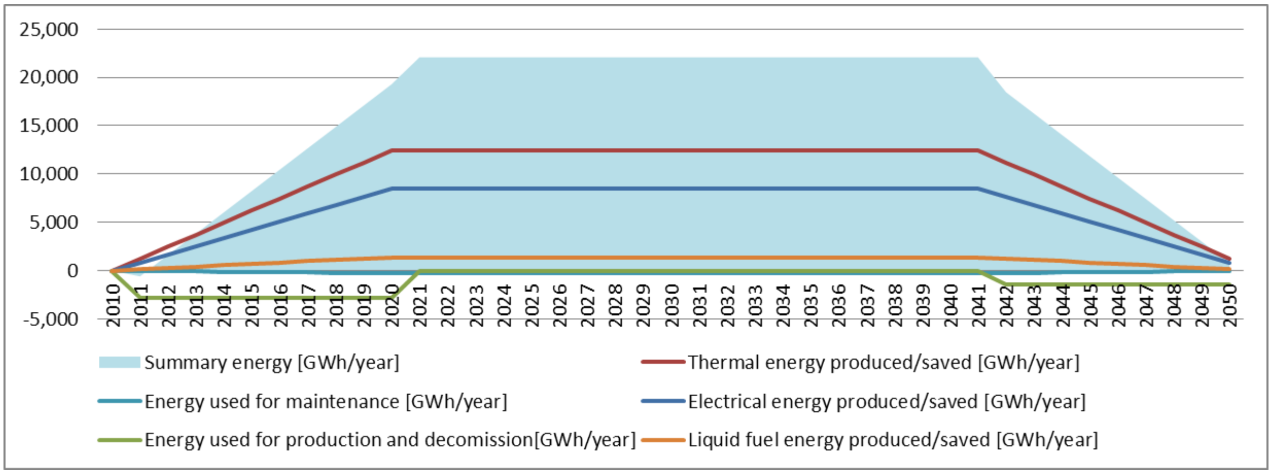


Figure 8-21 Energy produced and saved in lifetime of technologies supported, Scenario S3

8.2.2. GHG emissions produced and saved

The highest potential for reducing GHG emissions lies in planned new wind power plants and energy efficiency in the building sector: around 20,000 tCO_2 in the lifetime of technologies supported. It is followed by emission reductions from biomass CHP and biofuels for transport, around 18,000 tCO_2.

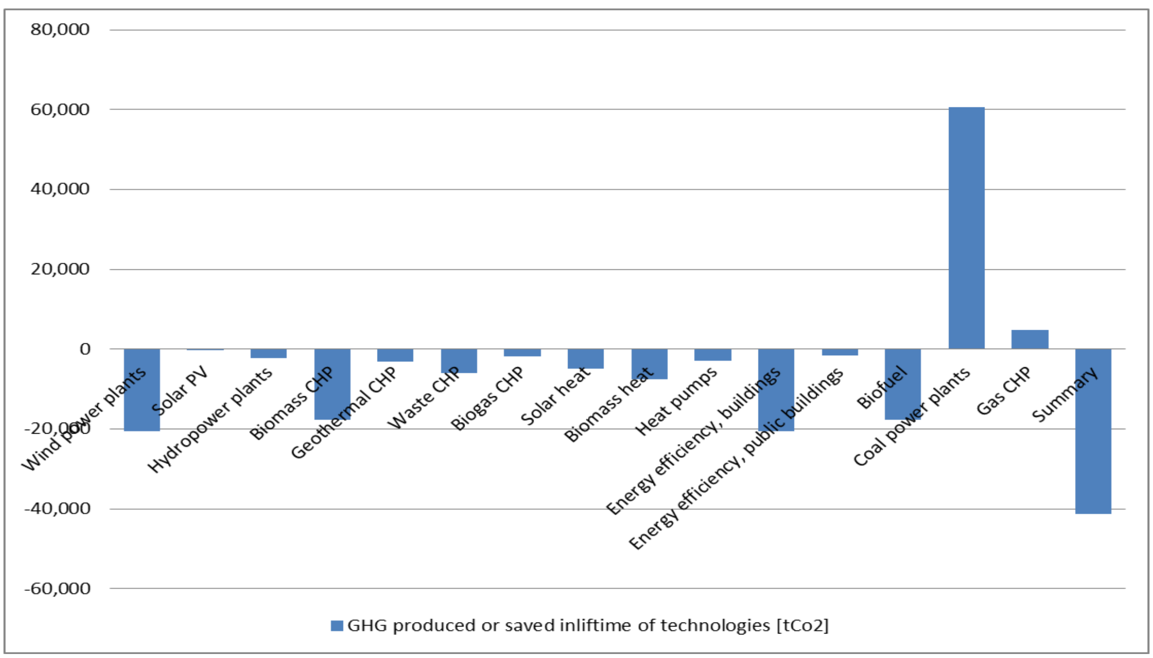


Figure 8-22: GHG emissions saved or produced in lifetime of technologies

In contrary, planned investments in fossil fuel fired power plants are expected to increase CO_2 emissions (coal power plant by 60,000 tCO_2 during the lifetime of the power plant). However, considering consequences of all measures, the CO_2 emission level is expected to decrease compared to the present average.

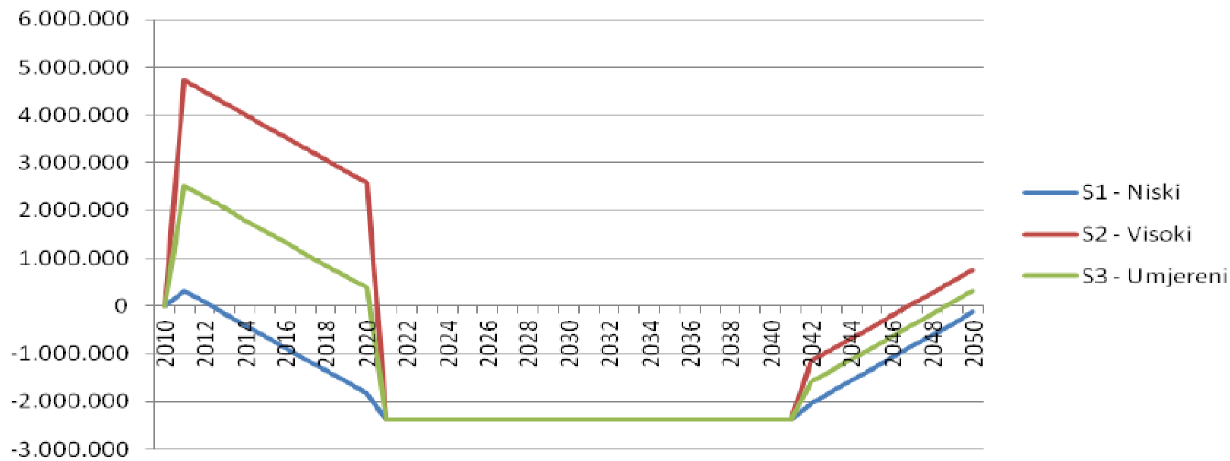


Figure 8-23: Annual total emissions for three scenarios until 2050

In second and third scenario there is initial increase of GHG emissions as a result of industrial activities (higher share of producing domestic technology).

8.2.3. Modeling results for new jobs created

The number of jobs created in 2020 varies significantly through scenarios. From 5,083 jobs in Scenario S1 to 16,242 jobs in Scenario S2.

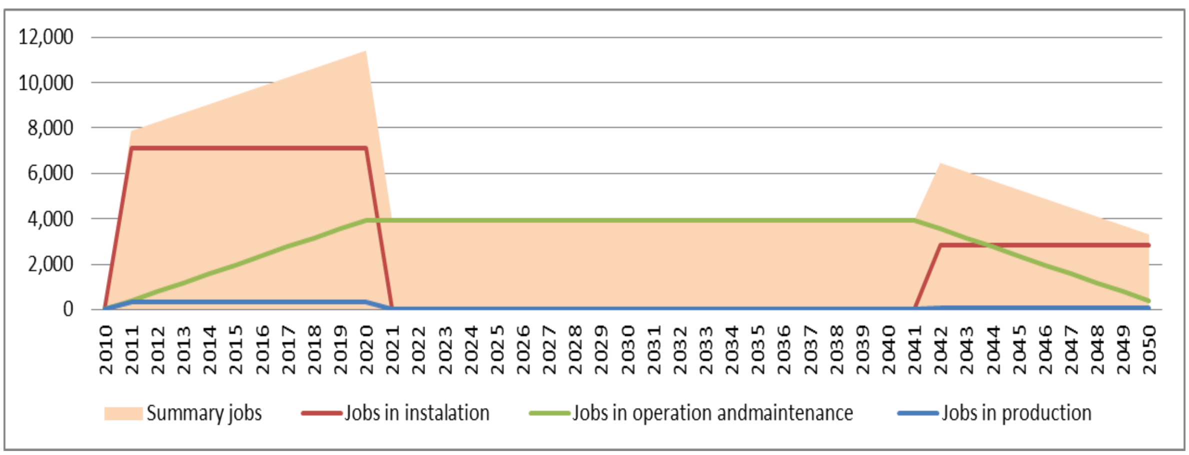


Figure 8-24. New jobs created in life-time of technologies, Scenario S3 – Moderate

Most of the jobs are created during the investment phase (Table 8-3). Different distribution of jobs between measures during the lifetime of technologies is important for the calculation of effects on direct employment during the lifetime of technologies.

Table 8-3: New jobs per year created in scenarios

	Scenario S1 - Low	Scenario S2 - High	Scenario S3 - Moderate
Wind power plants	146	528	367
Solar PV	29	104	72
Hydropower plants	14	61	41
Biomass CHP	109	281	222
Geothermal CHP	5	14	11
Waste CHP	18	48	37
Biogas CHP	8	21	17
Solar heat	96	320	229
Biomass heat	707	1,787	1,424
Heat pumps	51	165	119
Energy efficiency, buildings	3,377	11,316	7,721
Energy efficiency, public buildings	271	907	619
Biofuel	232	600	473
Coal power plants	20	71	50
Gas CHP	3	19	11
Summary 2020	**5,083**	**16,242**	**11,412**
Summary in lifetime of technologies	**121,360**	**334,271**	**242,334**

8.2.4. Monetary costs and benefits in lifetime of technologies for the society

Figure 8-25 shows a distribution of cost and benefits for the society during the lifetime of technologies supported by policy measures. It is obvious that with the type of support mechanisms described earlier, the society has to invest more during the period of investment in Scenario S3. In this period investment by the society: cost of incentive purchase price and cost of GHG emitted in industrial manufacturing for production of technologies with a moderate share of domestic production, is higher than benefits from VAT, taxes on earnings and social benefits (that go back to the benefits of the society).

However, after 2020, when the investment period for these measures ends, the State starts to experience more benefits in terms of collected taxes on earnings, lower price of energy for the society because of expiration of the period with the incentive purchase price for renewable energy producers of electricity. Besides those, the society can enjoy lower GHG emissions and jobs created in operation and maintenance of technologies.

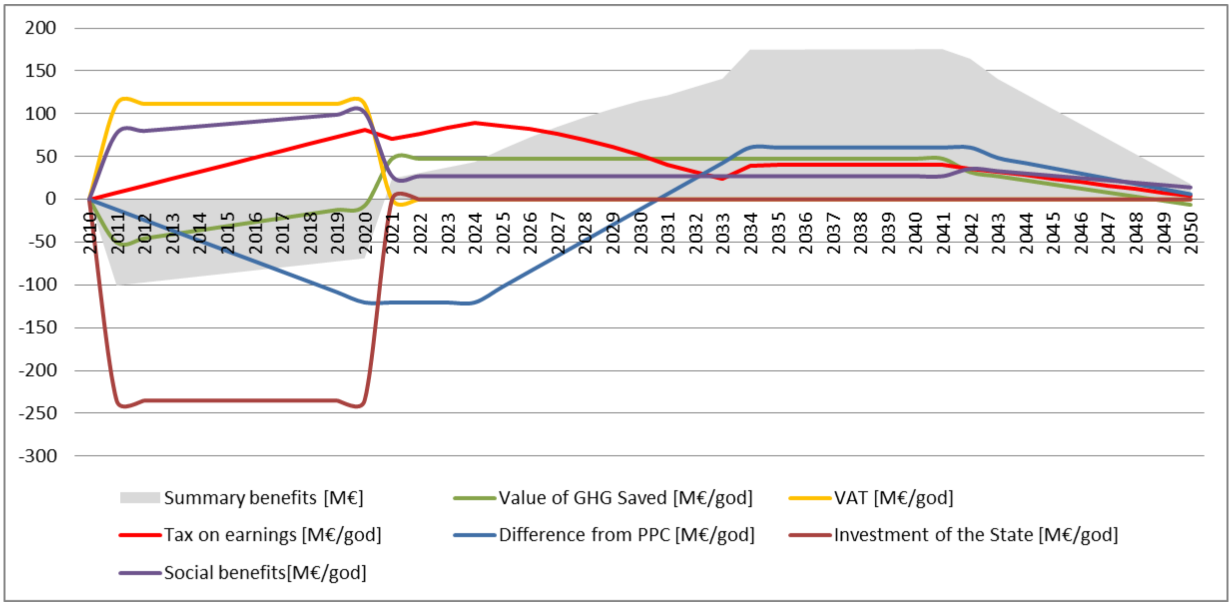


Figure 8-25: Costs and benefits during the lifetime of technologies, Scenario S3 - Moderate

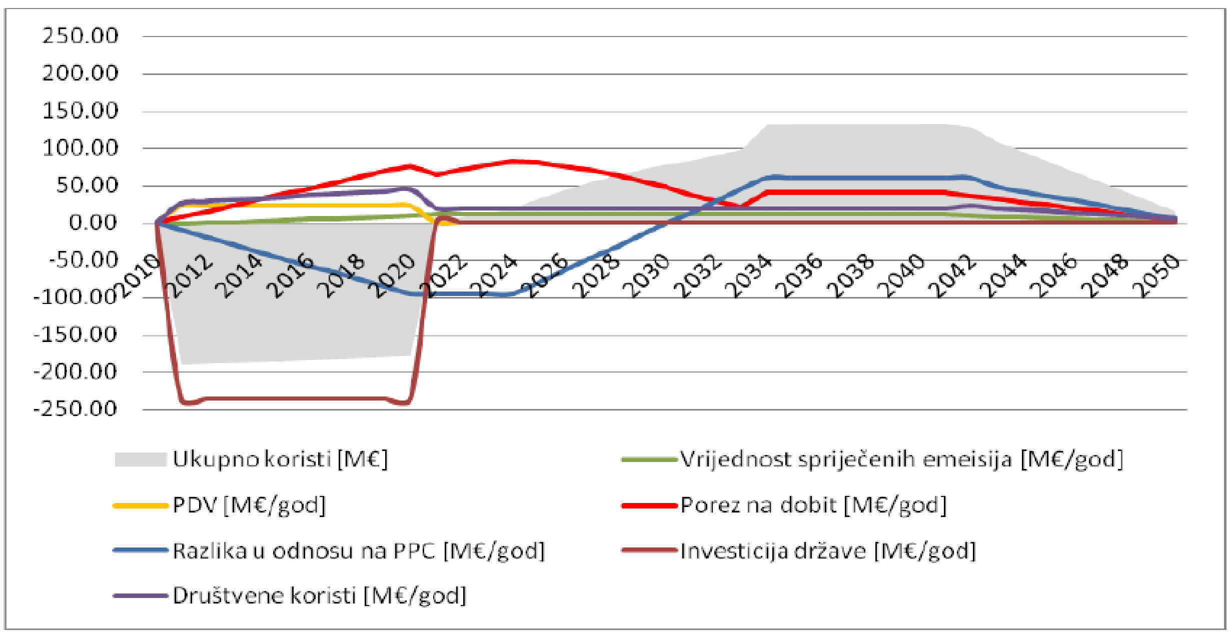


Figure 8-26: Costs and benefits during the lifetime of technologies, Scenario S1- Low

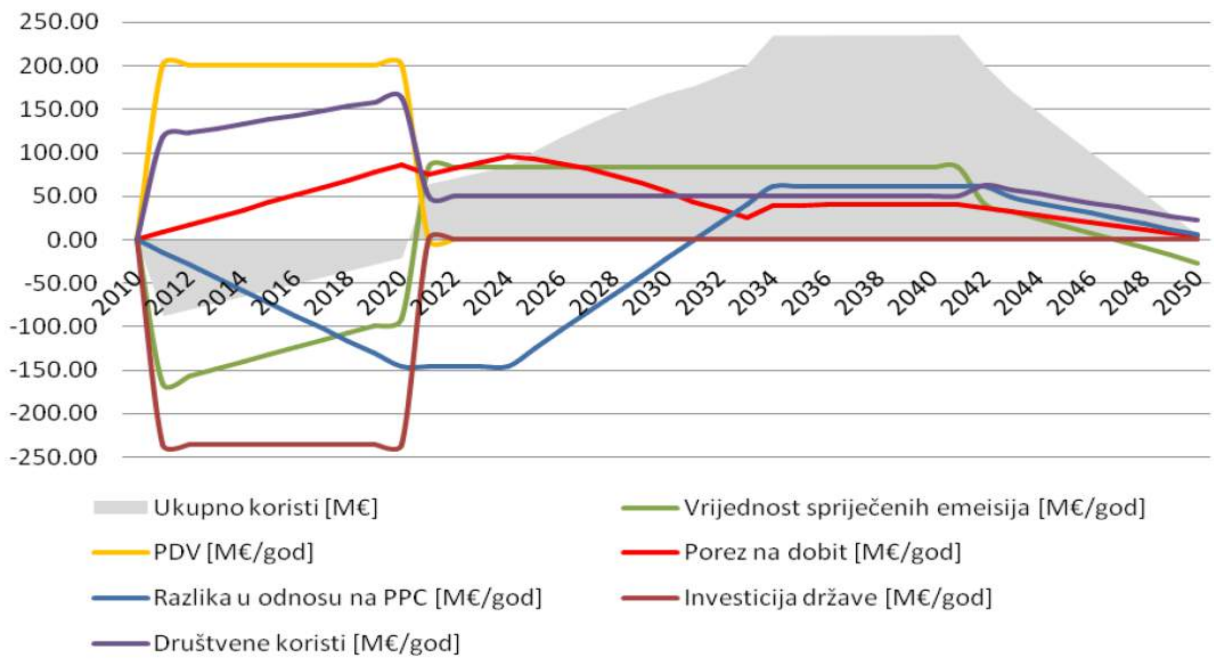


Figure 8-27: Costs and benefits during the lifetime of technologies, Scenario S2- High

Comparative analyses through other all three scenarios, is in Table 8-4: NPV of measures [M€]. Net present value for the society is positive for scenarios S2 and S3. Discount rate used in this calculation was 4%.

Table 8-4: NPV of measures [M€]

	Scenarij S1 - Low	Scenarij S2 - High	Scenarij S3 - Moderate
Wind power plants	-327	-6	-147
Solar PV	-86	-78	-80
Hydropower plants	-22	22	2
Biomass CHP	102	309	213
Geothermal CHP	-59	-3	-29
Waste CHP	-45	38	1
Biogas CHP	-42	-23	-32
Solar heat	-19	128	61
Biomass heat	18	194	114
Heat pumps	14	70	47
Energy efficiency, buildings	-475	521	236
Energy efficiency, public buildings	-92	-4	-31
Biofuel	84	401	251
Coal power plants	658	-163	272
Gas CHP	-366	-413	-377
Summary	**-658**	**993**	**501**

The total net present value of measures planned in the Energy Strategy is positive in the second and third scenario. This value is negative only for the first scenario, which is characterized by a low level of local jobs and the low price of allowances.

The difference of a simple period of return of investment through different scenarios for the society is visible in Figure 8-28. In Scenario S1, with low price of GHG emissions and a low share of local component in jobs created, the simple period of return is in year 2042, which is after 30 years. In the second scenario, with a high price of GHG emissions and a high share of local component in job creation, the return is in year 2027. In the third, moderate scenario, the return of investment is around year 2031.

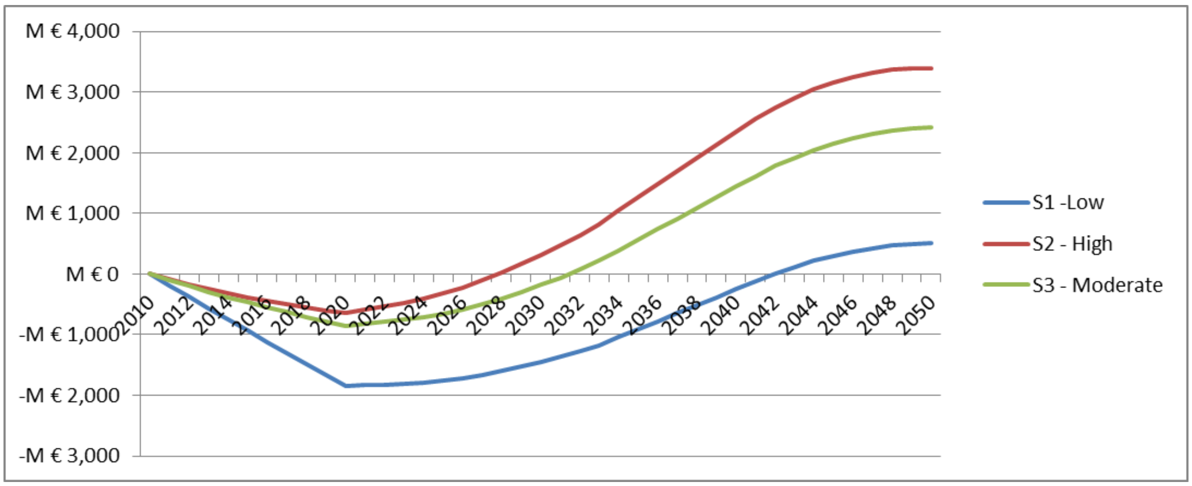


Figure 8-28: Simple period of return on investment for the society

8.2.5. Resulted share of new investments as a part of GDP

As one of the modeling results, share of new investments as a part of GDP can be calculated. Regarding historical GDP trend, real data was used (Figure 8-29): the Croatian economy was strongly affected by the global economic crisis; the GDP fell by about 6.9% in 2009 and before the crisis, GDP grew around 4% annually. For the purpose of modeling it is expected that in 2013 the GDP will grow by about 0.3%. Modeling results show that if all planned (modeled) investments would take place; this would make 2% of total GDP.

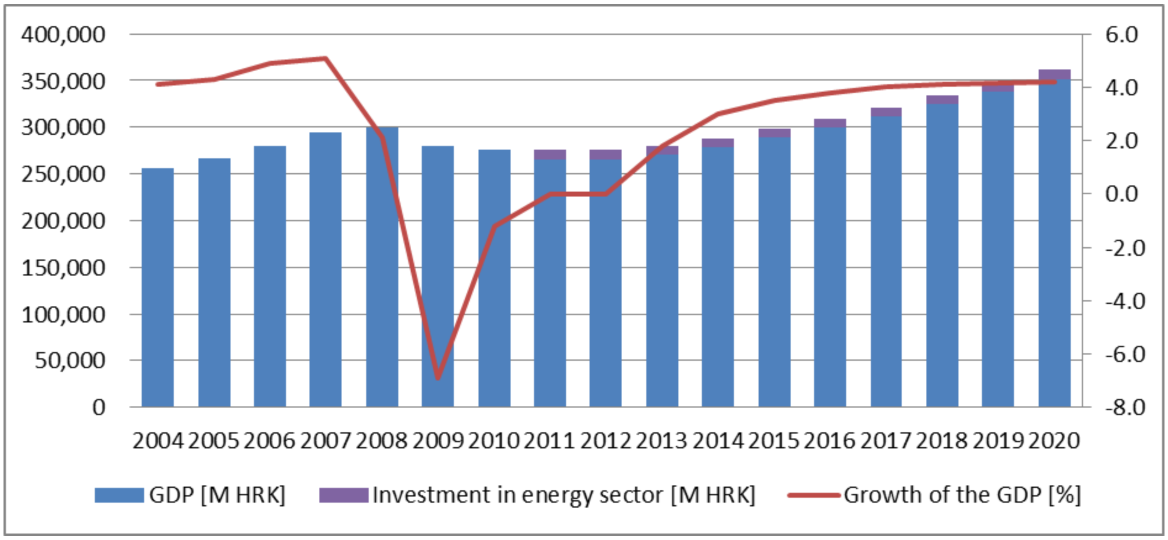


Figure 8-29: Share of investment in energy sector in GDP by 2020

8.2.6. Conclusions from modeling and measuring sustainable development indicators with use of developed model on Croatian power system by year 2020

Results from modeled scenarios are showing importance of GHG price on competitiveness of low emission technologies. It also shows importance of domestic component in manufacturing, installation and maintenance of this technology – in order to reduce its price to the society that supports it.

Reviewing the effectiveness of measures highlights the negative value of promoting wind power in all three scenarios in this way. Increase of installed capacity of wind power is the biggest out of all other proposed renewable energy sources since the adoption of the Energy Strategy. This can be explained by the high cost of incentive purchase price for electricity in relation to declining production costs, and further decrease in technology investment price will make wind power plants more competitive. Another reason is not so many jobs necessary for operation and maintenance compared to other technologies. It follows that it would be needed to reduce the incentive price for wind, thus lowering the price burden for electricity consumers. In addition, attempt to activate the domestic industry in the production is welcome, such as wind power plants manufacturing in shipyards.

Solar power technologies are very easy to put into operation, and production price is falling at the daily level, although it is still significantly higher compared to other technologies. Therefore, in Croatia PV has limited annual quota for which the incentives are given to avoid a strong burden on the price for electricity customers.

Solid biomass cogeneration proved to be the measure with the positive net present value in all three scenarios for the production of both heat and electricity, and with the employment of a significant number of people in the whole lifecycle of technology.

Good results suggest that measures of support for biomass heating, solar thermal systems and heat pumps are well balanced. Measures of smaller scale with net present value of around zero are hydroelectric, geothermal CHP, waste CHP, biogas CHP and implementation of energy efficiency in public buildings. These measures in terms of costs and benefits are not negligible, but are significantly less influential.

Implementation of energy efficiency in buildings has great potential but only if it encourages domestic industry and if the price of allowances in the market is at least at moderate level.

The support to biofuels production was shown as a measure worth of incentives, but this area is under discussion to what extent it is good to encourage biofuel production because of the competitiveness with food production. Many countries have corrected incentives to ensure the priority of food production from crops.

Of investments in fossil fuel power plants, coal was shown unprofitable only in the scenario with the high price of allowances of € 35/tCO_2. In the other two scenarios, it is shown as a good solution in terms of costs and benefits to the society.

In contrast, gas power plants are not profitable in all three scenarios with the current conditions and gas prices in Croatia. It is possible that the development of gas pipelines or LNG terminal in Croatia will reduce the cost, but risk will remain due to limited resources. However, cost-expensive gas power plants have a good possibility of energy regulation in the power system in terms of unforeseen production from renewable sources and therefore should not be so easily rejected when planning the future.

In light of the lively market and constant progress in manufacturing technologies, it could be possible to adjust or even remove incentives to meet desired goals in the best way. Therefore, the period of return could be significantly lowered. However, with growing complexity in environment, various risks and uncertainties will remain.

8.2.7. Application of MCAC model and PACE model

Results from the modeling presented above were further used as inputs to MCAC model for calculation of marginal cost abatement curves; and to PACE model for easier visualization and comparation of modeling results.

MCAC modeling results

Resulted marginal abatement cost is shown on the figure below. Marginal abatement cost is plotted on the y-axis, and the projects ranked against this metric from lowest to highest. The width of the column is equal to the amount of emission reduction from the calculated low emission solution, and the area of each column equals to the cost or benefit of the project. Negative MAC values indicate that the project is self-financing, whereas positive MAC values require judgment against the cost of inaction - in this case the cost of the purchase of emission allowances on the market.

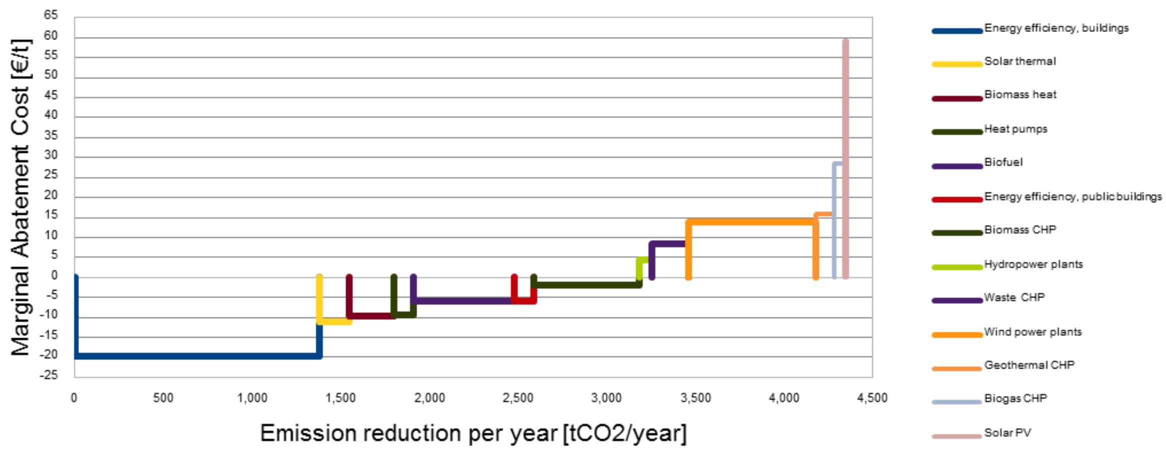


Figure 8-30: Marginal Cost Abatement Curve – presentation of results for applied technologies

From the resulted MCAC graph in Figure 8-30, it is also visible that increase of CO_2 price for example to 20 EUR/tCO_2 will make some other technologies competitive (in a way that a cost of reduction of CO_2 emissions will be negative). This price will make negative cost of emission reduction through wind power plants, geothermal energy, waste CHP and hydro power plants.

PACE model results

PACE model enables visualization and comparation of results for measures and modeled sustainable development indicators. In this case, three different indicators will be presented on the same graph for each of the scenarios:

- NPV of low emission technologies / measures for the society (y-axis);

- Emission reduction for low emission technology / measure (x-axis);
- Number of green jobs created with use of this low emission technology / measure (bigger bubble means more jobs created)

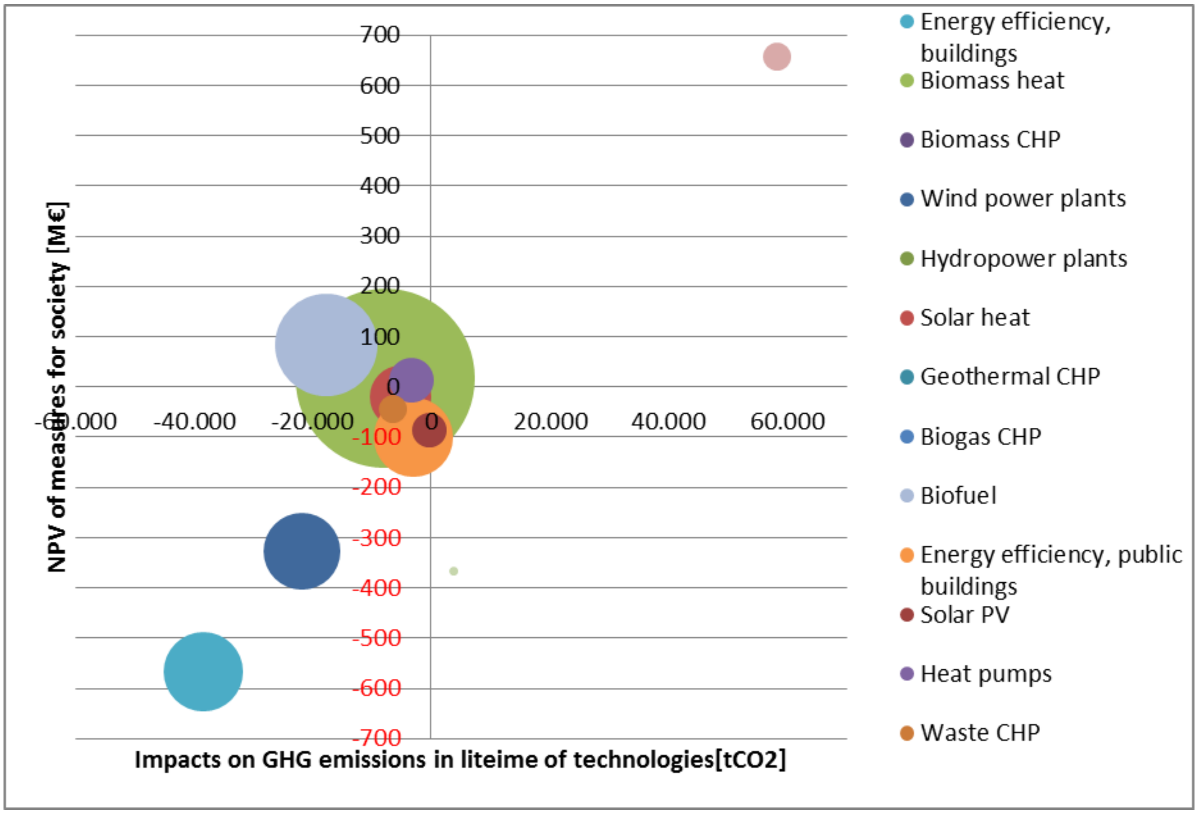


Figure 8-31 Visualization of measure impacts, Scenario S1 – Low

In the first scenario, the most cost-effective are investments in coal power plants, but they contribute to greenhouse gas emissions and create relatively few new direct jobs. On the other hand, they can provide cheaper energy and thus encourage cheaper production in economy. The first scenario is characterized by a low level of domestic production and a very low cost of CO_2 emissions (5 EUR/tCO_2), which is one of the most important reasons why coal power plant has such as positive NPV, and such a low CO_2 price is unlikely to be realistic in long term. In this scenario, encouraging investment in wind power and energy efficiency in buildings is proving to be a failure from the standpoint of cost, even though the impact on reduction of emissions and creation of new jobs is positive. In this scenario, considering all three pillars of sustainable development, investments in biofuels and biomass heating provided the best results.

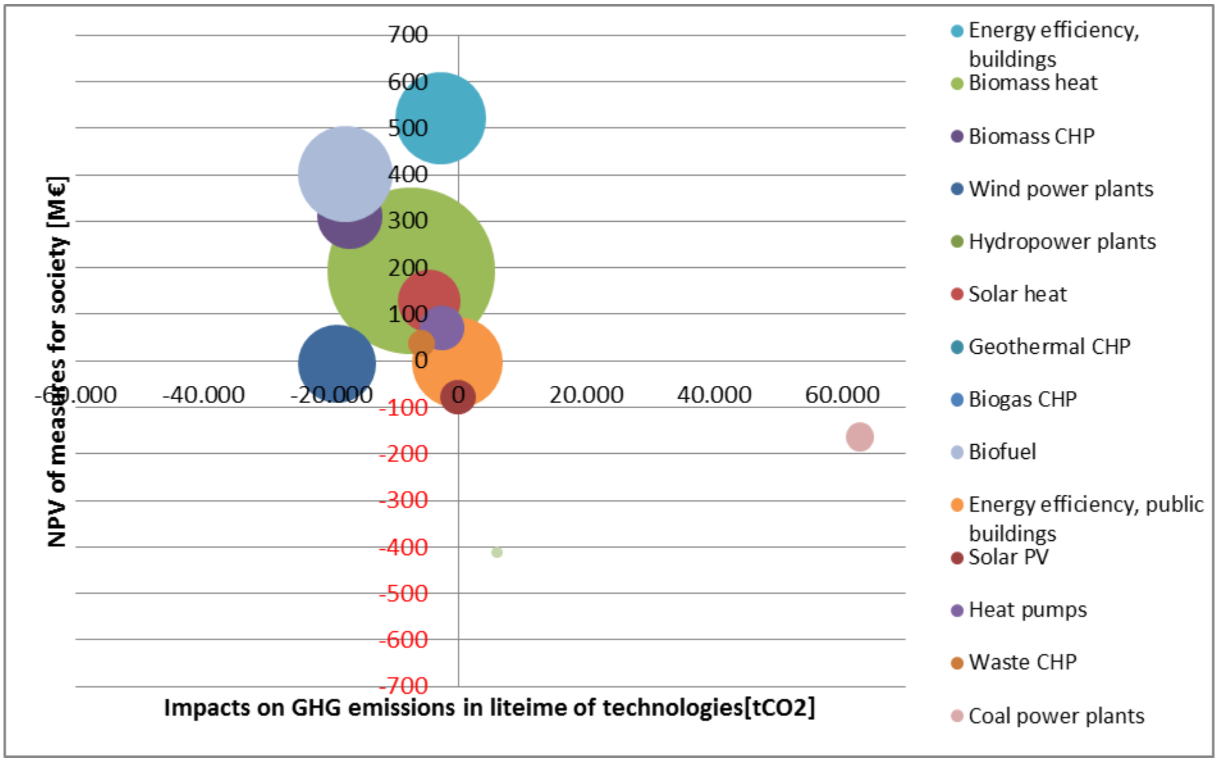


Figure 8-32: Visualization of measure impacts, Scenario S2 – High

The second scenario is characterized by high emission price (35 EUR/tCO_2) and a large proportion of domestic production. In this scenario, almost all investments in renewable energy sources appear to be justified in terms of emission reduction, cost-effectiveness and the number of new jobs created. On the other hand, investments in power plants, gas and coal are in the fourth quadrant which is the least good option because they affect the increase in greenhouse gases emissions and are neither justified regarding costs and benefits for the society. However, it is important to be careful when planning because the conventional power plants can be an important factor in the security of supply and stability of the system.

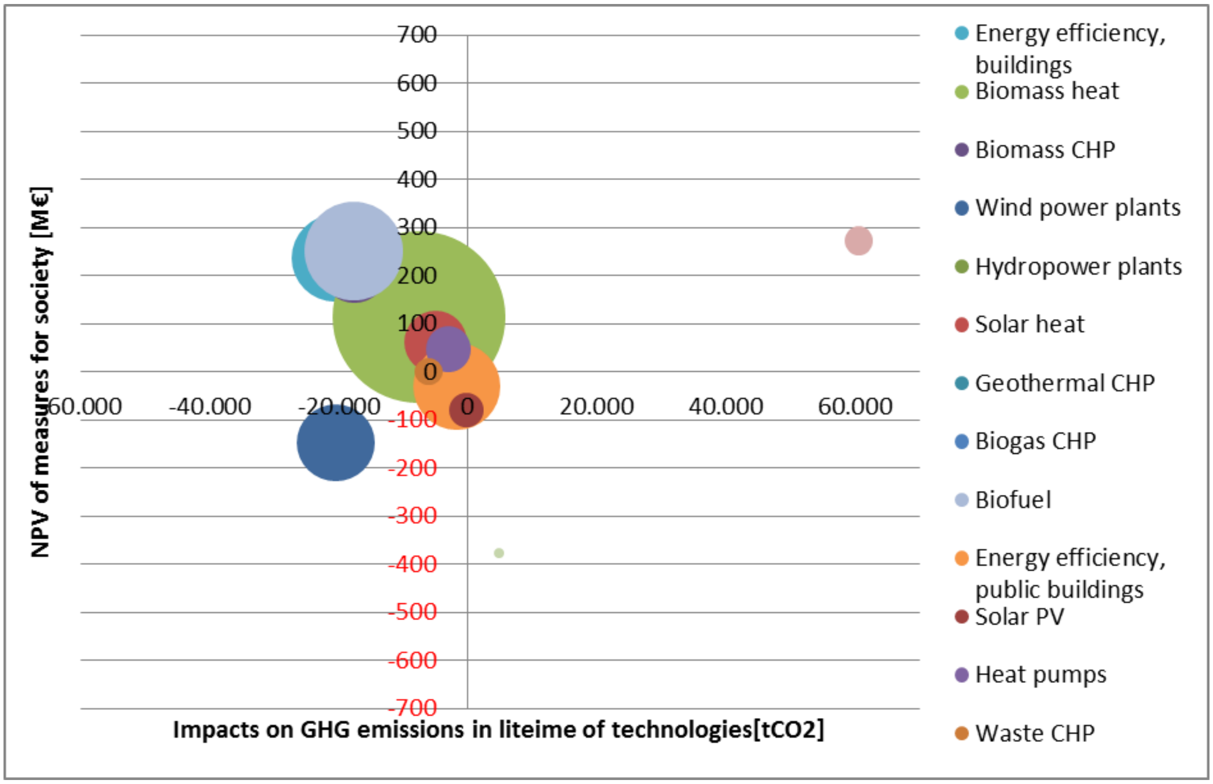


Figure 8-33: Visualization of measure impacts, Scenario S3 – Moderate

Finally, the third scenario with the moderate share of domestic components in manufacturing, installation and maintenance as well as moderate price of allowances has showed that investment in energy efficiency in buildings, biofuels, CHP and biomass heating, solar heating systems and using remaining potential of waterpower and waste for energy production is positive regarding holistic sustainable development. The current model of encouraging investment in wind power in this case proved economically not justified (negative NPV), although a significant number of jobs was created and GHG emission saved. Similarly, the model of financing investment in energy efficiency in public buildings should be re-examined to gain maximum benefits. As the price of solar power plants is in steady decline, lowering of the incentive purchase price will be possible and thus more cost-effective. An additional reason for investment in new technology even when they are costly is the development of knowledge, innovation and experience to compete in the open market. In this scenario, investment in coal, despite greenhouse gas emissions price (20 EUR/tCO_2 in this scenario) shows to be economically viable in the time of development of renewable energy sources and not-so high emission price. Another uncertainty for the coal power plants is the time and the application of the system for the storage of carbon dioxide, which would make coal power plants become less harmful to the environment. Gas power plants increase greenhouse gas emissions and are economically unjustified in the present scenario. However, as noted above it should not be ignored because of the quality for system regulation and possible future lower gas prices as a consequence of opening new supply routes for Croatia.

8.3. Climate change impacts on energy generation from renewable energy sources

Results of assessment of climate change impacts on renewable energy generation presented here are based on verification described in Chapter 7.4., first methodological step described.

8.3.1. Projected climate change impact in Croatia on wind, hydro and solar energy

The forecasted future climate change would clearly influence the availability of renewable energy sources in Croatia. The assessment presented in this study showed that the total effect of climate change on the generation of energy from photovoltaic sources might be neutral since it is balanced by opposing impacts (increase in the mean temperature, decrease of the mean cloud cover, more frequent extreme weather condition). However, this is not the case for the wind power potential, and hydro power electricity production. Energy production from wind power plants would potentially increase because, according to climate change studies [153] and the results presented in this study, an increase in the mean wind speed is projected in future climate. For Croatia, such an increase in the mean wind speed implies a potential significant increase in electricity production from wind power plants even in the near future. Negative impacts from the increased temperature and because of possible change in the variability of wind speed or the change in wind direction are either small or difficult to evaluate for specific region without further modeling of climate and of energy production. For the hydro power production, the influence of projected climate change would be negative because in all IPCC emission scenarios the reduction of precipitation is expected. Based on available estimates of such a reduction in precipitation amounts, a reduction of more than 10% in the Croatian electricity production from hydro power plants could be expected after 2050. This could be of extreme importance because of the relatively high share of hydro-power electricity production in the total energy generation in Croatia. A review of projected climate changes with potential impact on renewable sources of energy generation is given in Table 8-5.

Table 8-5: Summary of expected climate variable changes with potential impact on renewable production

Projected climate change	Impact on renewables production
Temperature The mean temperature increase up to 3.5 °C in the period 2041-2070.	**Photovoltaics:** For an increase in average temperature of 6°C, the efficiency and production of energy would decrease 3 to 5 % **Wind:** The temperature increase of one degree Celsius yields a decrease of about 0.5% of wind power electricity production. Overall, no more than 1% change expected. **Hydro:** The projected higher temperature would lead to more evaporation from hydro storages.
Precipitation Precipitation is projected to be reduced by 10 to 15% in the major Croatian basins.	**Photovoltaics:** Small positive influence. **Wind:** No impact expected. **Hydro:** A reduction in water inflow implies that the energy generation is expected to decrease by 10% by 2050 and 15-35% by the end of the 21st century.
Global horizontal irradiance An increase in irradiation is projected for all regions in Croatia.	**Photovoltaics:** Electricity generation increase by 3% during the summer and 1-2% during spring and winter months in the period to 2040. **Wind:** No impact expected. **Hydro:** No impact expected.
Days under snow cover Expected decrease in days under the snow cover.	**Photovoltaics:** An increase in electricity generation due to less snow on the panels. **Wind:** No impact expected. **Hydro:** An increase in evaporation from hydro storages should be taken into account.
Extreme weather events More forest fires expected in the Mediterranean due to more draughts in the summer; stronger winds can impact energy technology installations	**Photovoltaics:** A cautious choice of locations due to strong winds and forest fires. **Wind:** Winds stronger than the maximum anticipated in wind power plants could be expected. **Hydro:** More severe and more frequent draughts and precipitation should be taken into account than previous.
Hailstorms More severe hailstorms could be expected.	**Photovoltaics:** Large-size hail stones can damage some types of PVs **Wind:** No impact expected. **Hydro:** No impact expected.
Wind speed change Higher wind speeds projected in coastal and adjacent areas in the summer – an increase of 15-25% in 2011-2040 and 35-	**Photovoltaics:** Increased construction or maintenance cost. **Wind:** More electricity could be generated from wind power plants in the southern regions of Croatia during the summer - theoretically double than the current production

60% in 2041-2070.	(until 2040) or more than double up to 2070. **Hydro:** No impact expected.
Change in wind speed variability More variability should be expected in the future.	**Photovoltaics:** No impact expected. **Wind:** Can make a big impact on electricity generation from wind power plants: even with the wind speed increase, a higher variability of wind can lead to less generation of energy. **Hydro:** No impact expected.
Wind direction change In some regions wind direction changes could be expected.	**Photovoltaics:** No impact expected. **Wind:** Wind power plants are located according to prevailed (climatological) wind direction and any change in the wind direction influences their electricity production.

8.3.2. Conclusions from assessment of climate change impacts on renewable energy sources in Croatia

Results from the assessment are showing importance of addressing climate change impacts on long term power system planning. Especially this has high impact on wind and hydro energy.

In order to characterize the risks from future potential climate changes on the renewable energy production in Croatia it would be important to estimate uncertainties related to all influencing factors. This is related to, for example, more reliable estimates of climate change from improved regional and global models (the need to quantify uncertainties across different climate models) and more detailed analysis about impact of these changes on different renewable sources for energy production. However, the results of both regional and global models are still very much dependent on the projected emission scenarios. An estimate of the above uncertainties would, for example, include the development of additional tools to “translate” climate information into estimates of renewable energy potential. An estimation of the overall risk uncertainty might include the additional sources of uncertainties attributed to the natural climate variations (that can influence or commingle with human induced climate impacts) and future emissions uncertainty which depends on a wide range of socio-economic factors, but include, among others, the fuel mix in the energy sector [164]. This would ultimately yield an improved estimate of how climate changes affect the availability of sources of renewable energy.

8.4. Results from integrative modeling – application of methodology on Croatian power system by 2030

In this chapter modeling results for application of methodology on Croatian power system by 2030 (described in chapter 7.5.) will be presented and discussed. The purpose of this modeling is an integrative one, to follow all the methodology steps as described.

8.4.1. Assessment of LRMC for new power plant candidates

List of new power plant candidates is already described in STEP2 in chapter 7.5.; it consists of:

- Two gas power plants (TPP Sisak 2 with 230 MW and TPP Slavonia with 500 MW);
- Two coal power plants (TPP Plomin C with 500 MW and TPP Ploce with 500 MW);
- Four wind power plants, ranging from best wind potential conditions to the worst (WPP 1Best, WPP 2Best, WPP 3Best, WPP 4Best);

In order to provide wider emission trading impact information on these technologies, first they were described in "LRMC model" (which is described in chapter 6.2.). This will help with easier defining and comparation of input data for new power plant candidates that will be modeled in PLEXOS model. But also, it provides information on how different fuel prices have impact on long term competiveness on power generation technologies. Description of new power plant candidates in the model is presented in the Table 8-6.

Several cases in relevance to oil price are constructed, and it has an impact on gas and coal fuel prices:

- Oil price 95 USD/bbl – where coal fuel price is 4,16 EUR/GJ and gas price is 10 EUR/GJ;
- Oil price 125 USD/bbl - where coal fuel price is 4,6 EUR/GJ and gas price is 12 EUR/GJ;
- Oil price 140 USD/bbl - where coal fuel price is 5,2 EUR/GJ and gas price is 14 EUR/GJ;

Emission trading impact on LRMC of these technologies for different oil price scenarios is presented in Figures below.

Table 8-6: Description of new power plant candidates in developed "LRMC model" (for oil price 95 USD/bbl)

		Coal - Plomin C /Ploce	CCGT - Slavonia	Wind 1st best	Wind 2nd best	Wind 3rd best	Wind 4th best
Fuel price	€/GJ	4,16	10,00				
Thermal coefficient	%	43,00	58,00				
Heat Rate	GJ/MWh	8,37	6,21				
Fuel price (MWh)	€/MWh	34,83	62,07				
Number of hours on nominal power				3000,00	2700,00	2300,00	2000,00
Variable costs	€/MWh	3,48	1,52				
Emission coefficient	tCO2/MWh	0,823	0,348	0,000	0,000	0,000	0,000
Annual fixed costs	€/kWyear	40,00	20,00	30,00	30,00	30,00	30,00
Fixed costs	€/MWh	3,98	1,25	18,00	18,00	18,00	18,00
Investment costs	€/kW	2166	900	1300	1300	1300	1300
Expected life	year	35	25	25	25	25	25
Interest	%	8,5	8,5	8,5	8,5	8,5	8,5
Investment costs (MWh)	€/MWh	25,19	10,99	46,37	51,63	60,48	69,79
LRMC	€/MWh	67,48	75,83	64,37	69,63	78,48	87,79

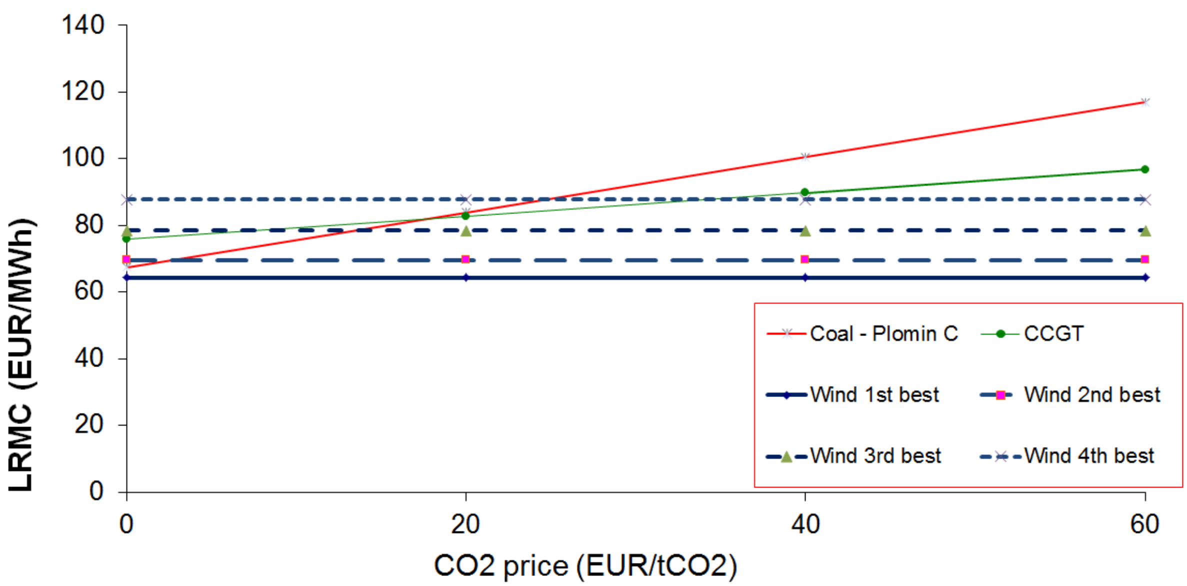


Figure 8-34: Emission price impact on LRMC technologies for oil price 95 USD/bbl; at the price of 18 EUR/tCO_2 CCGT plants become more competitive than coal power plants. At best wind positions (WPP 1Best) is the most competitive even with zero emission price, and for the worst positions (WPP 4Best) it is more competitive than coal after 44 EUR/tCO_2 while for CCGT this happens after 54 EUR/tCO_2

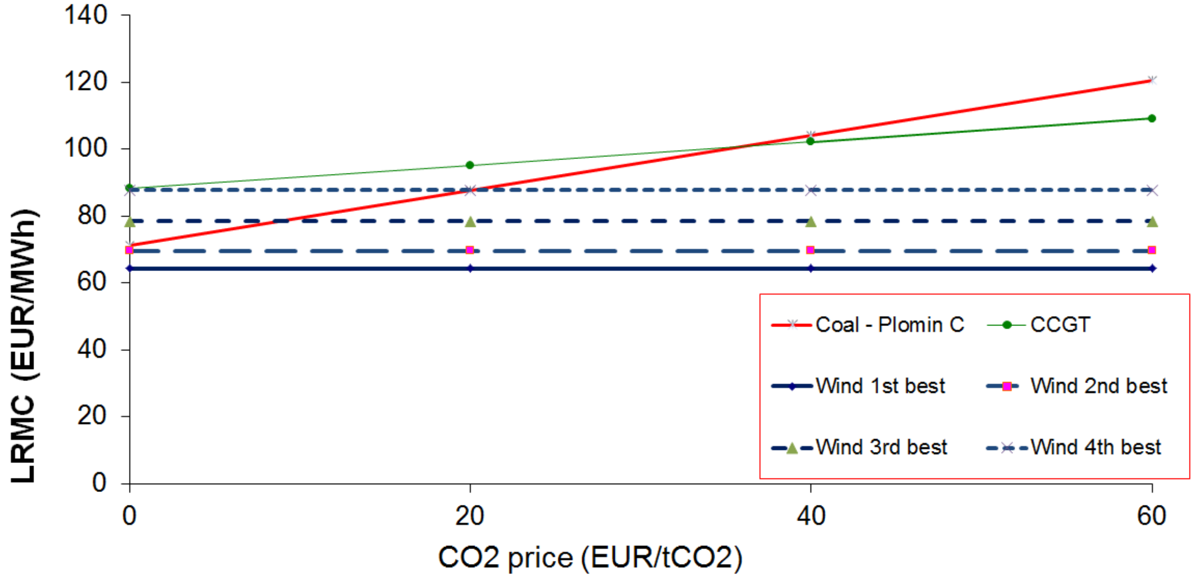


Figure 8-35: Emission price impact on LRMC technologies for oil price 125 USD/bbl; at the price of 37 EUR/tCO_2 CCGT plants become more competitive than coal power plants. At best wind positions (WPP 1Best) is the most competitive even with zero emission price, and for the worst positions (WPP 4Best) it is more competitive than coal after 21 EUR/tCO_2 while it is always more competitive than CCGT

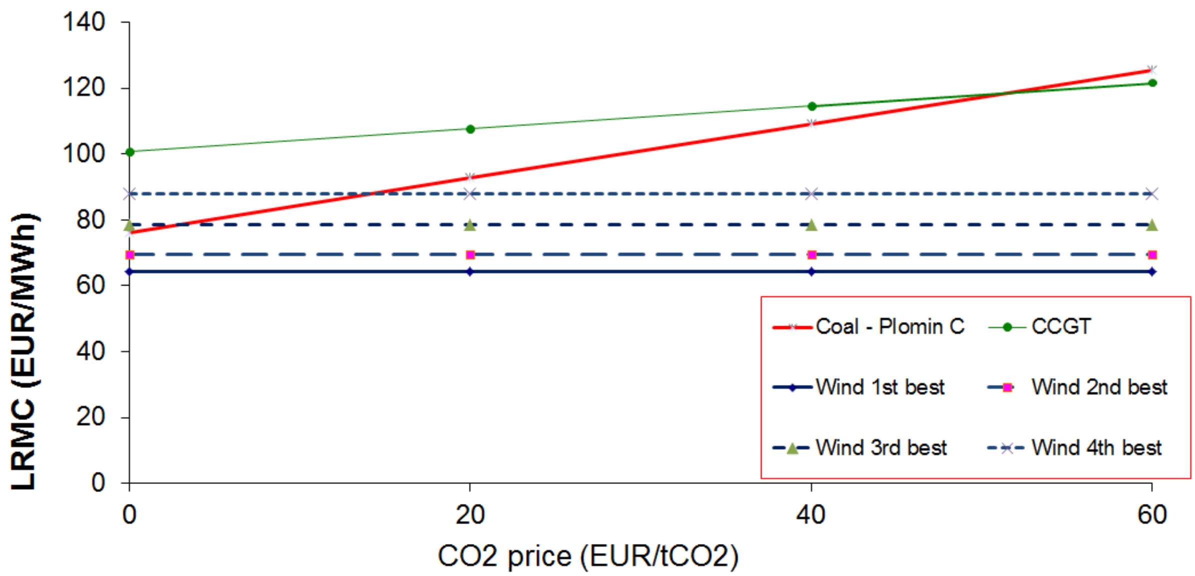


Figure 8-36: Emission price impact on LRMC technologies for oil price 140 USD/bbl; at the price of 52 EUR/tCO_2 CCGT plants become more competitive than coal power plants. At best wind positions (WPP 1Best) is the most competitive even with zero emission price, and for the worst positions (WPP 4Best) it is more competitive than coal after 15 EUR/tCO_2 while it is always more competitive than CCGT

Conclusions from modeling LRMC in regards to emission price and oil price, is that:

- On locations with best potential, wind power plants are already more competitive than coal and CCGT;
- Emission price is necessary to ensure competitiveness of wind power plants on locations with lower wind potential;
- Higher oil prices have important impact on CCGT generation price and after 125 USD/bbl, wind power is more competitive even on locations with the lowest wind potential;
- With oil price 95 USD/bbl, emission price should be at least 18 EUR/tCO_2 to ensure transition to CCGT technology instead of coal; with the oil price increase this breakeven needs higher emission price – at 140 USD/bbl it is just after 52 EUR/tCO_2.

8.4.2. Modeling power system development until 2030 in model PLEXOS

All new power plant candidates are described in PLEXOs in order to enable modeling of long term power system expansion. The referent power system scenario already described, tested and validated in 8.1. is used for long term modeling (LT Plan). Consumption rise until 2030, years of retirement of power plants are described in STEP 4 of chapter 6.5. An example of description of TPP Plomin C is given in the figure below.

TE Plomin 3

Membership	Property	Value	Units	Band	Date From	Date To
TE Plomin 3	Fixed Load Method	Relax When Zero	-	1		
TE Plomin 3	Units	0	-	1		
TE Plomin 3	Max Capacity	500	MW	1		
TE Plomin 3	Min Stable Level	150	MW	1		
TE Plomin 3	Heat Rate Base	100	GJ/hr	1		
TE Plomin 3	Heat Rate Incr	8,325	GJ/MWh	1		
TE Plomin 3	VO&M Charge	3,48	EUR/MWh	1		
TE Plomin 3	Start Cost	68000	EUR	1		
TE Plomin 3	Ramp Up Charge	20	EUR/MW	1		
TE Plomin 3	Ramp Down Charge	25	EUR/MW	1		
TE Plomin 3	Max Ramp Up	3	MW/min.	1		
TE Plomin 3	Max Ramp Down	3	MW/min.	1		
TE Plomin 3	Aux Base	18,8	MW	1		
TE Plomin 3	Aux Incr	1,5	%	1		
TE Plomin 3	FO&M Charge	40	EUR/kW/year	1		
TE Plomin 3	Forced Outage Rate	3,24	%	1		
TE Plomin 3	Mean Time to Repair	150	hrs	1		
TE Plomin 3	Build Cost	2166	EUR/kW	1		
TE Plomin 3	WACC	12	%	1		
TE Plomin 3	Max Units Built	1	-	1		
TE Plomin 3	Max Units Built	0	-	1		1.1.2017.

Figure 8-37: Example of description of Plomin C in power system PLEXOS (print screen)

8.4.3. Modeling results from PLEXOS for Referent scenario (without CO_2 price)

First modeling of power system expansion is performed for Referent scenario (without CO_2 price), after which modeling of other scenarios is performed and compared to the referent scenario results (scenarios with 20 EUR and 40 EUR emission price per ton).

Generator	Year	Build (MW)	Net Build (MW)	Cap. Cost (knMln's)
TE Ploce	2026	500,00	500,00	1.083,00
TE Plomin 3	2017	500,00	500,00	1.083,00
TE Slavonija	2020	500,00	500,00	400,00
WPP 1Best	2015	137,00	137,00	520,19
WPP 2Best	2015	123,00	123,00	520,04
System	2013	0,00	0,00	0,00
System	2014	0,00	0,00	0,00
System	2015	260,00	260,00	1.040,23
System	2016	0,00	0,00	0,00
System	2017	500,00	500,00	1.083,00
System	2018	0,00	0,00	0,00
System	2019	0,00	0,00	0,00
System	2020	500,00	500,00	400,00
System	2021	0,00	0,00	0,00
System	2022	0,00	0,00	0,00
System	2023	0,00	0,00	0,00
System	2024	0,00	0,00	0,00
System	2025	0,00	0,00	0,00
System	2026	500,00	500,00	1.083,00
System	2027	0,00	0,00	0,00
System	2028	0,00	0,00	0,00
System	2029	0,00	0,00	0,00
System	2030	0,00	0,00	0,00

Figure 8-38: Printout of modeling results - new power plants entering the power system (print screen)

In referent scenario without CO_2 price, main emphasize of power system development is on thermal power plants; two coal plants are built, one gas and two blocks of wind power plants. Lack of CO_2 price has significant impact on making coal plants the most competitive. WPP1 and WPP2 are entering in 2014, TPP Plomin C enters in 2016 (as this is the soonest year it could have been built), TPP Slavonia powered on gas is entering in 2019 and TPP Ploce entering in 2025 (after this TPP Slavonia serves only peak periods and coal is taking over base power and most of the shoulder power demand.

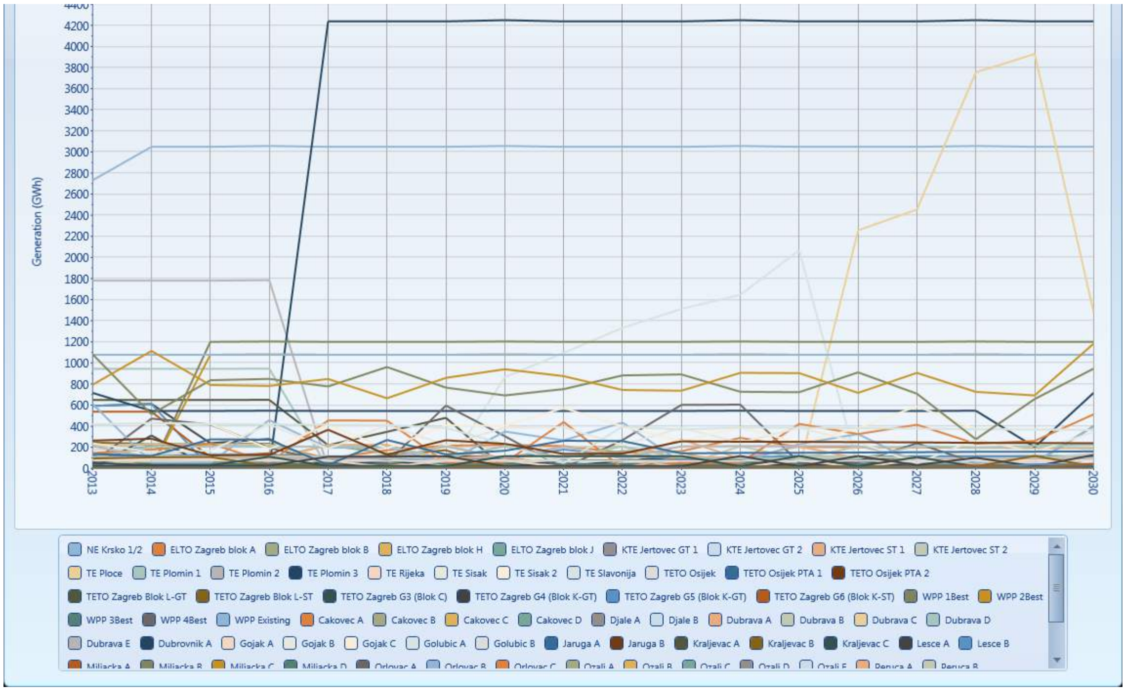


Figure 8-39: Modeled generation of different power plants between 2013-2020; it is visible that some of old power plants which are scheduled for retirement are closed down, and new candidates appeared

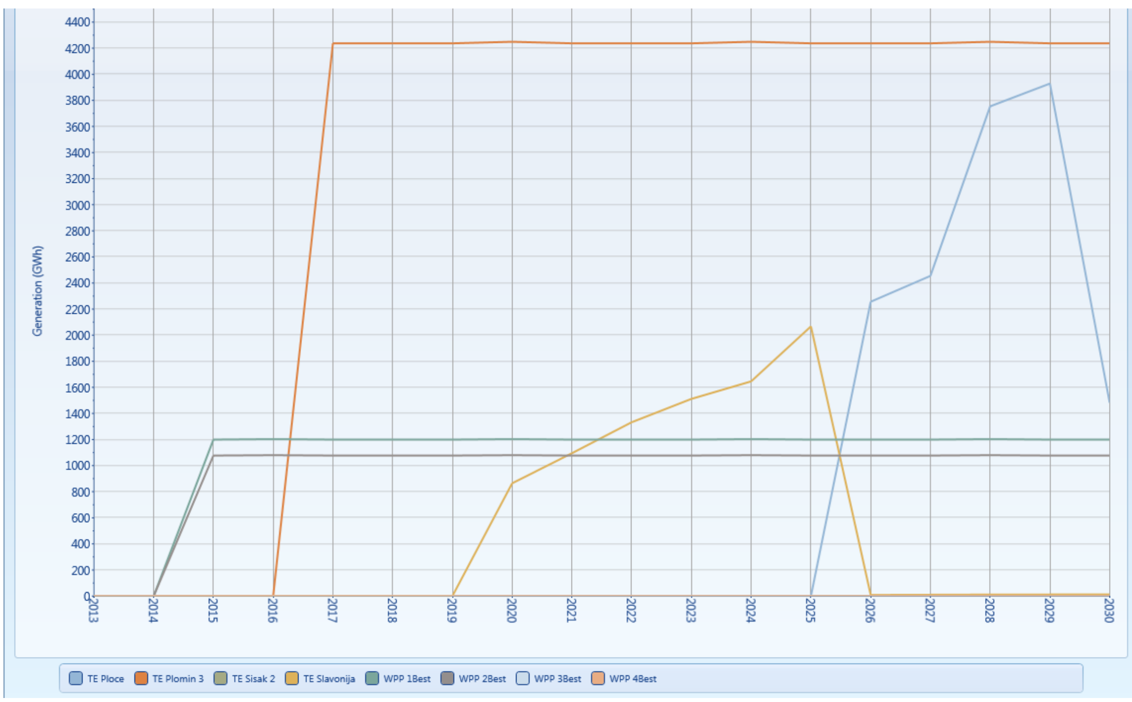


Figure 8-40: Representation of new power plants entering into the power system: WPP1 and WPP2 entering in 2014, TPP Plomin C entering in 2016, TPP Slavonia entering in 2019 and TPP Ploce entering in 2025

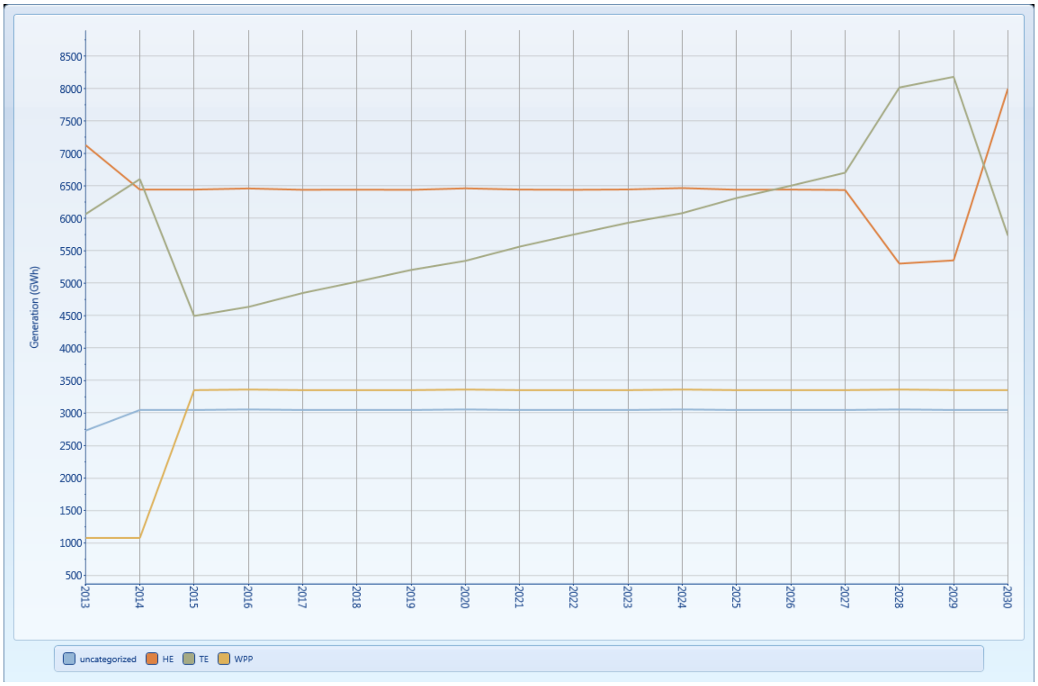


Figure 8-41: Representation of generation per type (hydro, thermal, wind and nuclear) during the period 2013-2030; it is obvious that after WPPs entered into the system, further consumption increase in completely covered by thermal power plants

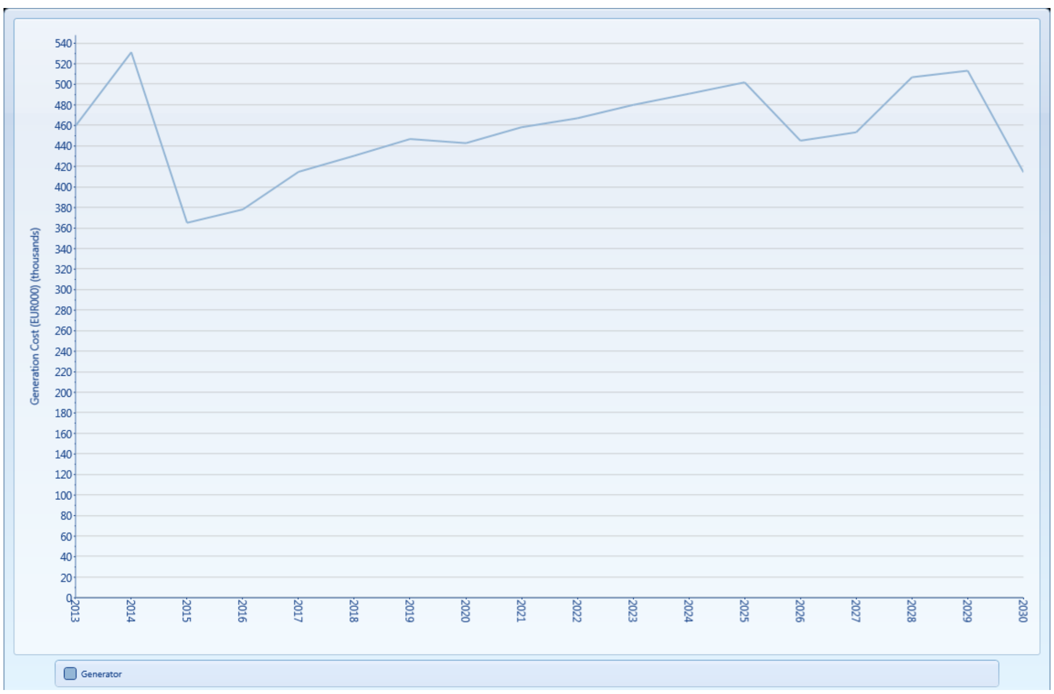


Figure 8-42: Generation costs in the period 2013-2030; it is visible that they drop down significantly with introduction of new wind power plants as their operational costs are low

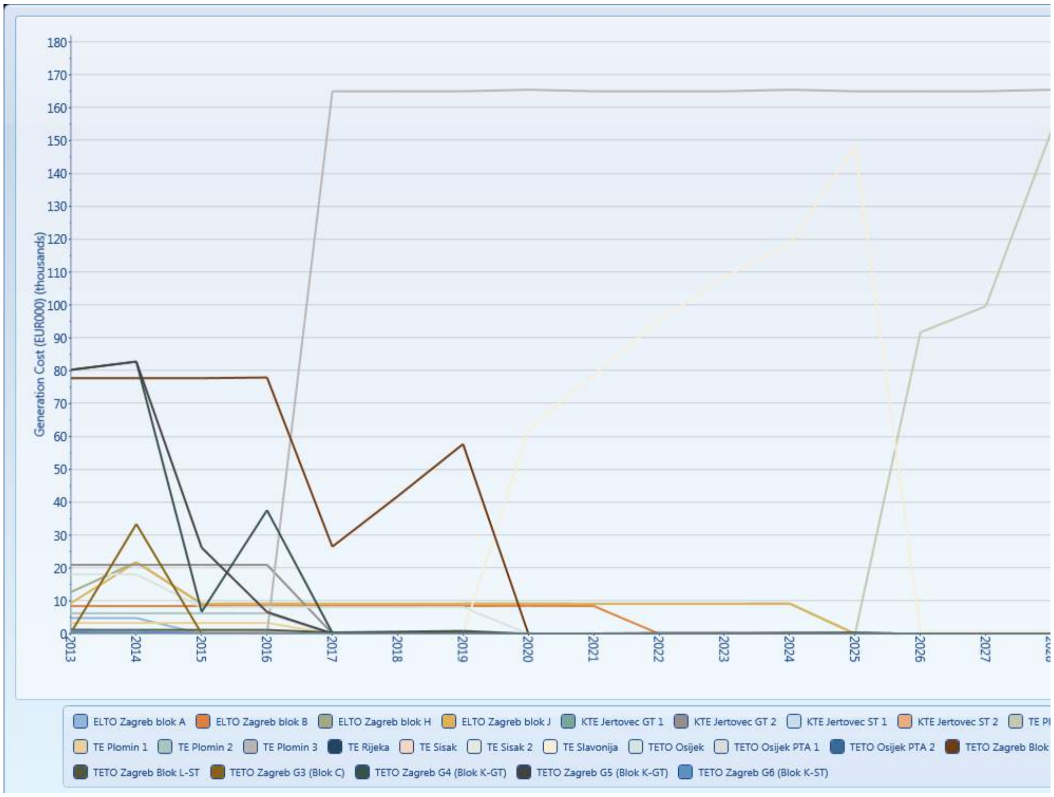


Figure 8-43: Generation costs for thermal power plants in the period 2013-2030; it is visible that old plants are getting retired and new ones are taking over

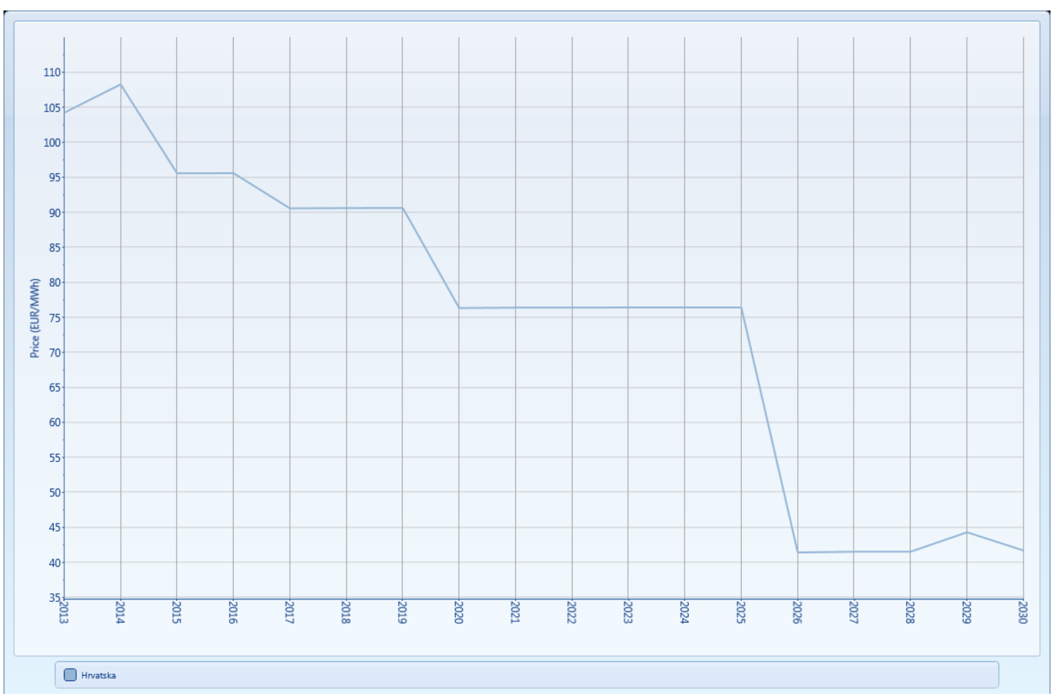


Figure 8-44: Average annual price of electricity drops down with installation of new power plants – the last dropping down happens with introduction of TPP Ploce into the system

8.4.4. Modeling results for Scenario 20 EUR (emission price)

With rise of CO_2 price, changes are visible in generation expansion plan by 2030. All wind power plant blocks are becoming competitive and are entering the power system (first two are entering in 2015, WPP 3Best enters the power system in 2018 and WPP 4Best enters in 2021. TPP Plomin C is still the most competitive and enters the system as first of thermal power plants in 2017, but due to two new WPPs, TPP Slavonia enters the system in 2022 (two years later than in the referent scenario) and TE Ploce enters the system in 2029 (four years after the referent scenario).

Generator	Year	Build (MW)	Net Build (MW)	Cap. Cost (knMln's)
TE Ploce	2029	500,00	500,00	1.083,00
TE Plomin 3	2017	500,00	500,00	1.083,00
TE Slavonija	2022	500,00	500,00	450,00
WPP 1Best	2015	137,00	137,00	520,19
WPP 2Best	2015	123,00	123,00	520,04
WPP 3Best	2018	105,00	105,00	519,96
WPP 4Best	2021	91,00	91,00	519,97
System	2013	0,00	0,00	0,00
System	2014	0,00	0,00	0,00
System	2015	260,00	260,00	1.040,23
System	2016	0,00	0,00	0,00
System	2017	500,00	500,00	1.083,00
System	2018	105,00	105,00	519,96
System	2019	0,00	0,00	0,00
System	2020	0,00	0,00	0,00
System	2021	91,00	91,00	519,97
System	2022	500,00	500,00	450,00
System	2023	0,00	0,00	0,00
System	2024	0,00	0,00	0,00
System	2025	0,00	0,00	0,00
System	2026	0,00	0,00	0,00
System	2027	0,00	0,00	0,00
System	2028	0,00	0,00	0,00
System	2029	500,00	500,00	1.083,00
System	2030	0,00	0,00	0,00

Figure 8-45: Printout of modeling results for scenario with CO_2 price = 20 EUR/tCO_2 - new power plants entering the power system

Figure 8-46: Generation from new power plants in the power system

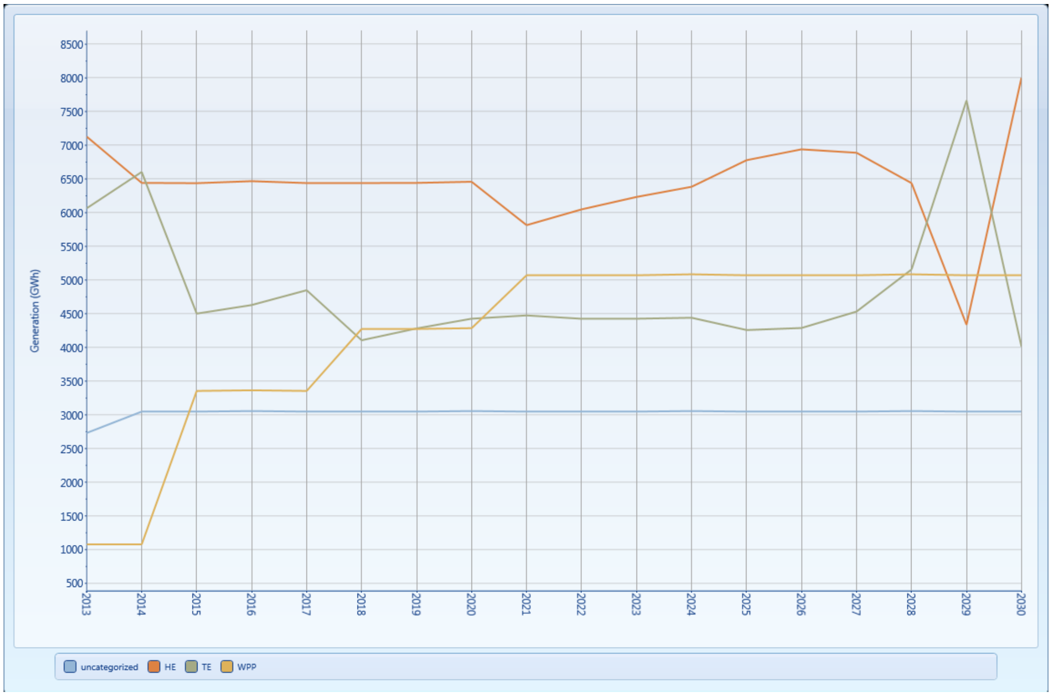


Figure 8-47: Generation per different categories; it is visible that generation from wind power plants is at the same level as from TPPs, and a bit lower than HPPs

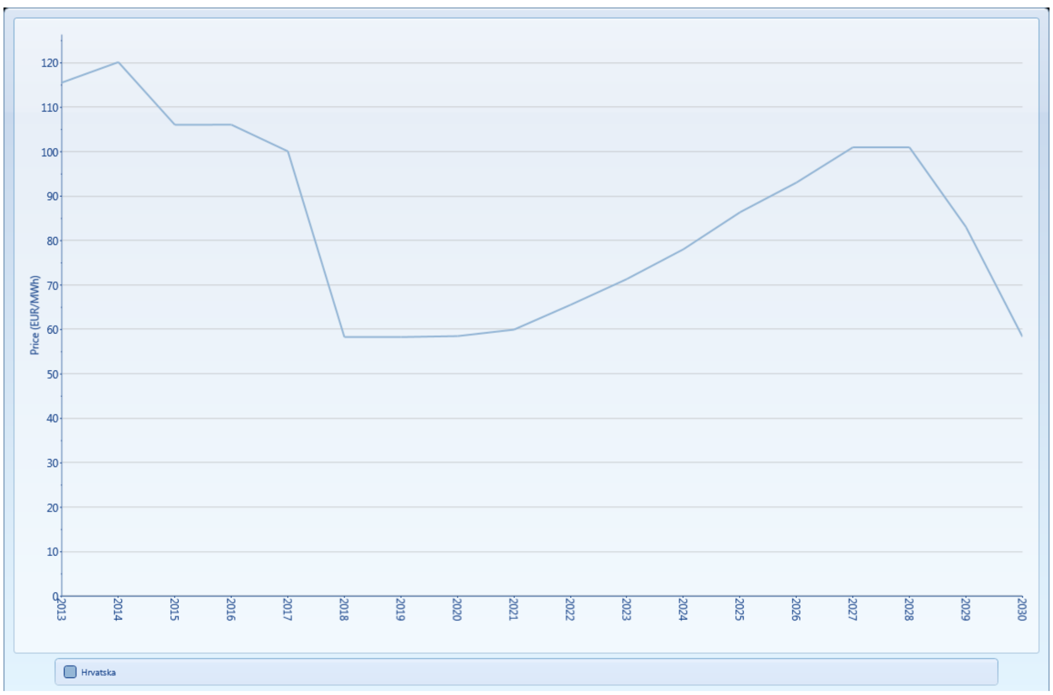


Figure 8-48: Average annual price of electricity drops down lower than in the referent case in the period 2017-2024; but then it is higher than in the referent case

8.4.5. Modeling results for Scenario 40 EUR (emission price)

With rise of CO_2 price to 40 EUR, generation expansion plan by 2030 is completely changed to the referent scenario. Breakeven point between coal and gas price is passed, and the most competitive from thermal power plants is TPP Slavonia which enters the system in 2017, followed by TPP Plomin C in 2022 and TPP Ploce which enters the system in 2029 (four years after the referent scenario). All wind power plant blocks are becoming competitive and are entering the power system (first two are entering in 2015, WPP 3Best enters the power system in 2018 and WPP 4Best enters in 2020 (one year before than in scenario with 20 EUR/tCO_2).

Generator	Year	Build (MW)	Net Build (MW)	Cap. Cost (knMln's)
TE Ploce	2029	500,00	500,00	1.083,00
TE Plomin 3	2022	500,00	500,00	1.083,00
TE Slavonija	2017	500,00	500,00	400,00
WPP 1Best	2015	137,00	137,00	520,19
WPP 2Best	2015	123,00	123,00	520,04
WPP 3Best	2018	105,00	105,00	519,96
WPP 4Best	2020	91,00	91,00	519,97
System	2013	0,00	0,00	0,00
System	2014	0,00	0,00	0,00
System	2015	260,00	260,00	1.040,23
System	2016	0,00	0,00	0,00
System	2017	500,00	500,00	400,00
System	2018	105,00	105,00	519,96
System	2019	0,00	0,00	0,00
System	2020	91,00	91,00	519,97
System	2021	0,00	0,00	0,00
System	2022	500,00	500,00	1.083,00
System	2023	0,00	0,00	0,00
System	2024	0,00	0,00	0,00
System	2025	0,00	0,00	0,00
System	2026	0,00	0,00	0,00
System	2027	0,00	0,00	0,00
System	2028	0,00	0,00	0,00
System	2029	500,00	500,00	1.083,00
System	2030	0,00	0,00	0,00

Figure 8-49: Printout of modeling results for scenario with CO_2 price = 20 EUR/tCO_2 - new power plants entering the power system

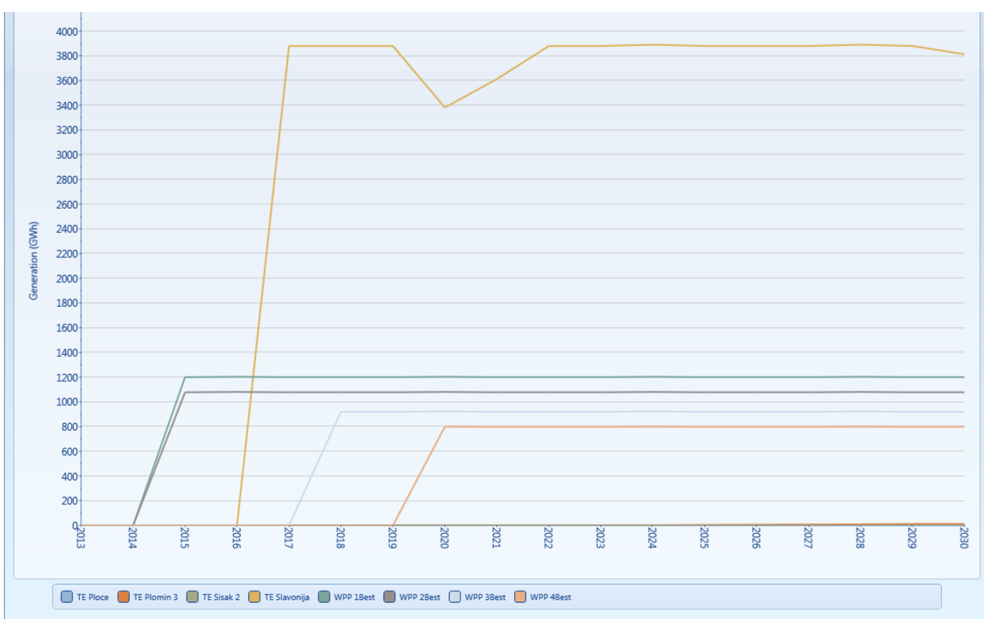


Figure 8-50: Generation from new power plants in the power system for scenario 40 EUR /tCO_2

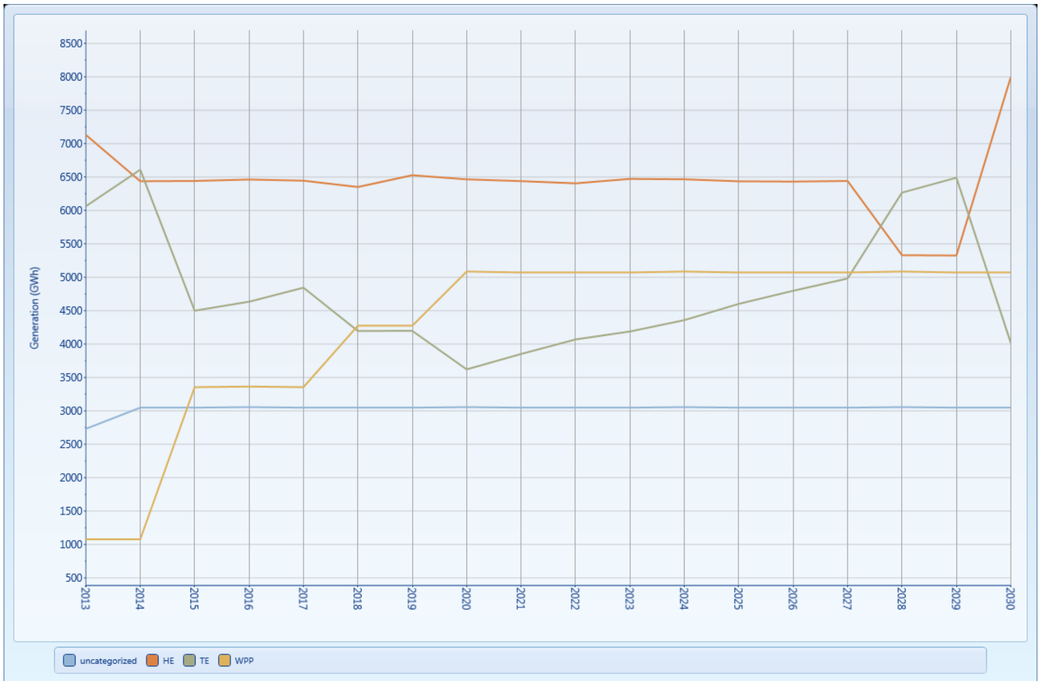


Figure 8-51: Generation from new power plants in the power system

8.4.6. Conclusions from modeling emission trading impacts on power system development in PLEXOS

Rise of CO_2 price has significant impact on competitiveness of low emission technologies in expansion of Croatian power system:

- For the referent scenario coal power plants are the most competitive and are scheduled first to enter the power system (TPP Plomin C in 2017 and TPP Ploce in 2026) – but if TPP Ploce was not pre-set to enter the system just after 2021 (by modeler) it might be expected that it would also enter the power system earlier than CCGT plant TPP Slavonia which entered the system in 2020;
- However, with scenario where emission price is 40 EUR/tCO_2, TPP Slavonia is the most competitive and enters the power system in 2017 (while TPP Plomin C enters in 2022 and TPP Ploce enters in 2029);
- In scenario where emission price is 20 EUR/tCO_2 breakeven point for investment decision between coal and gas is still not reached; but it has led to higher competitiveness of wind energy;
- Already at CO_2 price 20 EUR/tCO_2, all wind power plants have entered the power system and thus prolonged time for TPP Slavonia to enter the system in 2022 (two years later

than in the referent scenario) and TE Ploce enters the system in 2029 (four years after the referent scenario).

8.4.7. Scenario with climate change impact on hydro power production and wind power plants

This scenario is comparable to Referent scenario (zero emission price), but also models climate change impact on generation from hydro and wind power plants as an input to the power system model PLEXOS. As an input to further modeling, hydro power plants located in Southern Croatia are modeled with 10% lower generation in period 2020 – 2025; and with 20% lower generation in the period 2025 – 2030.

Wind power plants are modeled with 5% higher generation in period 2020 – 2025, and with 10% higher generation in the period 2025 – 2030 due to higher wind speed expected.

Figure 8-52: Organization of hydropower plants in PLEXOS according to geographical location of their storages and waterways – only those in Southern Croatia are modeled with climate change impact

Generator	Year	Build (MW)	Retire (MW)	Net Build (MW)	Cap. Cost (knMln's)
TE Ploce	2020	500,00	0,00	500,00	1.083,00
TE Plomin 3	2017	500,00	0,00	500,00	1.083,00
TE Slavonija	2027	500,00	0,00	500,00	400,00
WPP 1Best	2015	137,00	0,00	137,00	520,19
WPP 2Best	2015	123,00	0,00	123,00	520,04
System	2013	0,00	0,00	0,00	0,00
System	2014	0,00	0,00	0,00	0,00
System	2015	260,00	0,00	260,00	1.040,23
System	2016	0,00	0,00	0,00	0,00
System	2017	500,00	0,00	500,00	1.083,00
System	2018	0,00	0,00	0,00	0,00
System	2019	0,00	0,00	0,00	0,00
System	2020	500,00	0,00	500,00	1.083,00
System	2021	0,00	0,00	0,00	0,00
System	2022	0,00	0,00	0,00	0,00
System	2023	0,00	0,00	0,00	0,00
System	2024	0,00	0,00	0,00	0,00
System	2025	0,00	0,00	0,00	0,00
System	2026	0,00	0,00	0,00	0,00
System	2027	500,00	0,00	500,00	400,00
System	2028	0,00	0,00	0,00	0,00
System	2029	0,00	0,00	0,00	0,00
System	2030	0,00	0,00	0,00	0,00

Figure 8-53: Printout of modeling results for scenario with climate change impacts - new power plants entering the power system

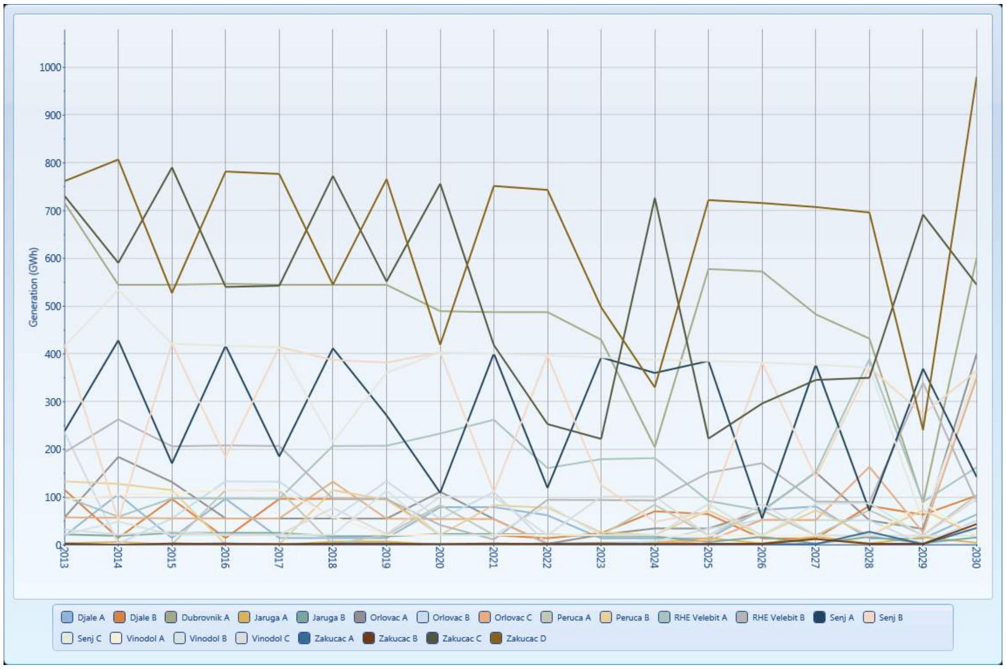


Figure 8-54: Change in generation from selected HPP due to climate change impact

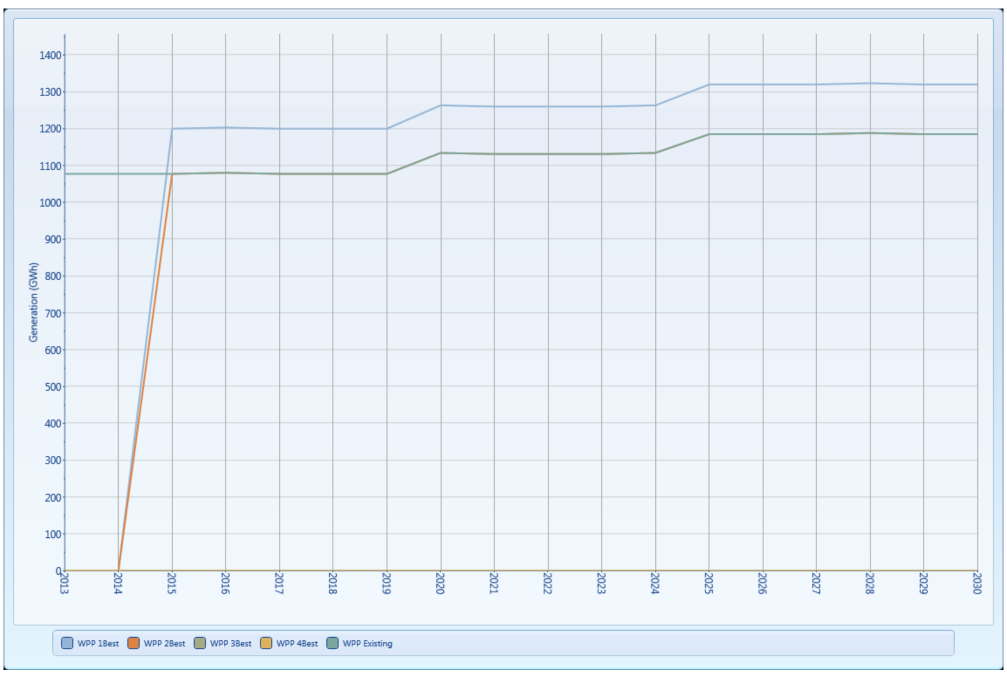


Figure 8-55: Rise in WPP generation due to modeled climate change impact on wind speed

From the modeling results it is visible that there is a decrease in generation from hydro power plants but on the other side there is an increase in generation from wind power plants that at some level offsets that decrease from hydro (not fully). Difference between referent scenario and climate change impact scenario is that TPP Ploce in this scenario enters the power system right after the TPP Plomin C, and TPP Slavonia enters only in 2027 – this happens as more base load is needed due to less generation from HPPs.

8.4.8. Measuring sustainable development indicators and prioritizing low emission technologies for Referent scenario

Impact on Referent scenario are measured and monitored, and compared to three other scenarios by using Model for measuring sustainable development indicators (such as already presented results in chapter 8.2.).

Also, in order to present importance of domestic manufacture of equipment, Referent scenario will be presented with three different sub-scenarios and results from their modeling will be presented and compared:

- Referent-Medium – assumes that low emission technologies are 50% domestically manufactured, 80% domestically installed and 80% domestically maintained;
- Referent-High – assumes that low emission technologies are 80% manufactured domestically, 100% domestically installed and 100% domestically maintained;
- Referent-Low – assumes that low emission technologies are 20% domestically manufactured, 50% domestically installed and 50% domestically maintained.

For representation of main model outputs, on a figure below result sheet is presented for main technologies. It is visible that low emission technologies are resulting in significant amount of GHG decrease – until 2030 wind reduces 6,9 MtCO_2, CHP biomass reduces 5 MtCO_2, EE measures in households reduce 9,8 MtCO_2. However in the same period coal power plants are generating 40 MtCO_2 more.

A total of more than 12.797 jobs is expected in 2030 from energy generation and EE sector, but main impact comes from EE measures in households (6.903 jobs), EE in public buildings (2.306 jobs), biomass heating (1.402 jobs). Wind energy brings 473 jobs, coal power plants 109 jobs and CCGT 13 jobs annually.

		Wind	PV	CHP biomass	Solar thermal	Biomass heating	Heat pumps	EE houses	EE public buildings	Coal	CCGT
Energy	Situation in 2030. compared to planned in Strategy [%]	60,00	100,00	82,76	100,00						
	New el.energy produced 2030. [GWh/year]	2.802,63	259,79	829,73						8.040,00	2.400,00
	New electrical power installed per year [MW/year]	65,94	11,76	6,51						59,12	23,53
	New thermal energy installed per year [MWt/year]				128,26	14,82	14,23	1.307,08	335,30		-59,88
	New thermal energy produced/saved 2030. [GWht/year]			1.383,35	1.762,27	1.007,62	464,72	5.228,30	1.341,20		2.400,00
	New biofuel energy produced 2030. [GWh/year]										
	Average new electrical energy per year produced [GWh/ye	1.401,31	129,89	414,86						4.020,00	1.200,00
	Average new thermal energy produced/saved per year [GWht/year]			633,35	881,13	503,81	232,36	2.614,15	670,60		
	Average biofuel energy per year produced [GWh/year]										
	Percentage of el. en. consumption 2030. [%]	13,92	1,29	4,12							
	Percentage of th. En consumption 2030 [%]										
Environment	GHG saved 2013. [t/year]	40.339,00	22,32	39.557,49	13.032,90	498.095,80	109.313,78	0,00	0,00	-1.392.400,00	-144.000,00
	New GHG saved 2030. [t/year]	812.761,25	48.320,34	591.661,20	440.567,10	251.904,20	106.886,22	1.150.226,00	295.064,00	-4.743.600,00	-216.000,00
	New GHG emissions for construction and running 2030. [t/y	112.105,00	37.409,30	41.818,14	17.622,68	10.076,17	13.941,68	209.132,00	53.648,00	7.396.800,00	1.008.000,00
	New GHG saved in the period [t]	6.908.470,63	410.722,93	5.029.120,20	3.744.820,35	2.141.185,70	908.532,87	9.776.921,00	2.508.044,00	-40.320.600,00	-1.836.000,00
Social (jobs)	Nuber of jobs created 2030 in manufacturing [jobs/year]	99	39	3	80	6	12	264	68	24	9
	Numbers of jobs created 2030 in instalation [jobs/year]	16	27	3	39	7	14	4.249	1.635	5	2
	Numbers of jobs created 2030 in maintenance [jobs/year]	359	211	213	411	1.408	79	2.390	613	80	2
	Number of jobs in 2030 [jobs/year]	473	277	219	530	1.421	105	6.903	2.316	109	13
											TOTAL JOBS: 12.797,64

Figure 8-56: Output sheet from Referent-Medium scenario and its impacts on energy environment and jobs

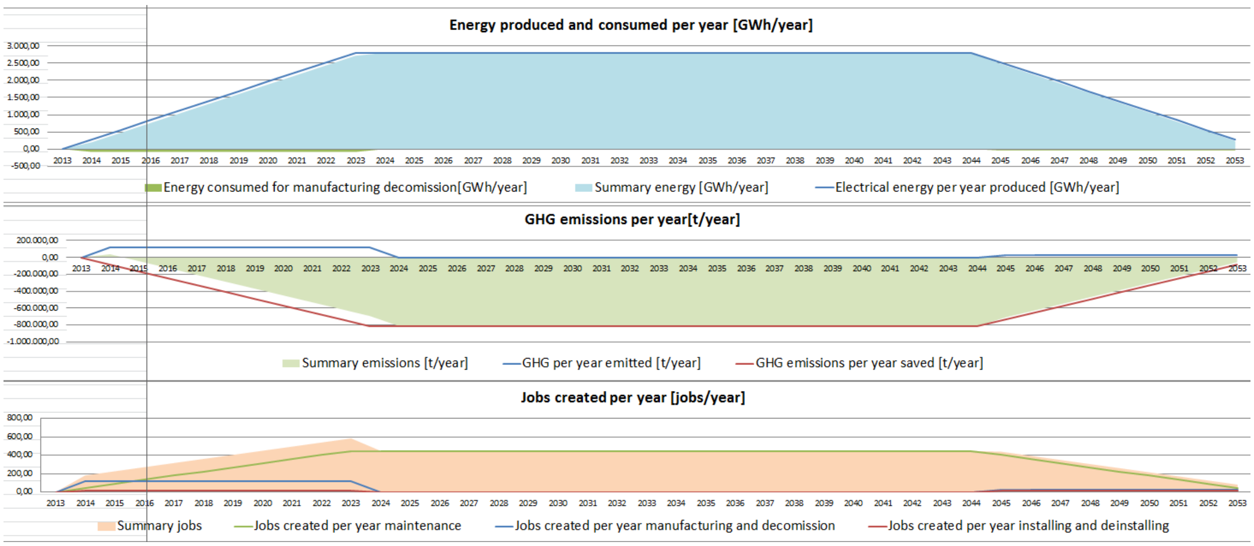


Figure 8-57: Output sheet for wind energy from Referent-Medium scenario and its impacts on energy, emission reduction and jobs

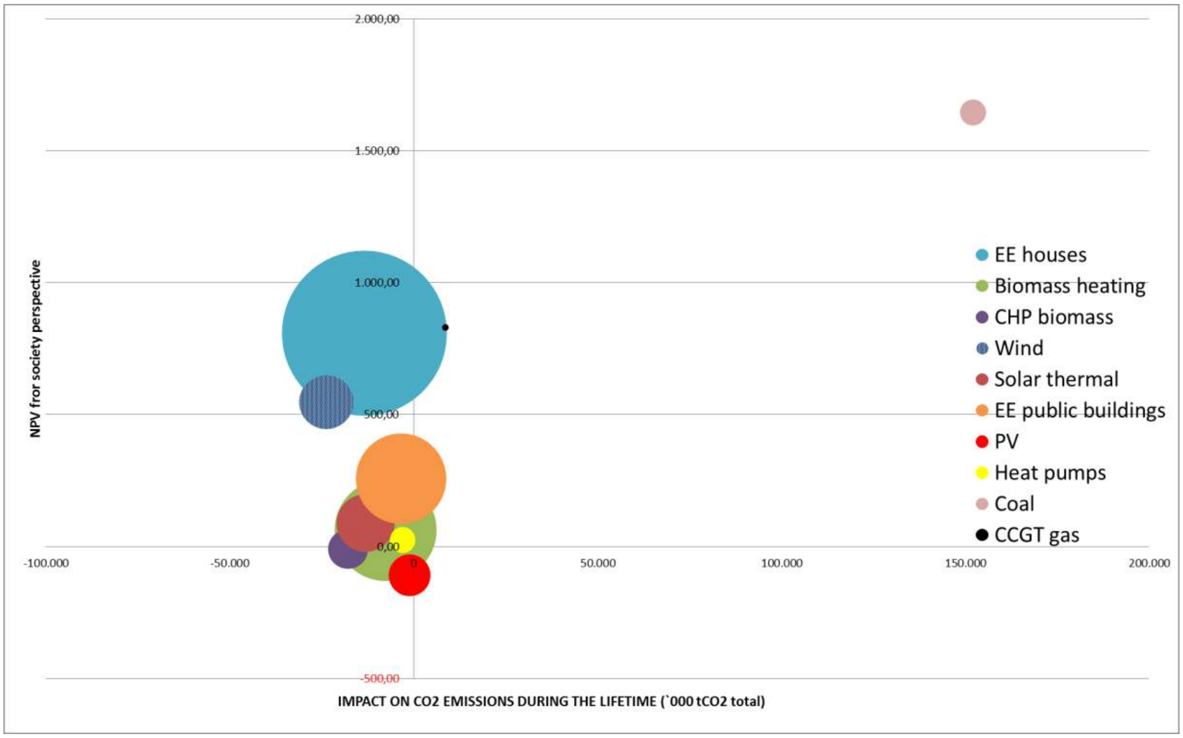


Figure 8-58: Comparation of energy generation and EE measures for Referent-Medium scenario: NPV (y–axis), impact on emission reduction (x-axis) and number of jobs (size of bubble).

From the Figure 8-58, it is visible that Coal has the highest NPV but also the highest emissions, while EE in houses has the highest impacts on jobs and together with wind energy highest impact on emission reduction.

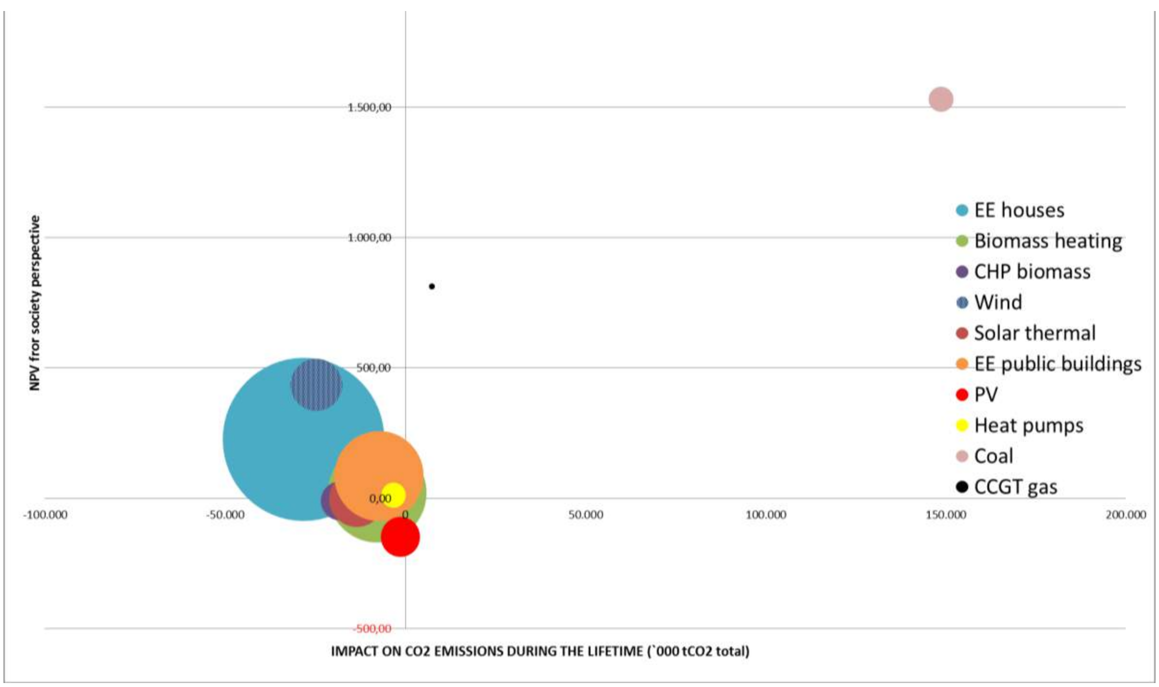


Figure 8-59: Comparation of energy generation technologies and EE measures for Referent-Low scenario

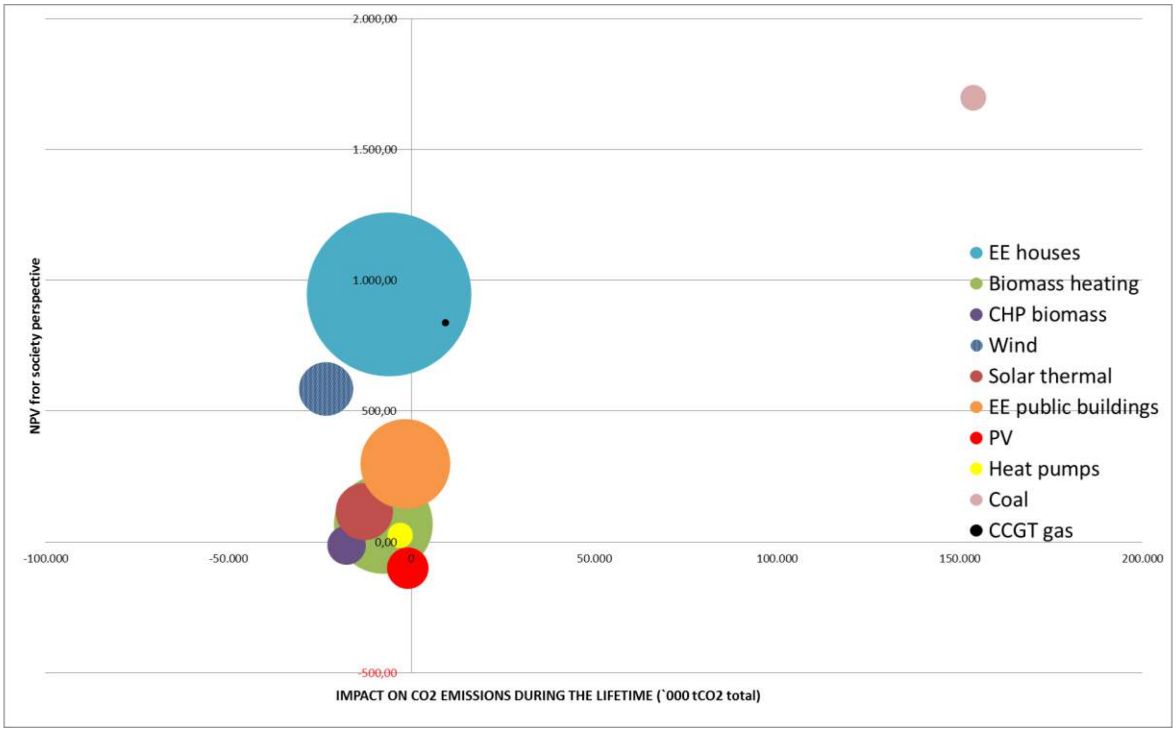


Figure 8-60: Comparation of energy generation technologies and EE measures for Referent-High scenario

It is visible from comparing results for Referent scenario with different sub-scenarios dependent on level of domestic production, installation and maintenance (Figures above) – that the biggest impact is on EE measures (refurbishment of houses and public buildings). Coal and CCGT are affected the least. Wind technology is not that much affected because they have a constant profit for energy they generated (10 EUR/MWh).

8.4.9. Measuring sustainable development indicators and prioritizing low emission technologies for Scenario 20EUR and Scenario 40EUR

Main difference in inputs for modeling scenarios 20EUR and 40EUR comes from higher CO_2 price –that influences profit of energy generating technologies (only wind, coal and CCGT are in focus of research). Another difference comes from the power plants that enter the power system – in both cases it means 800 MW more in wind power plants, while CCGT and coal remain the same (although as results from PLEXOS models have shown, they are coming later into power system and will have smaller operating working hours, especially coal power plants in Scenario 40EUR. Results from both scenarios with emission price are presented and compared below.

For both scenarios, only Medium sub-scenario of share of domestic equipment will be modeled and discussed. As output sheet depends on technology capacity installed, and it is the same in Scenario 20EUR and Scenario 40EUR; it is the same for both scenarios. The biggest difference towards Referent scenario comes from wind power plants (as other low emission technologies are not modeled in the same capacity in all scenarios – even though it is more likely that with rise of CO_2 price there would be more investments in EE measures and other renewable energy sources. But modeling other RES technologies was out of scope of research for this thesis, and only emission trading price on competitiveness of wind power plants was researched.

		Wind	PV	CHP biomass	Solar thermal	Biomass heating	Heat pumps	EE houses	EE public buildings	Coal	CCGT
Energy	Situation in 2030. compared to planned in Strategy [%]	100,00	100,00	82,76	100,00						
	New el.energy produced 2030. [GWh/year]	4.802,63	259,79	829,73						8.040,00	2.400,00
	New electrical power installed per year [MW/year]	113,00	11,76	6,51						59,12	23,53
	New thermal energy installed per year [MWt/year]				128,26	14,82	14,23	1.307,08	335,30		-59,88
	New thermal energy produced/saved 2030. [GWht/year]			1.383,35	1.762,27	1.007,62	464,72	5.228,30	1.341,20		2.400,00
	New biofuel energy produced 2030. [GWh/year]										
	Average new electrical energy per year produced [GWh/ye	2.401,31	129,89	414,86						4.020,00	1.200,00
	Average new thermal energy produced/saved per year [GWht/year]			633,35	881,13	503,81	232,36	2.614,15	670,60		
	Average biofuel energy per year produced [GWh/year]										
	Percentage of el. en. consumption 2030. [%]	23,85	1,29	4,12							
	Percentage of th. En consumption 2030 [%]										
Environment	GHG saved 2013. [t/year]	40.339,00	22,32	39.557,49	13.032,90	498.095,80	109.313,78	0,00	0,00	-1.392.400,00	-144.000,00
	New GHG saved 2030. [t/year]	1.392.761,25	48.320,34	591.661,20	440.567,10	251.904,20	106.886,22	1.150.226,00	295.064,00	-4.743.600,00	-216.000,00
	New GHG emissions for construction and running 2030. [t/y	192.105,00	37.409,30	41.818,14	17.622,68	10.076,17	13.941,68	209.132,00	53.648,00	7.396.800,00	1.008.000,00
	New GHG saved in the period [t]	###########	410.722,93	5.029.120,20	3.744.820,35	2.141.185,70	908.532,87	9.776.921,00	2.508.044,00	-40.320.600,00	-1.836.000,00
Social (jobs)	Nuber of jobs created 2030 in manufacturing [jobs/year]	170	39	3	80	6	12	264	68	24	9
	Numbers of jobs created 2030 in instalation [jobs/year]	27	27	3	39	7	14	4.249	1.635	5	2
	Numbers of jobs created 2030 in maintenance [jobs/year]	615	211	213	411	1.408	79	2.390	613	80	2
	Number of jobs in 2030 [jobs/year]	811	277	219	530	1.421	105	6.903	2.316	109	13
											TOTAL JOBS: 13.135,52

Figure 8-61: Output sheet from Scenarios 20EUR and 40EUR and its impacts on energy environment and jobs

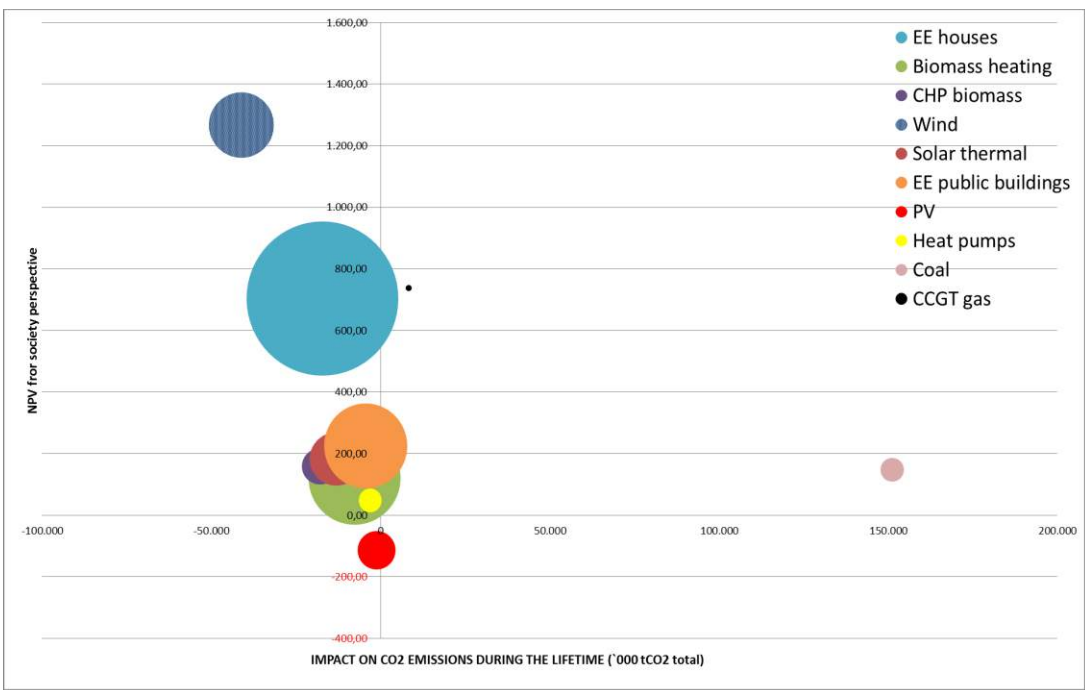


Figure 8-62: Comparation of energy generation and EE measures for Scenario 20EUR-Medium scenario

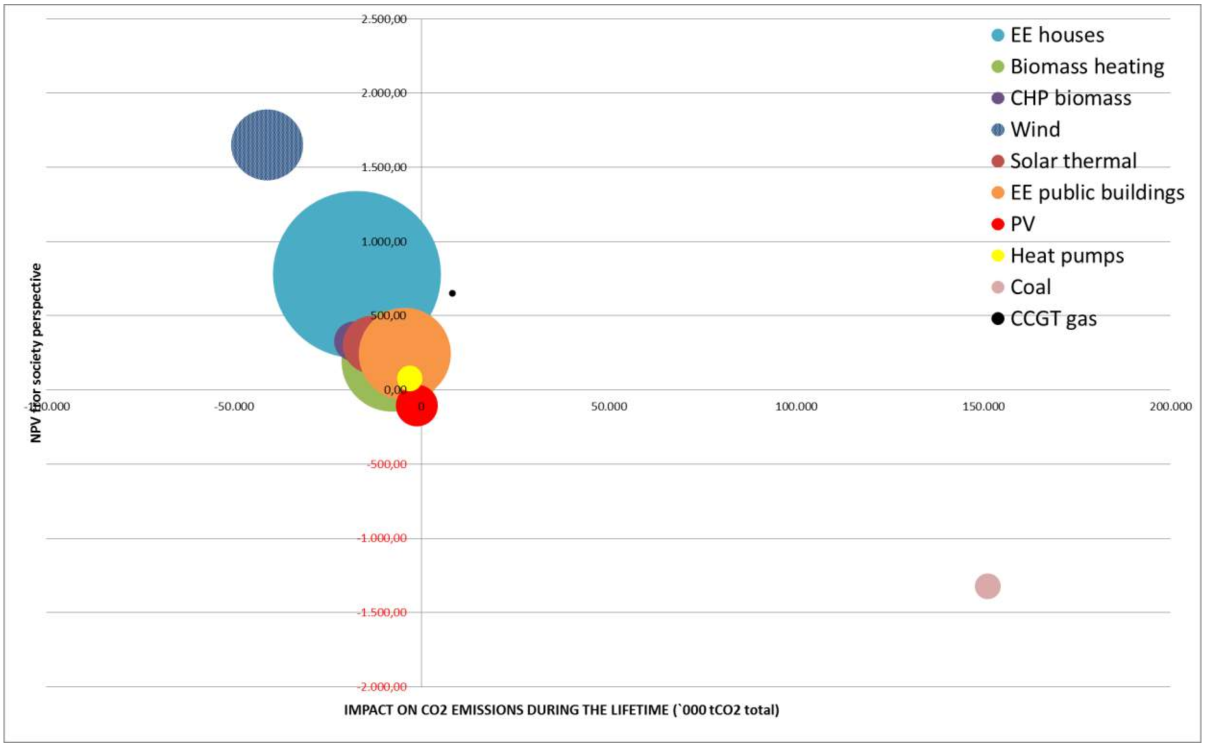


Figure 8-63: Comparation of energy generation and EE measures for Scenario 40EUR-Medium scenario

Three different scenarios were modeled in Model for measuring sustainable development indicators which was designed and verified within this thesis. Results from these modeling were further used as inputs to model PACE that enables easier visualization of these indicators. Three different indicators/characterizes of these scenarios were compared for different energy generation technologies and EE measures - NPV from society`s perspective, CO_2 reduction and number of jobs created.

When comparing Scenarios 20EUR and Scenario 40EUR to Referent scenario, it is visible from results presented that with rise of emission price, more jobs are created (from 473 to 811 green jobs in wind power plants for year 2030). In cumulative terms, during the lifetime of technology, in scenarios with emission price, total number of green jobs is 21.499 men-years compared to 12.546 men-years.

One of the results from emission price is emission reduction until 2030 due to higher wind capacity installed – 0,81 $MtCO_2$ in Referent scenario, compared to 1,4 $MtCO_2$ in two scenarios with emission price; cumulative amount of emission reduction during the lifetime of technology is 24,028 $MtCO_2$ compared to 41,175 $MtCO_2$.

8.4.10. Overall conclusions from integrative modeling

Results from integrative modeling performed on Croatian power system in this chapter are confirming set hypotheses that:

- Interpretation of climate change modeling data is necessary to be included in power system planning in order to address vulnerability and adaptation issues – there is expecting decrease of generation from hydro power plants, especially in southern Croatian in summer months; while there is expected increase in generation from wind power plants, especially in southern Croatia;
- Emission trading impacts on power system operation and development increases competitiveness of low emission technologies – as modeling results have shown, even modest emission price (between 10 and 20 EUR/tCO_2) makes wind power plants more competitive than coal and CCGT;
- Transition from fossil fuels to renewable energy sources brings positive measurable effects to sustainable development – economic, social and environmental – such as emission reduction, number of new jobs, reducing electricity prices etc;
- Climate change has important impact on competitiveness of low emission technologies, both in mitigation and in adaptation aspect!

9. CONCLUSIONS

Proposed methodology and developed models and algorithm are assessing emission trading and climate change impacts on sustainable power system development through the increase of competitiveness of low emission technologies. The holistic approach is in the center of research, to present how climate change adds new complexities to power system planning, and how choices on which power plants to build have impacts on society, economy and environment. With defined indicators that are traceable and measurable, impact of power system planning decisions on sustainable development can be understood.

9.1. Summary of research conclusions

Conclusions from the research performed in this thesis are summarized in the following:

- Climate change and emission trading impacts on power system planning and operation are becoming one of the important factors that should be considered;
- Existing models have proved not sufficient anymore and there is a need for modelers and planners to think differently in order to face new challenges and complexities coming from climate change impacts on power system. New methodologies and models need to be developed to understand these challenges that, on the basis on performed simulations, should enable planner to distinguish between different options, and think of them in a holistic approach – not only in the matter of satisfying energy needs, or maximization of profit, but to understand full impact on sustainable development;
- Power system planning is a dynamic iterative process with stochastic elements that demand inputs at several layers, defining realistic constraints and decision paths to analyze possible future scenarios of power system development, and the impacts from energy and emission markets, energy security issues and social demands. All of these challenges are bringing more complexity in the assessment of power system modeling and all the results from modeling different scenarios should be understood as a guiding hand for planning and in decision making;
- Models and methodologies are just a tool, a decision aid, and the planner is the one who (from modeling results and bearing in mind priorities for power system planning, and having the knowledge of the system and constraints) should bring conclusions;

- The crucial part of power system modeling process is the level of knowledge by the planner/modeler of the power system, understanding technologies and markets, long term perspectives and limitations in technical and economic side of power system, dispatch and market rules, special needs from renewable energy sources etc;
- Modeling emission price impact on a power system for a year ahead doesn't include investors' decisions as one year period is too short to have impact on a power system expansion;
- However, modeling emission trading impact on power system in short and medium term can be indicative for investors as they help in understanding competitiveness of existing power plants and how does it change with emission price increase – in such a way it sends a signal to investors and regulators;
- Impacts of emission price increase on a power system or power plant cannot be analyzed separately but generation and trade should be optimized with price developments on other connected markets (external electricity markets, coal/gas/oil markets, technology markets, emission markets) - these markets are closely interlinked and should be analyzed together;
- Power system modeling of emission trading impacts on a power system in the long term period can provide help in understanding important characteristic for regulators, planners and investors such as emission amount from the power system in the future, impacts on electricity price; rise in generation costs from power plants based on fossil fuels;
- Proposed methodology and models can help in measuring and understanding the rise in competitiveness of low emission technologies and in their investments in a power system;
- In order to measure sustainable dimension of power system development, new models and methodologies are needed, or existing models need to be upgraded with new functionalities;
- Centralized planning makes it easier to deliver emission reduction targets, and targets on renewable energy sources – which can be achieved with setting up appropriate market mechanisms and policies and adjusting them if they are not reaching the set targets;
- Results from modeled scenarios are showing importance of emission price on competitiveness of low emission technologies. It also shows the importance of domestic

component in manufacturing, installation and maintenance of this technology – in order to reduce its price to the society that supports it;

- Modeling results are showing that it is possible to measure effectiveness and cost efficiency of supporting low emission technologies with subventions (in the Croatian case with feed-in tariffs);
- The challenge of energy policy based on subsidies for renewable energy technologies is to achieve greater benefits in terms of new jobs, reduced GHG emissions, tax collection and the acquisition of knowledge and experience for competition on the open market than is the cost of the increased energy price in the start-up period;
- Even though some power generation technologies like PV still demand high subventions from the society, in a cost-benefit analysis they can be economically justified if high domestic component is ensured (in regard to the number of jobs created, transfer of new technology with high prospect for the future etc.), and if subventions are set realistically;
- Power systems models do not usually represent intermittent renewable energy sources realistically (especially for wind energy but also in solar and run-off hydro energy);
- Most power systems models assume perfect market conditions which does not realistically explain the relationships on electricity, energy and emission markets;
- When making decision for traditional power sources between coal, nuclear and gas, emission price can have determining role for choosing the right technology;
- In order to ensure emission price has a prevailing impact on investment decisions, it is important to have mature emission markets and maintain a certain emission price floor (minimal price) through policy interventions;
- Results from assessment of climate change impacts on renewable energy sources are showing importance of addressing these impacts in long term power system planning;
- Especially high impact on power system planning in Croatia are in wind and hydro power plants; therefore vulnerability and adaptation measures need to take place to ensure climate change impacts in the future;
- Developed models and methodology could serve as a very useful tool in optimizing strategic policy measures and planning of low-carbon and sustainable future.

9.2. Future research directions

As explained in the Introduction chapter, the scope of this thesis is limited in order to present wide area of needs in power system operation and planning. One of the outcomes from this are proposed future research directions:

- Expanding power system models so they can simulate non-perfect market conditions;
- Expanding power system models to be able to model more realistically intermittent renewable energy sources;
- Existing power system models need to be improved (or new tools developed) that would enable using sustainable development indicators for holistic understanding of planning decisions;
- Improving regional and global climate models for achieving more reliable estimates of climate change on a regional and local levels, and more detailed analysis about impact of these changes on different renewable sources for energy production;
- Improving power system planning and power system models that would enable better understanding of climate change impacts on a power system;
- Detailed assessment is needed on climate change impacts on the demand side (consumption patterns) and conventional power plants (that was not covered in this thesis);

9.3. Recommendations for power system planners, policy and decision makers

Having in mind limits and scope of the research performed in this thesis, some of the recommendations for power system planners and policy and decision makers as a result of this thesis include:

- Existing power system plans and strategies should be revised, ensuring that power system development is focused on delivering net positive sustainable development impact;
- Climate change adaptation should be included in process of planning future generation and demand;

- Before some policies are implemented, they should be carefully studied and modeled in order to understand its full range of impacts on sustainable development (social, economic and environmental aspect);
- Regional power system modeling is necessary to understand relationships in neighboring countries, so this should be the priority to enable more cooperation in long term generation expansion;
- New mechanisms need to be set up that would support less risky long term investment in power system infrastructure which delivers benefits to sustainable development.

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ANNEX 1: A LIST OF PUBLICATIONS REVIEWED DURING THE WORK ON THESIS, ON TOPICS OF GREEN GROWTH, GREEN ECONOMY AND LOW EMISSION GROWTH STRATEGIES

Title: A guidebook to the Green Economy

Author/publisher: United Nations Division for Sustainable Development

Year: 2012

Topic: Introduces the Related concepts: Green economy, green growth and low-carbon development then lists Publications.

Dimensions: Defining the Green Economy and listing resources and national strategies, Defining the Green Growth and listing resources and national strategies, Defining the Low carbon development and listing resources and national strategies.

Title: Towards Green Leapfrogging- successful transition to green growth – Korean Case

Author/publisher: M.K. Lee

Year: 2012

Topic: Transition to green growth. Provides short overview of global trends in green growth from different countries, introduces the Global Green Growth Initiative (GGGI) and explores in detail Koreas Transition to Green Growth, the history, motivation, plan/vision and objectives, finance and challenges and the road ahead.

Dimensions: Explores the economic dimension thoroughly with indicators of environmental and social sustainability, emissions reduction

Title: Institutional Arrangements For Advancing Sustainable, Low Carbon Growth And Development

Author/publisher: Project Catalyst

Year: 2009

Topic: Specifically the institutional arrangements and capacity development necessary for low carbon growth and development - key design parameters and options and the institutional imperatives for low carbon pathways to green growth.

Dimensions: Explores the institutional aspects of management towards green growth. Does not cover environmental, social or economic imperatives in detail, rather the institutional dimension necessary to achieve green growth.

Title: Green jobs in Croatia

Author/publisher: UNDP Croatia

Year: 2009

Topic: Analysis of investment in renewable energy and the possibility to develop the local economy, create jobs and competitive Croatian products. Analysis attempts to identify strategic areas and achievable goals for the implementation of energy efficiency in building construction and the production from renewable energy sources in Croatia. The analysis provides an overview of the potential number of green jobs through the achievement of those goals, estimates the total reduction in greenhouse gas emissions

Dimensions: Job creation and social development

Title: National Strategies for Sustainable Development

Author/publisher: Darren Swanson and László Pintér - International Institute for Sustainable Development

Year: 2004

Topic: Utilizing a case study of 19 different countries this article explores the challenges, approaches and innovations in strategic and coordinated action. Prepared to assist government managers and policy-makers, more about sustainable development than green growth

Dimensions: All aspects of sustainable development

Title: Green Growth - The impact of wind energy on jobs and the economy

Author/publisher: European Wind Energy Association

Year: 2012

Topic: Explores how wind energy as not only a solution to climate change and a way to improve energy security, but also a way to boost economic growth and competitiveness.

Dimensions: Economic investments, economic stimulation, growth and job creation

Title: Green Growth, Resources and Resilience – environmental sustainability in Asia and the Pacific

Author/publisher: Asian Development Bank and UNEP

Year: 2012

Topic: Describes an evolving policy landscape in which rising demand for resources, along with increasingly apparent impacts from climate change. Provides a detailed examination of resource use and efficiency trends, showing the complex nature of resource risks posed by the scale and speed of the economic transition and resource-intensive patterns of growth. Outlines key policy actions for bringing economic growth strategies in closer alignment with the objective of sustainable development. How new governance challenges can be addressed at a number of levels, from international and regional governance structures down to national and local levels. Finally provides illustrative strategies to promote improved resilience, a concept that centers on the capacity of societies and economies to resist and adapt to shocks and, whenever possible, turn crisis into opportunity.

Dimensions: All aspects, environmental, economic and social dimensions of green growth

Title: Towards Green Economy – Pathways to sustainable development and poverty eradication

Author/publisher: UNEP

Year: 2011

Topic: UNEP's report, Towards a Green Economy, aims to debunk several myths and misconceptions about greening the global economy, and provides timely and practical guidance to policy makers on what reforms they need to unlock the productive and employment potential of a green economy.

Dimensions: All aspects, environmental, economic and social dimensions of green growth and specifically what reforms are needed to achieve green growth

Title: Green Growth Indicators Database

Author/publisher: OECD

Year: 2012

Topic: Contains information and indicators of green growth for many countries

Dimensions: The socio-economic context and characteristics of growth, Environmental and resource productivity, Monitoring the natural asset base, Monitoring the environmental quality of life, Monitoring economic opportunities and policy responses,

Title: Fostering Innovation for Green Growth – Green Growth Studies

Author/publisher: OECD

Year: 2012

Topic: Addresses the role of innovation in green growth strategies and their contribution to OECD Green Growth Strategy

Dimensions: Explores mainly innovation in Green Growth

Title: Energy Roadmap 2050

Author/publisher: European Commission

Year: 2011

Topic: Explores the challenges posed by delivering the EU's decarbonisation objective while at the same time ensuring security of energy supply and competitiveness

Dimensions: Routes towards decarbonisation of energy system in a number of scenarios, Structural changes for energy system transformation, Challenges and opportunities in moving from 2020. to 2050.

Title: Re-thinking 2050. A 100% Renewable Energy Vision for the European Union

Author/publisher: European Renewable Energy Council

Year: 2010

Topic: Outlines a pathway towards a 100% renewable energy supply system by 2050 for European Union.

Dimensions: Comprehensive estimate of the economic, environmental and social benefits associated with this move; Focuses on the policy recommendations considered necessary to tackle the non-technical barriers to achieve this vision

Title: Low Carbon Growth Country Studies – Getting Started

Author/publisher: Energy Sector Management Assistance Program

Year: 2010

Topic: Explores six emerging economies and their proactive seek to identify opportunities and related financial, technical and policy requirements to move towards a low carbon growth path.

Dimensions: Review of country –specific studies to assess their development goals and priorities, in conjunction with GHG mitigation opportunities, and examine the additional costs and benefits of lower carbon growth

Title: A Roadmap for moving to a competitive low carbon economy in 2050

Author/publisher: European Commission

Year: 2011

Topic: Sets out key elements that should shape the EU's climate action helping the EU became a competitive low carbon economy by 2050.

Dimensions: The approach is based on the view that innovative solutions are required to mobilise investments in energy, transport, industry and information and communication technologies, and that more focus is needed on energy efficiency policies. Key deliverable under the Resource Efficiency Flagship. Presents a Roadmap for possible action up to 2050 which could enable the EU to deliver greenhouse gas reductions in line with the 80 to 95% target agreed.

Title: Working for the climate – Renewable energy & the green job [r]evolution

Author/publisher: European Renewable Energy Council

Year: 2009

Topic: Elaborate thesis that the climate crisis and the financial crisis are not two competing issues that need to be addressed separately by the world community. Investment in energy efficiency and renewable energy helps the community by increasing employment in the power sector, while reducing energy costs and easing the over-use of preclous natural resources.

Dimensions: Sets out a vision of how to achieve cutting carbon emissions. Scenario explains how, technically and financially, the world could increase its production of renewable energy by nine times, replacing nuclear and a proportion of coal-fired power, to avoid catastrophic climate change.

Title: 100% renewable electricity – A roadmap to 2050 for Europe and North Africa

Author/publisher: Pricewaterhouse Coopers

Year: 2010

Topic: This report gives a comprehensive outlook towards an electricity system for Europe and North Africa based completely on renewable energy in 2050. Focuses on the pan-regional policy and market developments that would be necessary.

Dimensions: Points out that this goal will be the result of an evolutionary development mainly of the economical, legal and regulatory framework and does not require fundamental technological breakthroughs.

Title: Moving towards 100% renewable electricity in Europe & North Africa by 2050

Author/publisher: Pricewaterhouse Coopers

Year: 2011

Topic: This latest report provides a complementary analysis to the original roadmap (A roadmap to 2050 for Europe and North Africa)

Dimensions: Examines five areas that are most critical to achieving progress and, through the lens of these five areas, looks at the impact of recent and current events.

Title: Case studies of sustainable development in practice – Triple wins for sustainable development

Author/publisher: UNDP

Year: 2012

Topic: Suggests what it takes to move towards sustainable development and sets out national examples of progress toward sustainable development.

Dimensions: Shows progress in developing countries like Nepal and Niger, as well as emerging economies like South Africa and Croatia. These examples show how social, environmental and economic progress can be integrated to make a more sustainable future. Suggests six key principles that are needed to reset the global development agenda.

Title: Readiness for Climate Finance

Author/publisher: UNDP

Year: 2012

Topic: Presents a framework for understanding what It means to be "ready" to use climate finance in a transformative way at the national level.

Dimensions: In the context of the financial challenges posed by climate change, including the scale of financing required and the barriers to the effective use of climate finance, the paper presents a four-part framework through which to understand the different components of readiness and the specific capacities needed to underpin it.

Title: Towards a green economy

Author/publisher: UNEP

Year: 2011

Topic: Makes a compelling economic and social case for investing two per cent of global GDP in greening ten central sectors of the economy in order to shift development and unleash public and private capital flows onto low-carbon, resource-efficient path.

Dimensions: Offers not only a roadmap to Rio+20 but beyond 2012.

Title: Towards a green economy – Pathways to Sustainable Development and Poverty Reduction

Author/publisher: UNEP

Year: 2011

Topic: Towards a Green Economy is among UNEPS's key contributions to the Rio+20 process and the overall goal of addressing poverty and delivering a sustainable 21st century.

Dimensions: The report makes a compelling economic and social case for investing two per cent of global GDP in greening ten central sectors of economy in order to shift development and unleash public and private capital flows onto a low-carbon, resource-efficient path.

Title: Green Jobs: Towards decent work in a sustainable, low-carbon world

Author/publisher: UNEP

Year: 2008

Topic: this report shows for the first time at global level that green jobs are being generated in some sectors and economies

Dimensions: The bulk of documented growth in Green Jobs has so far occurred mostly in developed countries, some rapidly developing countries like Brazil and China, but are also beginning to be seen in other developing economies. It appears that a green economy can generate more and better jobs everywhere and that these can be decent jobs.

Title: Renewable Revolution: Low-Carbon Energy by 2030

Author/publisher: Janet L. Sawin and William R. Moomaw

Year: 2009

Topic: This report examines the potential for renewable energy to provide needed energy services for all societies while lowering heat-trapping emissions of greenhouse gases.

Dimensions: Recent advance in technology and policy will allow renewable energy and energy efficiency to play major roles in meeting global energy service demand while reducing carbon dioxide emissions in the next two decades.

Title: The Energy Report – 100% renewable energy by 2050

Author/publisher: WWF

Year: 2009

Topic: This report shows that transition to renewable sources is not only possible but also cost-effective, providing energy that is affordable for all and producing it in ways that can be sustained by the global economy and the planet.

Dimensions: Presents bold and ambitious scenario – which demonstrates that it is technically possible to achieve almost 100 per cent renewable energy sources within next four decades.

ANNEX 2: A LIST OF MODELS USED IN POWER SYSTEM MODELING

MESSAGE/MARKAL/NEEDS

MARKAL and MESSAGE models both belong to group of optimization models for long-term energy system planning. MESSAGE model was developed by IIASA (International Institute for Applied System Analysis). It is optimization model for long-term energy system planning. MARKAL is developed within project by IEA (International Energy Agency).

GREEN

GREEN is General Equilibrium Environmental Model. It is developed by the OECD Secretariat and presents an example of general equilibrium model for multi-region, multi-sector, dynamic applied modeling to quantify the economy-wide and global costs of policies to curb carbon dioxide (CO_2) emissions.

SIPRA

SIPRA model was developed in Croatia. The name stands for simulation of generation expansion planning (SImulacija Planova RAzvoja), and is used for determination of number, type and dynamics of new power plants to enter the power system. SIPRA allows comparison of more power plants by comparing their technical and economical characteristic. Results from this comparison are used for determination of optimal generation mix. Candidate power plants are modeled together with their individual characteristics and costs.

SIPRA model finds optimal solutions by providing big number of simulations, after which the one with minimal costs is chosen (optimization with mathematic programming is not used in modeling). This is a model disadvantage since number of combinations gets very large and it is not practical to simulate each one of them separately.

ENPEP (MAED, WASP, VALORAGUA, BALANCE, GTMAX)

ENPEP (Energy and Power Evaluation Program) is a group of analytical models for energy-economic-environmental analysis of energy sector. It was developed in Argonne National Laboratory (Illinois, USA) under sponsorship of IAEA (International Atomic Energy Agency).

Different models within ENPAP are connected between themselves (as presented on the figure bellow), but can also be used autonomously.

Model MAED is used for long term demand forecast of whole energy sector. By using various indicators, in bottom-up approach this model is calculating total energy consumption for each sector. MAED defines social, economic and technological parameters that have influence on energy consumption. These parameters are used to construct various development scenarios, upon which the most probable scenario is chosen. From this scenario, electricity consumption is converted to hourly schedule and is ready to be used by WASP model.

BALANCE model is used for calculation of total energy balance. Simulation is using market share approach and has possibility to implement subsidies, energy and environmental taxes. Disadvantages are that electricity load distribution is the same for base and additional years and that just a limited scale of energy conversion node is available.

WASP model (Wien Automatic System Planning Package) is focused on optimal long-term generation expansion planning. Optimal solution is minimal net present value of total costs from electrical energy system. Main disadvantage is that it cannot be properly used in open electricity market. Once formulated, optimization problem is solved with mathematical programming.

GTMax

GTMax is focused on medium and short-term operation planning of power plants in deregulated market conditions. The GTMax was developed by Argonne National Laboratory (Illinois, USA), with aim to provide detailed analysis of utility systems operations and costs in an open market. With GTMax, utility operators and managers can maximize the value of the power system taking into account not only its limited energy and transmission resources, but also firm contracts, independent power producer (IPP) agreements, and bulk power transaction opportunities on the spot market.

GTMax maximizes net revenues of power systems by finding solutions that increase income while minimizing expenses. At the same time, the model ensures that market transactions and system operations remain within the physical and institutional limitations of the power system. When multiple systems are simulated, GTMax identifies utilities that can successfully compete in the market by tracking hourly energy transactions, costs, and revenues.

An added benefit of GTMax is that it simulates some limitations, including power plant seasonal capabilities, limited energy constraints, transmission capabilities, and terms specified in firm and IPP contracts. Moreover, GTMax also considers detailed operational limitations, such as power plant ramp rates and hydropower reservoir constraints. Currently, power utilities are using GTMax to determine hourly, weekly, and seasonal power and energy offers to customers and to compute the costs of environmental legislation. GTMax can also be used to fine-tune hourly resource generation patterns, spot market transactions, energy interchanges, and power wheeling on the transmission system.

Valoragua

Objective in development of this model was to determine the optimal generating strategy in a mixed hydrothermal power system. The optimal operation strategy is obtained for the system as a whole, with an emphasis on detailed simulation and optimization of the hydro subsystem operation. Model VALORAGUA can simulate the operation of all types of hydropower plants (run-of-river, weekly, monthly, seasonal, or multiannual regulation), including pumped-storage plants and multipurpose hydro projects. The model calculates possible production by hydropower plants on the basis of either a historical series of monthly water inflows or synthetic water inflows with associated probabilities of occurrence. VALORAGUA can determine the optimal operation of up to 50 reservoirs in as many as 18 hydro-cascades in the system. It can calculate the marginal value of water in reservoirs at all times of the year. The mathematical expectancy of the future value of water is the basis for deciding whether to use the water from the reservoirs now or to retain it for later use (when water value could be higher for the same quantity of water).

Great advantage of VALORAGUA models is the possibility to link with other models (such as DECPAC or EMCAS) and to provide better modeling possibilities on production from hydro power plants. It can be also used for generation expansion planning (long-term planning). Model disadvantage is static representation of system, so dynamic long term planning cannot be modeled sufficiently (as it would demand large number of different simulation scenarios).

Table 0-1: list of models depending on the application. Source: own review

Deregulated power market analysis	GTMax, EMCAS, Power Market Simulator, PLEXOS, PROMOD, Griedview
Capacity expansion analysis	WASP, PACE, DECADES, PLEXOS, SIPRA, Strategist
Electricity demand forecasting and analysis	MAED, MARKAL, MESSAGE, NEEDS, Powerbase
Optimizing of hydropower resources	VALORAGUA, PLEXOS, PROMOD
Production cost analysis	VALORAGUA, PLEXOS, MarketPower, Griedview
Marginal cost analysis	WASP, VALORAGUA, PLEXOS, MarketPower, Griedview
Emission trading	PLEXOS, PowerACE, PERSEUS
Intermittent renewable energy sources	PLEXOS, PROMOD

DECADES/DECPAC

In order to achieve better understanding on electrical system planning, international joint project focused on data bases and methodologies was set in 1993 under name DECADES (Data Bases and Methodologies for Comparative Assessment of Different Energy Sources for Electricity Generation). University of Zagreb participated in project development from its start, developing country-specific. Model developed within project consists of three different parts: databases, methodologies and graphical interface.

The DECADES project addresses some, but not all of the issues involved in comparative assessments of different electricity generation options and strategies. The project principally aims toward providing comprehensive information about different energy chains for electricity generation and user friendly tools for accessing, handling, and processing key information needed for planning and decision making purposes.

DECADES data bases consist of newest data on different technology chains for electricity generation. Different data bases were developed, focused on reference technologies (RTDB), country specific data bases (CSDB), toxicology data base (TXDB), health and environmental impacts of different power systems (HEIES) and vendor specific database of available commercial technologies.

DECADES methodology describes electricity generation technology chains (but unlike life cycle analysis, material production for various components were not taken in account). Several algorithms were developed for estimation of emissions from power plants. Implied methodology gives possibility to analyze emissions and production costs from different power plants, and also to directly compare available electricity generation technologies.

DECPAC is integrated program package which aims to help in complete analysis of power system and in valuation of different development strategies in next 30 years. Already mentioned WASP model was readjusted and expanded with new features so it is able to analyze environmental impacts of electricity generation technologies. It has rather simplified computational routine than WASP. Users can evaluate not only electric power generation technologies, but also the fuel supply chain for each technology. DECPAC allows comparative analyses of alternative power generation technologies. DECPAC consists of three modules:

(i) ELECSAM for power system expansion;
(ii) PRENSAM for primary energy supply analysis and
(iii) ENVIRAM for the environmental analysis

PowerBase Suite

PowerBase Suite is a set of models from Ventyx Energy Company. PowerBase Suite gives comprehensive energy market data repository (generating units, fuels, demands, transmission…). It uses powerful scenario / case data management system that provide a flexible and robust way to organize data into subsets and to manage data changes. Developed containers (each one referred to a case) can hold data at any level of detail and for any number of entities.

PROMOD IV is detailed nodal electricity market simulation tool that incorporates full transmission modeling and a security constrained unit commitment and dispatch, with Monte Carlo modeling of generator unit random outages. PROMOD models the dynamics of the electricity market by determining the effects on hourly locational marginal prices (LMP) prices of transmission congestion, fuel costs, generator and transmission availability, marginal costs approach (or bidding behavior) and load growth.

In addition to unit capacity changes, users can enter data for modeling future changes of unit variable O&M, heat rates, emission production rates, and most other inputs. Detailed unit operational parameters such as must-run status, minimum unit capacity, minimum downtime, minimum runtime, startup costs, ramp rates, heat rate curves, and operating reserve contribution may also be entered on a specific unit basis. Model includes equipment outage scheduling and simulation of future generators and transmission upgrade projects, retirements etc.

The hourly decomposition of LMP prices into energy, congestion and loss components allows understanding of the drivers of LMP for a particular hour or for multiple hours in the system. Some features from PROMOD that are not available in PLEXOS or other models:

- PROMOD diagnostic that states which generator influenced the marginal cost of the run or binding constraint;
- Error checking;
- Detailed description of wind generation in the model;
- Easy representation of various cases. Different cases can be simulated in multiple scenarios and can easily be added or removed from a scenario using "drag and drop" functionality. A traditional difficulty with many applications that utilize different data cases is the inability to see the final merged scenario data that will be used in a simulation.

Models key design features are:

- Maximizing profit by assessing market opportunities and evaluating individual transaction costs and feasibility;
- Analyzing complexities and risks associated with transmission access to plant locations, power contracts, and unit production costs;
- Evaluation of system resource needs and fuel requirements, generation asset utilization and plant profitability;
- Evaluation of competing bids, plant schedules, transmission services, generation costs, and historical performance.

Market Power is a complete market price forecasting system that forecasts energy market prices as well as capacity market prices. It performs Monte Carlo simulations around uncertain demand, generator availability, hydro conditions, fuel prices, and economic conditions. It can be used to evaluate capacity mothballing, expansion and retirement alternatives based on economic analysis. Market-driven algorithms give opportunity for adaptive market simulations, flexible data structure, and customized reports. Model also evaluates deviations from economic equilibrium supply markets and their inputs.

Gridview

Gridview is ABB`s market simulator. What makes GridView distinctive from the competition is very detailed representation of power transmission networks (as most industry models bear little resemblance to real power systems and ignore transmission constraints). Model was developed to simulate security constrained unit commitment and economic dispatch in large-scale transmission networks. It produces unit commitments and economic dispatches that respect the physical laws of power flow and transmission reliability requirements. As such, the generation dispatch and market clearing price are feasible market solutions within real power transmission networks. Following generation and market studies can be performed with Gridview:

Generation Studies

- Plant sitting and cycle optimization;
- Bidding strategy assessment;
- Asset evaluation and management;
- Portfolio optimization and risk management;
- Plant market performance analysis;
- Generation interconnection evaluation;

Market Studies

- Price forecasting and volatility analysis;
- Benefit and cost evaluation for stakeholders;
- Congestion management and value of congestion relief;
- Evaluation of forward energy contracts;
- Capacity value studies;
- Market power analysis and monitoring;
- Market performance benchmarking;
- Alternative market designs.

PERSEUS

PERSEUS stands for “Program package for emission reduction strategies in energy use and supply”. It is an optimizing inter-regional long term model of the European power system (consists of 42 regions covering all Western, Central and Eastern European countries), which has been used for various electricity market modeling analysis. The PERSEUS model is a fundamental model, based on linear programming. The model itself is programmed in GAMS. In order to solve the problem, commercial solvers like CPLEX are applied.

Energy system model PERSEUS-NAP (PERSEUS-National Allocation Plans) tends to provide an analysis tool for the quantification of the economic and technological impacts that a CO2-emission trading system and the design of emission allocation plans may have on electricity prices, technology choices, CO2-allowance prices and interregional power exchanges. PERSEUS-NAP is an energy and material flow model applying a multi-periodic linear programming approach. The target function demands a minimization of all decision-relevant expenditure within the entire energy supply system.

EMCAS

EMCAS (Electricity Market Complex Adaptive System, developed by Argonne National Laboratory in Illinois, USA) is agent-based modeling approach (ABMS, Agent Based Modeling and Simulation) to simulate the operation of today’s electrical energy systems. Agents are modeled as independent entities that make decisions and take actions using limited and/or uncertain information available to them, similar to how organizations and individuals operate in the real world. EMCAS includes all the entities participating in power markets, including consumers, generation, transmission, distribution and demand companies, independent system operators, regional transmission organizations and regulators. Advantage of EMCAS model is that all market participants have decentralized decision making, wide range of market strategies, and agents` adaptation to variable conditions…

Basic innovation of this model is that it doesn’t use one objective function for whole system (like cost minimization), but it allows to simulate different objectives for different companies (like profit maximization for each market participant). This makes it possible to get more realistic results in deregulated market simulation (with bigger number of market participants where they have different strategies and objectives).

EMCAS simulates the operation of a power system and computes electricity prices for each hour and each location in the transmission network. Electricity prices are driven by demand for electricity, cost of electricity generation, the extent of transmission congestion, external random or non-random events, such as unit outages or system disruptions, and company strategies. EMCAS has also possibility to calculate uncertainties of generation units' outages in market simulation.

Agents interact on several different layers. In the physical layer, the transmission grid is represented with interconnected nodes that allow a full-scale load flow analysis. Here, the system operator dispatches the available generators to meet the load while maintaining the constraints and limitations of the transmission system. If needed, this representation can be simplified by developing a "reduced" transmission network. One or more business layers can be used to model the various forward markets (e.g., pool energy markets, bilateral contract market) where generation companies can buy and sell power. The operation of the transmission and distribution companies is included in a separate business layer. On the regulatory layer the user can set various operational and markets rules.

PowerACE

PowerACE is a multi-agent simulator under development by University of Karlsruhe. It considers both short-term (spot market and on balancing power markets) and long-term aspects. Besides electricity markets, the PowerACE simulation model also represents markets for CO2 emission allowances. Focus is also on the interplay between emission allowance markets and power markets. In the first step of development it is planned to model emission market as a double-auction with closed order book and uniform price calculation. Trading will be held twice per year, and bids for buying or selling CO2 emission allowances in these auctions will consist of basic set of specifications (buy/sell, price, quantity, and period). In the long term, model will be able to deal with generation expansion and plant decommissioning, and merger.

CURRICULUM VITAE

Robert Pasicko graduated Electrical Engineering in 2003 from the University of Zagreb Faculty of Electrical Engineering and Computing (FER) with diploma thesis "Assessment of wind generator`s characteristics". He received Diploma in Management Studies in 2008 from the same university.

After two years working in the field of power system relay protection, he got employed at FER's Department for Power and Energy Systems as research and teaching assistant from 2005 to 2009. During this time, his research and expert work is dedicated to emission trading, power system planning, renewable energy sources and climate change adaptation.

From 2009 he is working for United Nations Development Programme (UNDP) in Croatia as a project developer and project manager in the field of renewable energy sources, emission trading and climate change issues.

He participated as one of the authors in many strategic and legislative documents (such as Energy Strategy where he was mostly active in power system modeling, renewable enrgy sources and emission trading), and project coordinator during development of Framework for Low Emission Development Strategy for Croatia. During his carrier he participated (and in most of them he was in charge of national activities) in nine EU projects funded through Framework Package 6 and 7, Intelligent Energy Europe. Currently he is managing several EU funded and national projects in the field of climate change, power system planning, transition to low emission economy and renewable energy sources. He is author of more than 30 scientific papers, expert studies and other publications.

He is a member of Society for Sustainable Development Design, Croatian Society for Mitigation of Carbon Footprint and Adaptation, and constituting member for Green Energy Cooperative.

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ŽIVOTOPIS

Robert Pasicko je diplomirao 2003. godine na Sveučilištu u Zagrebu Fakultetu elektrotehnike i računarstva, s temom diplomskog rada „Procjena karakteristika vjetroagregata". Na istom sveučilištu je 2008. godine primio Diplomu iz poslovnog upravljanja (Diploma Study in Management).

Nakon dvije godine rada kao inženjer u području relejne zaštite elektroenergetskog sustava, zaposlio se na Fakultetu elektrotehnike i računarstva, Zavodu za visoki napon i energetiku, kao vanjski suradnik od 2005 do 2009. godine. Tijekom tog vremena, njegov znanstveni i stručni rad je usmjeren na područje trgovanja emisijama, planiranja elektroenergetskog sustava, obnovljivih izvora energije i adaptacije na klimatske promjene.

Od 2009. godine do danas radi u Programu Ujedinih naroda za razvoj (UNDP) u Hrvatskoj kao stručnjak za razvoj projekata i projektni menadžer u području obnovljivih izvora energije, trgovanja emisijama i klimatskih promjena.

Kao jedan od vodećih autora, sudjelovao je u mnogim strateškim i legislativnim dokumentima (poput Strategije energetskog razvitka Republike Hrvatske gdje je bio vodeći autor na području planiranja elektroenergetskog sustava i trgovanja emisijama), i voditelj projekta Okvir za izradu Strategije niskougljičnog razvoja Republike Hrvatske. Tijekom karijere sudjelovao je (i u većini njih je bio voditelj nacionalnih aktivnosti) u devet europskih projekata financiranih iz programa Šesti i Sedmi okvirni program, te Program inteligentne energije u Europi. Trenutno radi na nekoliko europskih i nacionalnih projekata u području klimatskih promjena, planiranja elektroenergetskog sustava, tranzicije prema niskougljičnom razvoju i obnovljivih izvora energije. Autor je više od 30 znanstvenih radova, stručnih studija, i ostalih publikacija.

Član je Društva za oblikovanje održivog razvoja, Hrvatske udruge za smanjenje emisije stakleničkih plinova i adaptacije na klimatske promjene, te Zelene energetske zadruge.