MODELLING CO_2 EMISSIONS IMPACTS ON CROATIAN POWER SYSTEM

by

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Today's electrical energy landscape is characterized by new challenges such as deregulation, liberalization of energy markets, increased competition, growing demands on security of supply, price insecurities, and demand to cut CO_2 emissions. All mentioned challenges are calling for consideration of various options (like nuclear, coal, gas or renewable scenarios) and for better understanding of energy systems modelling in order to optimize proper energy mix. Existing models are not sufficient any more and planners will need to think differently in order to face these challenges. European emission trading scheme (EU ETS) started in 2005 and it has great influence on power system short term and long term planning. Croatia is obliged to establish a national scheme for trading of greenhouse gas emission allowances from the year 2010, which will be focused on monitoring and reporting only until accession to EU when it will be linked with EU ETS. Thus, for Croatian power system it is very important to analyze possible impacts of CO_2 emissions. Analysis presented in this paper was done by two different models: mathematical model, based on short run marginal costs (SRMC, relevant for fuel switch in existing power plant and merit order change) and long run marginal costs (LRMC, relevant for new investment decisions); and electricity market simulation model PLEXOS, which was used for modelling Croatian power system during development of the Croatian energy strategy in 2008. Results of the analysis show important impacts that emission trading has on Croatian power system, such as influence of emission price rise on price of electricity and on emission quantity, and changes in power plants output that appear with emission price rise. Breakeven point after which gas power plant becomes more competitive than coal is 62 €/tCO_2 for SRMC and 40 €/tCO_2 for LRMC. With CO_2 prices above 31 €/tCO_2 wind is more competitive than gas or coal, which emphasizes importance that emission price has on competitiveness of renewables.

Key words: *emission trading, modelling, power system planning, optimization, generation expansion*

Introduction

Modeling of power system in Croatia has started together with energy system modeling in 1980's by first using general equilibrium techniques and then developing domestic model

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SIPRA [1], and was later followed by models WASP, MAED, and DECADES in the 1990's. With new challenges in power systems planning these models become insufficient, and in 2005 electricity market simulation model PLEXOS was used for the first time for modelling impacts of emission trading and electricity market liberalization on Croatian power system.

This paper presents results from modeling Croatian power system during development of Croatian Energy Strategy in 2008, where important impacts from emission trading and CO_2 price on different development scenarios were modelled. Analysis presented in this paper was done by two different models: PLEXOS (which was upgraded with new algorithm during modelling in order to include emission price) and mathematical model based on short run and long run marginal costs. Questions analyzed in this paper were how emission price rise can influence economical competitiveness of different electricity generating technologies, and how to valorise emission trading and Kyoto protocol impacts on power system (influence of emission price rise on price of electricity and on emission quantity, and changes in power plants' output that appear with emission trading).

By the term model, mathematical description in the form of mathematical algorithm is implied. First energy system modelling was performed by using economic theories and mathematical models. Today's electrical energy sector is characterized by new challenges such as deregulation, liberalization of energy markets, increased competition with growing demand for security of supply (together with ever growing percentage of imported energy resources) [2, 3]. Decentralization and liberalization of the national energy sectors appeared in 1990's [4], and systems that were once nationally owned and integrated have been transformed with the idea that market mechanisms will increase efficiency of 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 [5]. 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 from renewable energy sources (broad overview of modeling renewables given in [6]), constraints on emissions or minimal energy efficiency goals. Other challenges in energy planning that need to be modelled are price insecurities of investments and energy resources and 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) in order to optimize energy mix and lead to satisfying development of power system [7]. Power system modelling usually requires the representation of the underlying technical characteristics and constraints of the production assets. Methodologies commonly used in power system models are [8, 9]:

– Optimization models used for reaching optimal investment or resource allocation strategies [10]. Usually based on mathematical optimization algorithms such as linear programming (LP), dynamic programming (DP), quadratic programming (QP), and mixed integer linear programming (MILP). Most have economic objective, a set of decision variables and a set of constraints.
– Simulation models are based on logical description of a system, which might get very complex. These models work by performing and analyzing different what-if scenarios.
– Multi-criteria models are analyzing the situation where the available options have to be judged against several criteria (economical, ecological, social…) [11].

– Multi-agent systems have two or more software agents that can simulate many market participants with centralized decision making [12], ability to modify, wide possibility to implement market strategies, and possibility to influence other market participants by communication.
– Other methodologies which are nowadays used for energy sector modelling are econometric, macro-economic, and general equilibrium.

Modelling emission trading impacts on power system

Within project "Assessment and Improvement of Methodologies used for GHG Projections" [13] in 2008, various EU climate change policies and measures were analyzed (EU-ETS, EU directives: Renewables directive, Combined heat and power (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. Analyses performed (tab. 1) have shown rather high use of models for modelling impacts of renewable energy sources and CHP, while modelling is less used for emission trading scheme and even less for flexible Kyoto mechanisms (Joint implementation and clean development mechanism).

Table 1. Overview of model use for EU ETS simulation in EU member states [13]

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 Rep.	Optimization	CO_2 tax	The Netherlands	Engineering	Yes
Denmark	Econometric	Partial	Poland	Simulation	Partial
Estonia	Optimization	CO_2 tax	Portugal		
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. K.	Econometric	Partial			

Croatian power system today

Croatia is currently importing about 50% of its energy (80% of this is oil) [14]. In the period from 2000 to 2006 (fig. 1) the annual growth rate of final electricity demand was 4.1% which was higher than for any other energy form. Energy supplied in 2006 was 18.051 TWh, while net

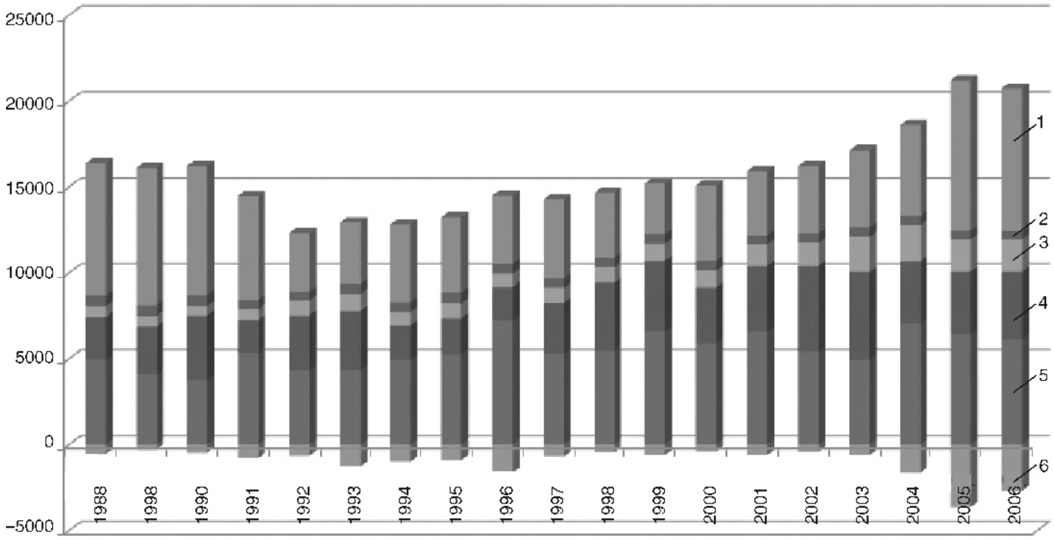


Figure 1. Electricity supply in the Republic of Croatia [14]
1 – import, 2 – industrial co-generation plants, 3 – public co-generation plants, 4 – thermal power plants, 5 – hydro power plants, 6 – export

import makes 5.622 TWh – 31.1% of total energy supplied (2.8 TWh from joint Croatian-Slovenian nuclear power plant is in this number). Almost all electricity generation capacity is in ownership of Croatian Electrical Utility, HEP Group (from 3993 MW installed, 2056 MW is in hydro, 1589 MW in thermal power plants and 348 in Croatian part of nuclear power plant Krško) [14]. Beside this, there are 210 MW installed in industrial power plants and 23 MW installed in private ownership, namely wind and small hydro. Specificity of Croatian power system is large percentage of installed power in hydro (52%), which requires reserve capacity during summer period when water level is low. Ever growing electricity consumption is not offset with new generation capacities and electricity import is rapidly rising, which emphasizes need for new generation capacities.

First model used: PLEXOS

For the purpose of modelling Croatian power systems presented in this paper, two models were used – simple mathematical model and electricity market simulation model PLEXOS. The idea behind PLEXOS is to be simulation model that is easily and efficiently maintained, extended and modified, and that can be applied with no customization to every electricity market and modelling project. Model uses Microsoft Access database for data handling, it is based on .NET technology and is run on Windows operating system.

There are four basic simulation engines in PLEXOS (fig. 2): LT Plan (long-term planning module), PASA (for modelling scheduled maintenance and forced outages), MT Schedule (model medium to long term decisions, "decomposes" user-definable constraints to shorter term constraints suitable for detailed modelling in ST Schedule) and ST Schedule (short term modelling, can get to five-minute resolution). Each one of the engines can be used separately, but they can also be used sequentially. In that way, each engine gathers results from the previous engine as an input. After preparation of the input parameters from the Microsoft Access and input textual data, AMMO optimization core is being used for dynamic formulation of the mathematical problem. When problem is formulated, commercial MOSEK software is 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 solved, PLEXOS engine prepares data for interpretation in output users' interface.

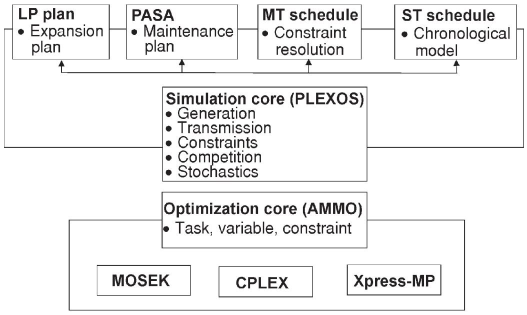


Figure 2. PLEXOS simulation engines

The solution simulations are founded in mathematical programming techniques, LP, QP, MIP, and DP. 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 [15], 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 [16]:
– the software can scale to any problem size,
– the analyst controls simulation performance by "switching" data on/off – thus allowing exploration of tradeoffs between simulation runtime and result accuracy,
– there is no hardwired functional specification – model capabilities can be expanded at will,
– simulation performance is maximized (problem size minimized) because the optimization problems are built at runtime to suit the data, and
– the analyst may define any "generic" constraint which can involve a combination of decision variables or input data used inside the simulation.

Croatian energy development strategy and emission targets

The energy development 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 (overview of Croatian RES legislation given in [17]). The newest Energy development strategy of the Republic of Croatia [18] 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".

Energy development strategy provides final energy demand projections for both a business as usual scenario (BAU) – projection of final energy consumption according to market trends and consumers' habits, without government interventions; and for a 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 [19], 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. The Croatian energy strategy set three basic energy objectives, respecting specific situation in Croatia and its national interests: security of energy supply, competitive energy system, and sustainable energy sector development.

Challenges considering CO_2 emissions impacts on energy sector are coming out from meeting the Kyoto protocol commitments and integration into the EU emission trading scheme and burden-sharing agreement between EU member states.

UN Kyoto protocol compliance committee has banned Croatia from Kyoto flexible mechanisms (including international emission trading) until Croatia submits new Report on emission inventory with base year emissions lower for 3.5 $MtCO_2$ than initial report [20]. Reason for this dispute between Croatia and the Compliance committee is that Croatia is calculating base year emissions with additional 3.5 $MtCO_2$ that were allocated by the Convention of parties (COP12) in Nairobi in 2006 [21], but not accepted by the Compliance committee. Without disputed 3.5 $MtCO_2$, Croatia's Kyoto target equals 29.777 $MtCO_2$ (5% reduction from base year emissions). Emissions recorded in year 2007 amount 32.385 $MtCO_2$ [22], which means that in 2007 Croatia was 2.6 $MtCO_2$ short in Kyoto target. It is hard to estimate emission's development in 2008 and 2009 due to economical crisis, but it is clear that Croatia will miss its Kyoto target and problems will continue in Post-Kyoto period as well. Even though Croatia is banned from international emission trading within Kyoto protocol, Croatia is obliged to establish a national scheme for trading of greenhouse gas emission allowances from the year 2010, which will be focused on monitoring and reporting only until accession to EU when it will be linked with EU ETS (probably 2012 or 2013).

New Energy Development Strategy considers EU objectives from new EU Energy and Climate Change Package [23]: share of renewable energy in total primary energy for Croatia predicted by strategy is 20% in 2020 (future renewable project in Croatia given in [24]), emission reduction goal – 20% until 2020, energy efficiency goal is to lower final energy consumption by 9% from 2008 until 2016 (according to an average level between 2001-2005), and to increase the share of biofuels by 10% until 2020. Also, in case of international agreement for emission reduction, EU proposed the possibility to increase its emission reduction goal to 30% in 2020.

Development scenarios

Based on the expected electricity consumption and on the forecasted load factor of 0.7, expected peak load in 2020 amounts 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, minimum stable level, maximum ramp up/down, equity costs, debt costs, variable and fixed O&M costs, fuel price, start costs, *etc*. Transmission capacities were modelled only for 400 kV lines and nodes, with two forecasted "by-passes" planned until year 2020. First by-pass 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 was modelled in 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 modelled as coming from one power plant block with fixed output. Electricity consumption is modelled according to hourly values and according to load share on different nodes. 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 is showing that 1130 MW of installed capacities will be retired until year 2020, and additional 260 MW until 2030 (fig. 3). Total installed capacity with demanded peak and required capacity, with a 30% reserve margin, is shown on fig. 4.

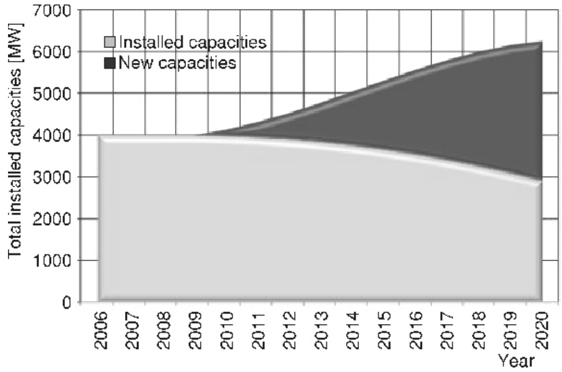


Figure 3. Decommission of existing power generation facilities and required installation capacities to satisfy the demand (2006-2020)

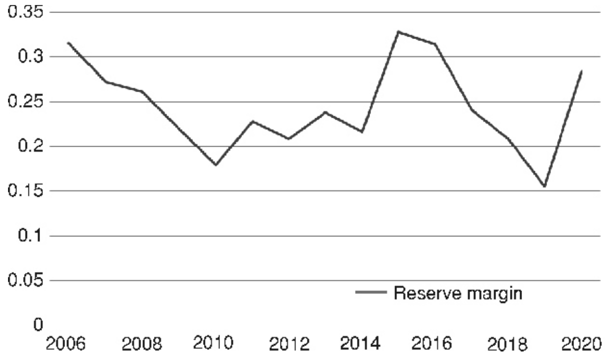


Figure 4. Reserve margin in White scenario fluctuates between 16% and 33% of installed capacity

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 scenario focuses on gas and nuclear, while Blue scenario 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 much.

The difference between White scenario (tab. 2) 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, co-generation and old power plants remain the same).

Blue scenario schedules 2 TPP 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.

Table 2. Forecasted start up dates of new power generation units by 2020 according to the white scenario

Facility/unit/part of	Nominal power on generator, MW	Foreseeable year for
TE-TO Zagreb unit L	100	2009
TPP Sisak unit C	250	2012
TPP gas I	400	2013
TPP coal I	60	2015
Nuclear I	1000	2020
(CHP) co-generation	Progressive yearly increasing by 30 MW, additional total 300 MW	2011-2020
HPP other	Progressive yearly increaisng 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	2011-2020
Total gas	1050	
Total coal	600	
Total nucl	1000	
HPP + REN	1845	

Second model: Theoretical mathematical model

Theoretical mathematical model presented in this paper for assessment of the CO_2 price impacts is based on the approach in IEA study [25] and [26] on investment decisions for new power plants and change in merit order in existing plants. While decisions regarding merit order change are based on the SRMC, investment decisions in new plants are usually based on the LRMC. This model assesses the influence of emission price on the SRMC and the LRMC. 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. 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 and in tab. 3 is 8000 hours annually, while for wind power plants 25% of time is assumed in full load hours (2190

Table 3. Economic parameters used to describe new power plants (PP) within scenarios*

Economic and technical parameters	Units	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	40.0
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	€/kW year	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	140	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 cost [MWh]	€/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**

* Energy prices are defined according to oil prices of 84 USD/bbl while costs are according to average costs in USA from 2008 [28-30]

hours annually). Since total investment costs in recent nuclear projects proved to be higher than expected [27], 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 favourable wind power plant is considered (variable 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.

From figs. 5 (SRMC) and 6 (LRMC), it can be seen that with CO_2 prices higher than 40 €/tCO_2, CCGT becomes more competitive than coal, 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.

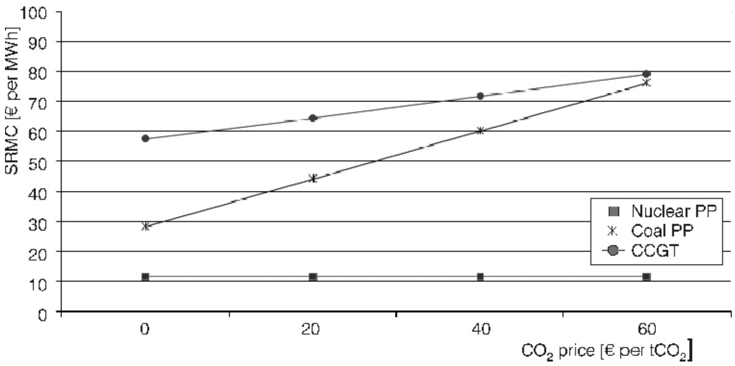


Figure 5. Impacts of emission allowances price on rise of SRMC for different electricity generation technologies. At prices of CO_2 higher than 62 €/tCO_2, CCGT becomes more competitive than coal

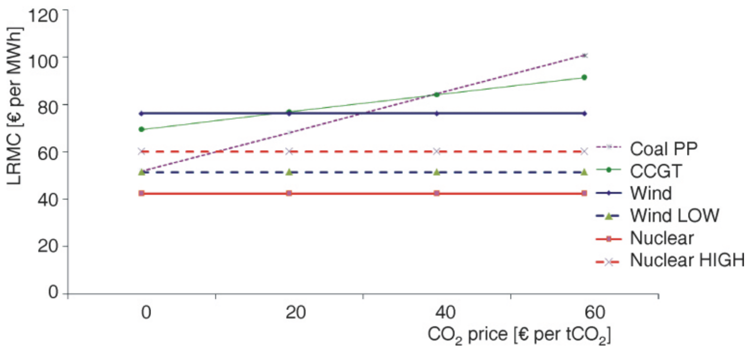


Figure 6. Impacts of emission allowances price on rise of LRMC for different electricity generation technologies, with oil price 84 USD/bbl*

A sensitivity analysis was also done for higher oil price – 126 USD/bbl instead 84 USD/bbl in the referent case. Price of natural gas and coal are influenced by the price of oil (pricing model described in [29]), 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 on the fig. 7, 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.

In case where lower fuel prices are applied (42 USD/bbl), according to the pricing model [29] coal price is 1.81/GJ and natural gas price is 4.28 €/GJ. In this case, CCGT is more

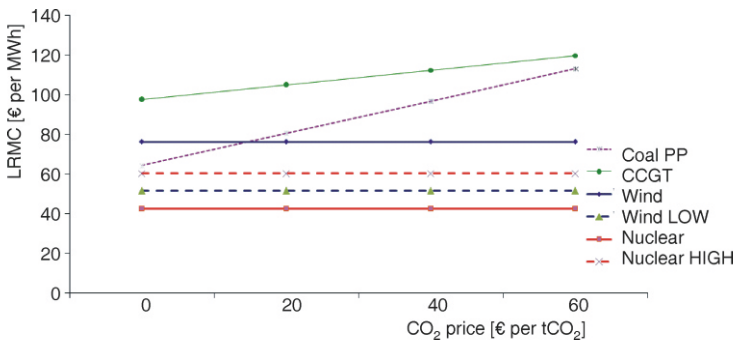
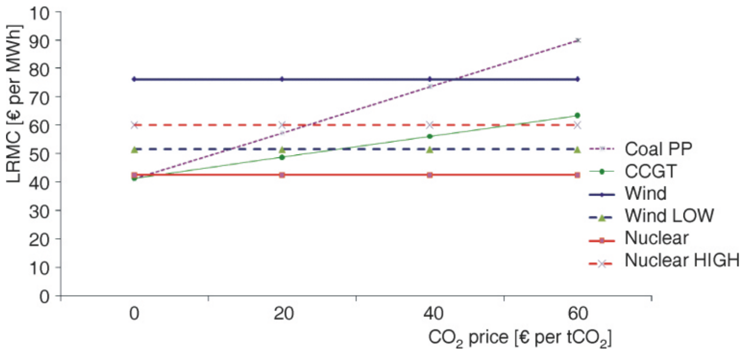


Figure 7. Impacts of emission allowances price on rise of LRMC for different electricity generation technologies, with oil price 126 USD/bbl

* oil barrel

Figure 8. Impacts of emission allowances price on rise of LRMC for different electricity generation technologies, with oil price 42 USD/bbl



competitive than coal regardless the CO_2 price (fig. 8). Wind is more competitive than coal only after 45 €/tCO_2, and even with its lower investment costs it is more competitive than CCGT and coal only after 28 €/tCO_2.

Results from analysis should not be taken as projections but more as tools to explore emission trading and various other impacts on investment decision within power system. In that perspective also previous IEA study should be seen – as many uncertainties are included in definition of relevant parameters such as investment costs or fuel prices that have huge impacts on results. Results from IEA study are in line with results presented above – for lower fuel prices and for lower CO_2 prices gas tends to become preferred fuel (along with nuclear if higher investment costs are not applied in the project). Fuel price has also great impact on competitiveness of renewables – on liberalized market it is hard to expect high share of wind if low fuel costs are expected. With medium fuel price, renewables need highest ever recorded emission price in order to become more competitive (above 30 €/tCO_2).

Emission trading modelling in Croatian power system by PLEXOS

In addition to modelling physical emission limits, the so called "hard constraint", until recently PLEXOS had possibility to model emission taxes/prices either by:
- *Emission Soft Constraint*, constraint with one or more bands of penalty price, and
- *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 emission trading impacts in power system should be able to add additional costs to SRMC from each generator. This problem was recognized within research program *Simulator Development for Analysis of Emission Trading Impacts on Electricity Market* at Faculty of Electrical Engineering and Computing in Zagreb [31]. The solution that we proposed 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). In communication with model developers, this was added as a new function in PLEXOS model and makes it possible to model emission trading in a more realistic manner. New algorithm for calculation of generation costs for each generation unit now is presented as:

$$\textit{Generation cost} = (\textit{Fuel offtake} \quad \textit{Fuel price}) + (\textit{Generation} \quad \textit{Variable operation and Maintenance cost}) + (\textit{Generation} \quad \textit{Emission coefficient} \quad \textit{Emission price}) \tag{1}$$

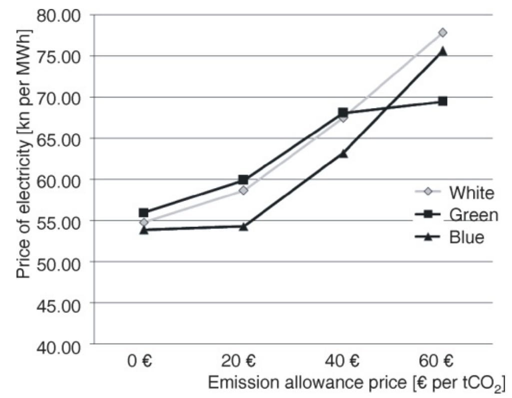


Figure 9. Impacts of emission allowance price on electricity price in different scenarios in year 2020 (7 kn approx. 1 €)

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.

To analyze impacts of emission allowances' price on electricity market in Croatian power system four different scenarios were modelled, with different prices per ton of CO_2 emissions: 0, 20, 40, and 60 €/tCO_2. Results have proved dependence of coal in-

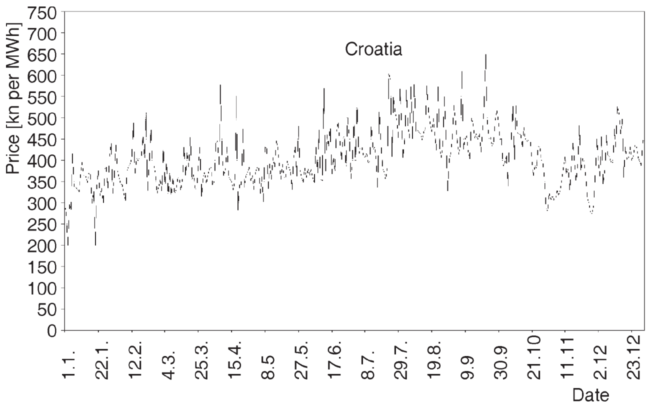


Figure 10. Daily amounts of electricity prices for Croatia in White scenario in year 2020 – summer months have higher prices because of low production from hydro (7 kn approx. 1 €)

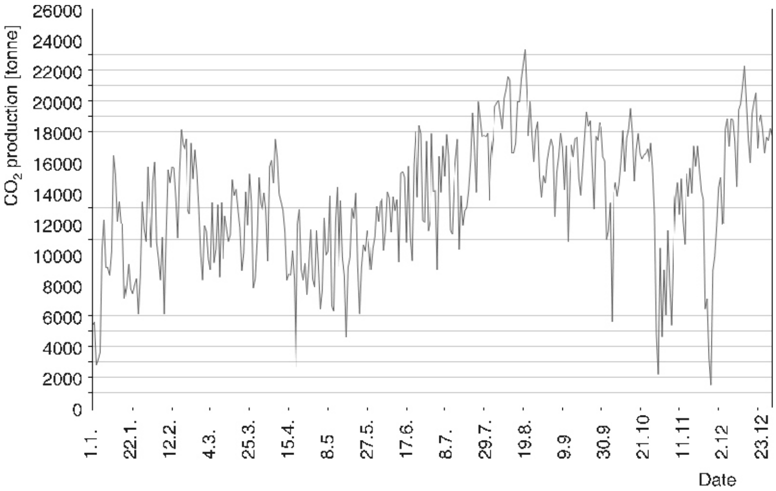


Figure 11. Daily CO_2 emission in White scenario in year 2020

tensive scenarios on rise of emission allowance price. This dependence especially shows in the Blue scenario which has the highest share of coal (figs. 9-11). Because of high share of nuclear and gas produced electricity, the Green scenario is most immune to emission allowance price rise.

The analysis is focused on isolated Croatian energy system – without interaction with regional markets (other than nuclear power plant in Slovenia which is 50% in Croatian ownership). If analysis would take in account regional electricity market, this would have two dominant effects in the future on competitiveness of power plants in Croatia. First comes from connection with EEX electricity market through Slovenia, and would mean that power plants could sell their electricity at higher prices (especially hydro power plants that can sell on peak hours). Other effect comes from connection with Serbia and Bosnia and Herzegovina that have predominately coal power plants with cheaper electricity (due to locally produced cheap lignite in these countries). As Serbia and Bosnia and Herzegovina are non-Annex I countries (and have no emission target under Kyoto protocol), price of electricity from coal will not be influenced by emission targets or emission price – and therefore will be more competitive on the market. This market distortion would have impact on Croatian energy security issues, as investing in coal power plants is more competitive in these countries than in any other base load in Croatia (except nuclear if high investment costs are not applied).

Conclusions

In order to fully understand impacts of CO_2 emissions on power system, new improved models are needed. In this paper, two different models are presented in order to assess how emission trading influences today's power system, specifically Croatian power system. With mathematical model, changes in SRMC and LRMC were analyzed. Breakeven point after which gas power plant becomes more competitive than coal is 62 €/tCO_2 for SRMC and 40 €/tCO_2 for LRMC (with 84 USD/bbl for oil). Great advantage that wind power plants gain as the result of emission trading is seen in the fact that for CO_2 prices above 31 €/tCO_2 wind is more competitive than gas or coal. Sensitivity analyses show that with lower fuel prices (42 USD/bbl for oil) and with lower CO_2 prices gas tends to become preferred fuel. It is hard to expect high share of wind power if low fuel costs prevail, but with medium fuel price, renewables need highest ever recorded emission price in order to become more competitive than other technologies. With high fuel prices (126 USD/bbl for oil), coal is more competitive than gas regardless the CO_2 prices, and wind becomes more competitive than coal with emission price higher than 15 €/tCO_2.

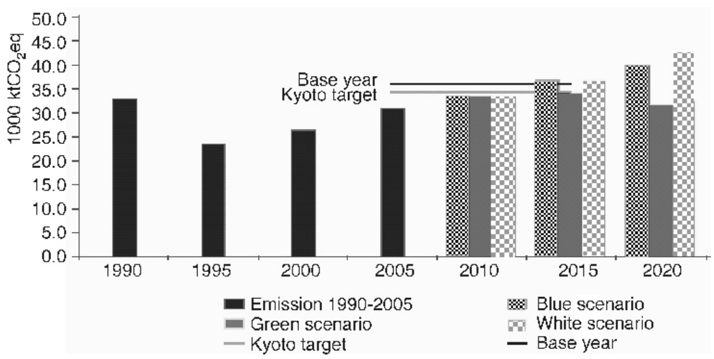


Figure 12. Influence of different scenarios on Croatian Kyoto targets (electricity sector added to total of other sectors) – in year 2015, only Green scenario is meets target, while in 2020 White and Green scenarios are under Croatian Kyoto obligation

Dynamic CO_2 price impacts on three different scenarios from Croatian energy strategy were modelled in market simulator PLEXOS. Changes in price of electricity in dependence of emission price rise were assessed, as well as total amounts of emission per scenario. As shown in the fig. 12, only Green scenario meets the Kyoto obligations in both 2015 and 2020, while White scenario meets the Kyoto targets in 2020 if disputed 3.5 millions CO_2 tones are also calculated. Without these 3.5 $MtCO_2$ none of the modelled scenarios would meets Kyoto target, and more effort would need to be put in energy efficiency and renewables – otherwise emission reduction would have to be met by purchase on carbon markets.

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