WORK PLACEMENT

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Promotion 2012

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AGH

Impacts of the implementation of

European Union policy
Emission Trading System

on Polish power sector

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ACKNOWLEDGEMENTS

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ABSTRACT

AGH-University of Science and Technology is nowadays one of the most famous technical universities in Poland. Among its 15 faculties, I joined the Faculty of Energy and Fuels and particularly the department of Mr Artur Wyrwa, my internship supervisor.

For sixteen weeks, I was part of the research team whose work was mainly focused on the development of new power technologies, such as renewable energy sources, or the environmental impacts of Polish power sector.

During this work placement, I experienced the research field, dealing particularly with electricity production. I had the opportunity to carry out a whole project, modelling Polish power sector. I had to develop an energy model aiming at representing Polish energy requirements and facilities to implement so as to meet the demand, using a 25 year modelling period and optimizing costs. I had to insert into this model European policies and norms about greenhouse gas emissions and renewable energy production quotas.

My first task was taking software GAMS in hand, since I was going to use it to develop the model, and looking for information about European energy policies and financial engineering. Then I could develop the model and carrying out sensitivity analysis. Finally, I wrote an article exploiting different results taken from simulations in order to publish it in a Polish scientific magazine.

This work experience has been extremely interesting and a real opportunity for me to get a rewarding experience in the field of research.

KEYWORDS

- ♦ Energy modelling
- ♦ European energy policy
- ♦ Polish power sector
- ♦ Renewable energy
- ♦ Greenhouse gas emissions
- ♦ Financial engineering

INTRODUCTION

Polish power sector is nowadays essentially based on coal. Approximately 95% of electricity is generated by hard or brown coal power plants. However, since Poland belongs to the European Union, it will soon have to fulfil European energy policies concerning electricity generation from renewable energy sources and limitation of greenhouse gas emissions. The implementation of these new norms constitutes an important challenge to take up for Poland.

As a major university of Poland, AGH-University of Science and Technology educates students and employs researchers within the Faculty of Energy and Fuels in order to face energy issues. Making development of new technologies at the heart of its concerns, the Faculty of Energy and Fuels strives to meet the growing demand for energy, placing it in a process of sustainable development.

As an Energy Engineering student, I feel particularly involved in problems dealing with growing energy demand and needs to reduce energy consumption and greenhouse gas emissions. As a consequence, I joined with great pleasure the department of Artur Wyrwa for sixteen weeks during which I could focus on country scale energy and economical issues.

INTERNSHIP PRESENTATION

The aim of this work placement was to analyse the aftermaths of the implementation of the European Union policy "Emission Trading System" on Polish power sector.

To carry out this study, I had to develop an energy model using software GAMS. This model was able to simulate the evolution of Polish power sector according to different energy scenarios based on EU policy. Then, I wrote an article analysing the results. This article will be suggested to a scientific Polish magazine to be published. Finally, all along my work, I did bibliographical research in order to base my data and methodology on reliable sources.

Choosing AGH-University of Science and Technology to do my assistant engineer internship was an opportunity for me to reach different objectives. First, I wanted to complement my formation with an in-depth experience in the field of research. Furthermore, since I am decided to continue my studies with the specialisation "Bâtiment à Energie Positive" which leads to very specific fields, I wanted to have an experience in a broader domain dealing with topics that particularly interest me, such as renewable energy or decrease of greenhouse gas emissions. This experience, widening the range of my skills, could consequently be a real asset.

PRESENTATION OF THE WORK ENVIRONMENT

AGH-University of Science and Technology

Akademii Górniczo-Hutniczej – University of Science and Technology, located in Krakow, is one of the best and most famous universities of Poland.

The creation of AGH-UST was born from the will of a group of mining engineers and activists. In 1919, the Academy of Mining was inaugurated by the Head of the State Józef Piłsudski and soon, the school reached a very high educational level being one of the best European mining schools. However, the activities of the University were stopped during the Second World War, because of the occupation of the main building by the German General Government. At the end of the war, a handful of teachers and students rehabilitated the University and started its development and expansion. In 1969 the University, which counted then ten faculties, was given the name of Stanisław Staszic University of Mining and Metallurgy.

Nowadays AGH-UST is the third best technical university in Poland. With sixteen faculties and one inter-faculty school of engineering and biomedicine, AGH-UST educates more than 35 000 full-time and extramural students as well as 550 doctoral students. Students can qualify in 33 branches and more than 170 specializations dealing with numerous fields such as mining and metallurgy, robotics or management. As AGH-UST employs more than 2000 research workers, the University has many links with industrial companies, both national and international.

The University serves science and industry educating students and developing research with all respect due to his history and traditions.

Figure 1: AGH-UST main building

Faculty of Energy and Fuels

The Faculty of Energy and Fuels is one of the youngest faculties of AGH-UST. It was created in 1991 in order to face the increasing demand of energy and fuels. At the beginning, the faculty focused on energochemical coal processing and development of sorbent technologies. From this time, the faculty extended its educational fields to new ones such as sustainable energy development or environment protection in chemical and power industry. In 2008, the Senate of the University decided to amalgamate the Interfaculty School of Power Engineering and the Faculty of Energy and Fuels in order to create a larger and more

Figure 2: Symbol of the Faculty of Energy and Fuels

significant faculty, capable of providing both education and research in technology and power engineering. Each year, about sixty students graduate from the Faculty of Energy and Fuels and start their careers in many domains such as power engineering, chemical industry or environmental protection.

Work Team

During this internship, I worked at the department of Artur Wyrwa, PhD and Assistant Professor at the Faculty of Energy and Fuels. His fields of research mainly cover modelling of development of energy system and integrated assessment modelling.

I also worked with different members of his team. Marcin Pluta, Master of Science and Energy Specialist at the Faculty of Energy and Fuels, is specialized on analysis of the development of Polish power system under environmental constraints, mainly emission caps and standards or use of renewable energy sources. Janusz Zyśk, Master of Science and Energy Specialist at the Faculty of Energy and Fuels, mainly focuses his field of research on modelling of atmospheric dispersion of pollutants from the power sector, particularly heavy metals such as mercury. Kamila Drebszok, who joined the team in June, works on the analysis of the impact of particle emissions from power sector on human health. Finally, Manon Pernin from Ecole des Mines de Douai was doing her technician internship. She principally worked on website design and database management.

Due to their field of skills, I mainly worked with Artur Wyrwa, my tutor, and Marcin Pluta. Even if I carried out my project in autonomy, we regularly met to take stock of my advances, analysing my results and improving the model.

WORK ACHIEVEMENTS

The implementation of European energy policies is about to change significantly Polish power system, essentially based on coal. As a consequence, my role was to develop an energy model in order to analyse the aftermaths of these new rules on the development of Polish power sector.

I. EUROPEAN UNION ENERGY POLICY

First, it is interesting to present the policy that European Union is implementing in order to face energy and climate issues.

The European Union is unquestionably a leader regarding efforts to mitigate climate change. Kyoto expectations are nowadays on the way of being implemented thanks to the European Climate Change Program (ECCP) which aim is to cut climate emissions. To reach this goal, EU wants to develop and increase the use of renewable energy sources. Consequently, important investments on green technologies are currently done, in order to reduce greenhouse gas emissions and to reach the "20-20-20" target (20% decrease of greenhouse gas emissions, 20% of energy consumption from renewable sources, 20% decrease of primary energy use).

To make this goal easier to reach, the European Climate Change Program implemented a new policy called Emission Trading System (ETS). The EU ETS covers nowadays about 11 000 power stations in 30 countries. Based on a cap and trade principle, it aims at limiting the total European greenhouse gas emissions. This system is implemented in three stages:

1st stage: 2005-2007

During this first stage, each country belonging to the European program has to prepare and publish a National Allocation Plan aiming at evaluating the amount of allowances about CO_2 emissions needed for each company.

2nd stage: 2008-2012

The second stage is used to implement the system of free CO_2 allowances and to publish another National Allocation Plan to assess the system efficiency, in order to adjust the needed amount of allowances.

<u>3rd stage: 2013-2020</u>

During the last stage, contrary to the previous stages, greenhouse gas emissions are not considered independently by countries but in a whole European way. Indeed, an EU-wide cap of emissions, instead of National Allocation Plans, is implemented. Decreasing by 1.74% per year, its goal is to globally reduce European emissions. From this moment, CO_2 allowances are not free anymore and are also reduced over time, which leads to start CO_2 allowances auctioning. For this period CO_2 allowances can be bought for 20 € per ton of CO_2 emissions and then, after 2020, they can be bought for 50 € per ton. This implementation of CO_2 cost is going to change deeply countries power sector.

This policy could seem binding and even economically non sustainable for countries like Poland which electricity is essentially based on coal, regarding the substantial increase of production cost due to CO_2 allowances. In addition, companies could be tempted to relocate their production in countries outside the EU in order not to pay CO_2 allowances. To avoid this carbon leakage, a limited number of free allowances for a transitional period are granted for these countries. In addition, to promote electricity production from renewable energy sources, different strategies are possible.

The first one, which was adopted by countries like France or United Kingdom, is the REFIT system (Renewable Energy Feed-In Tariffs). It is a state help guarantying payment for generated electricity to people producing green energy. This strategy encourages particularly the deployment of additional small scale of low carbon electricity generation.

The second one, implemented in Poland, is the RPS/TGC system (Renewable Portfolio Standard / Tradable Green Certificate). In this case, certified renewable energy generators earn certificates for every unit of electricity they produce. Contrary to the REFIT system, RPS/TGC allows price competition. In addition, it makes renewable energy able to compete with cheaper fossil fuel energy sources.

The aim of my study was to analyse the influence of this EU policy on Poland energy system. For this purpose, I used software GAMS. It enabled to study under scrutiny the evolution of electricity production, greenhouse gas emissions and MWh generation cost according to different energy policy scenarios.

II. METHODOLOGY

1. GAMS Model

GAMS (General Algebraic Modeling System) is software used for mathematical programming and optimization. With this tool, the user has to develop his own problem modelling, meaning implementing his own data, parameters and equations.
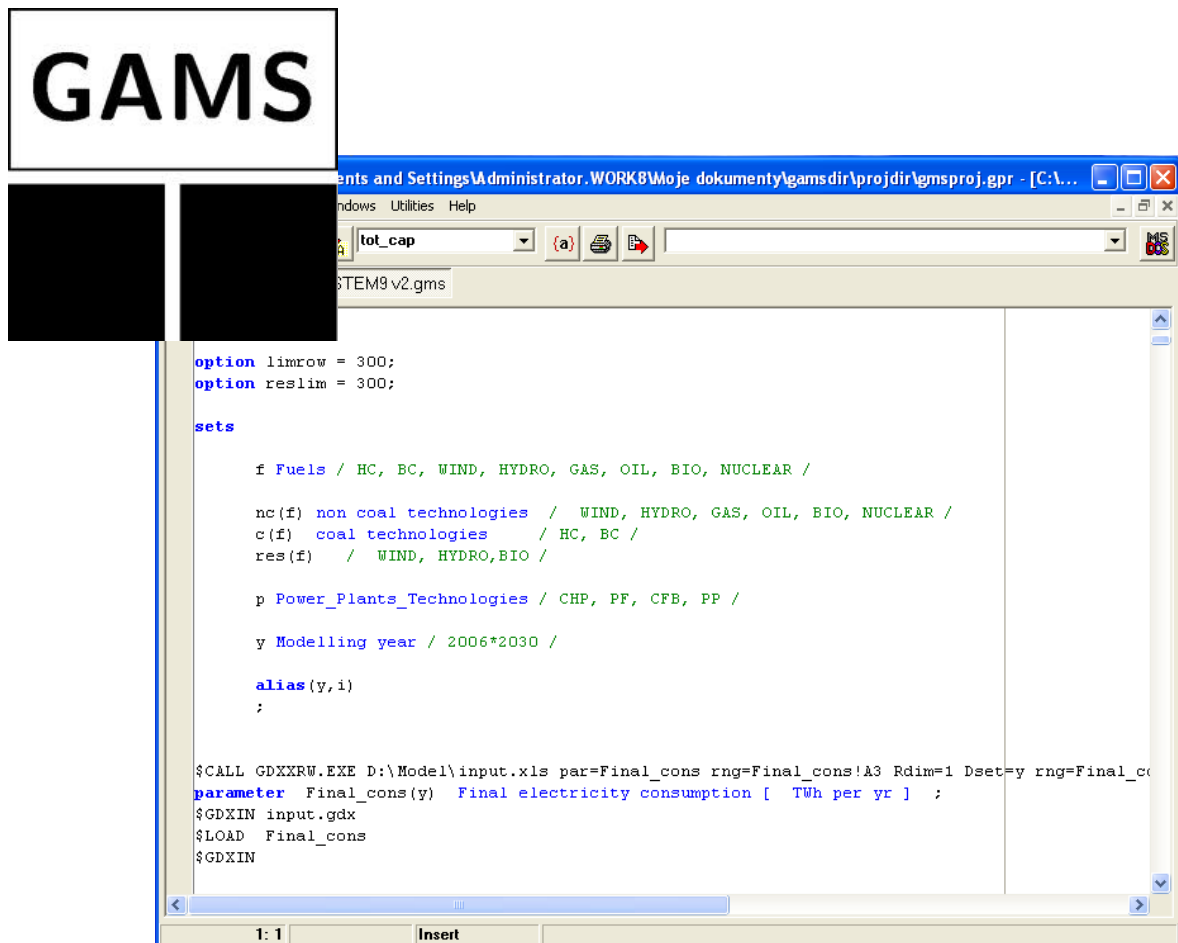
Figure 3: GAMS interface

The program I developed is a linear model, which means without nonlinear terms or discrete variables (such as binary or integer variables), based on a goal function and on constraints. To solve the model optimizing the goal function and satisfying all model requests and constraints, decision variables are created. In this study, the goal function is the optimization of total costs dedicated to the development of Polish power sector. This objective function is modelled

by the sum of different types of costs generated by electricity production which are discounted according to a base year and a discount rate.

Equation 1: Goal function

$$Total\_\cos t = Tc = \sum_{y \in [2006, 2030]} Disc(r, y).\begin{pmatrix} construction\_\cos t(y) + fixed\_\cos t(y) \\ + \mathrm{var}iable\_\cos t(y) + fuel\_\cos t(y) \\ + CO2\_\cos t(y) \end{pmatrix}$$

with

y : year belonging to the modelling period

r : discount rate

$Disc(r, y)$: discount factor

$$Disc(r, y) = \frac{1}{(1+r)^{ord(y)-1}}$$

$ord(y)$: ordinal number of year y in modelling period

$construction\_cost$: cost generated by the construction of power structures

$fixed\_cost$: fixed operating & maintenance cost

$variable\_cost$: variable operating & maintenance cost

$fuel\_cost$: cost generated by fuel consumption

$CO2\_cost$: cost generated by CO2 emissions

The costs are discounted in order to take into account the inflation effect on money devaluation (indeed, 1000 EUR in 2010 will not have the same value as 1000 EUR in 2020, consequently this fact is considered in the model).

After taking this new software in hand, I could start the development of the model.

2. Modelling Approach Of The Study

For this study, GAMS was used to model technology development of Polish energy system with the aim of determining its optimal configuration, depending on different EU emission policy scenarios. To reach this goal, I introduced input parameters taken from reliable sources, and then I implemented equation and constraints in order to reflect real power sector behaviour the best. In the following part, I will describe the methodology I used but I will not detail the elements of the model (available in the appendix "**Model elements**").

Parameters

The analysis is run on a 25 years modelling period, from 2006 (considered as the base year) to 2030 and considers different plant technologies and types of fuel.

Table 1: **Combinations of fuels and technologies**

Technology	Fuel	Technology	Fuel
Pulverized Fuel	Hard coal	Power Plant	Gas
	Brown coal	(for non-coal	Oil
Coal Fluidized Bed	Hard coal	fuels)	Wind
	Brown coal		Hydro
Combined Heat and Power	Hard coal		Biomass
			Nuclear

In addition, reliable data were collected for each plant technology to characterize the structure, such as efficiency, lifetime, emission factor or types of costs generated by electricity production.

Table 2: **Example of plant characteristics**

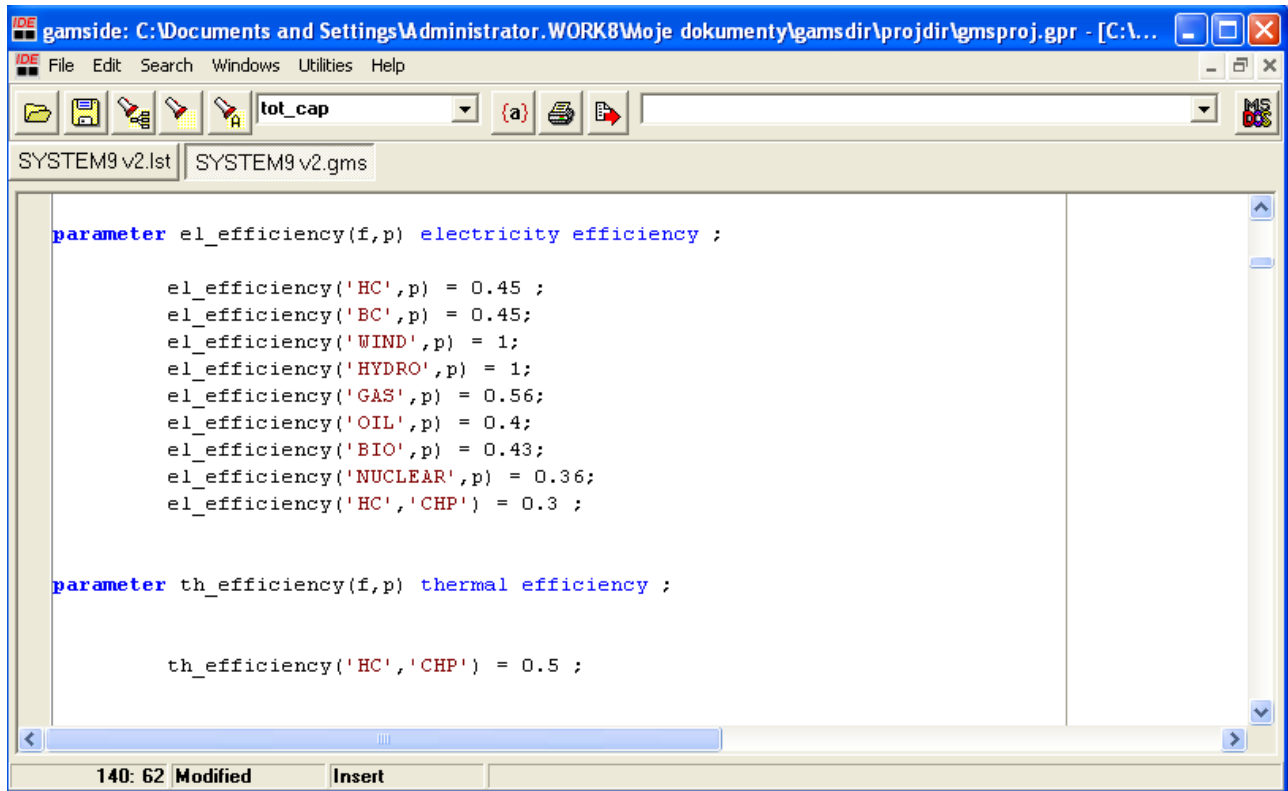| Technology	Lifetime	Investment cost [M EUR per GWe]	Fixed O&M cost [M EUR per Gwe]	Variable O&M cost [M EUR per Gje]
Pulverized coal	30	921	13	0,128
Coal: atmospheric fluidized bed	30	997	19	0,128
Combined heat and power	30	900	10	0,128
Gas steam	30	399	5	0,055
Oil steam	30	798	5	0,347
Nuclear: advanced light water reactor	40	2345	36	0,16
Biomass: direct combustion	30	1359	31	0,971
Wind: centralized	20	773	13	0,069
Hydro: dam	200	1269	8	0,347

Costs were converted from USD to EUR using the conversion factor 1.4 $/ €

* base year monetary units per unit of capacity (M€ /GWe)

** base year monetary units per unit of installed capacity (M€ /GWe)
*** base year monetary units per unit of activity (M€ /GJe)

These are just examples of parameters needed in the model. Altogether, thirty-two types of parameters were implemented.

Figure 4: Example of parameter implementation in GAMS

Equations and constraints

Using these different parameters and decision variables, I developed equations to calculate electricity and heat production, but also costs, fuel consumption and greenhouse gas emissions generated by electricity production. These equations, useful to optimize the goal function, are regulated by different constraints.
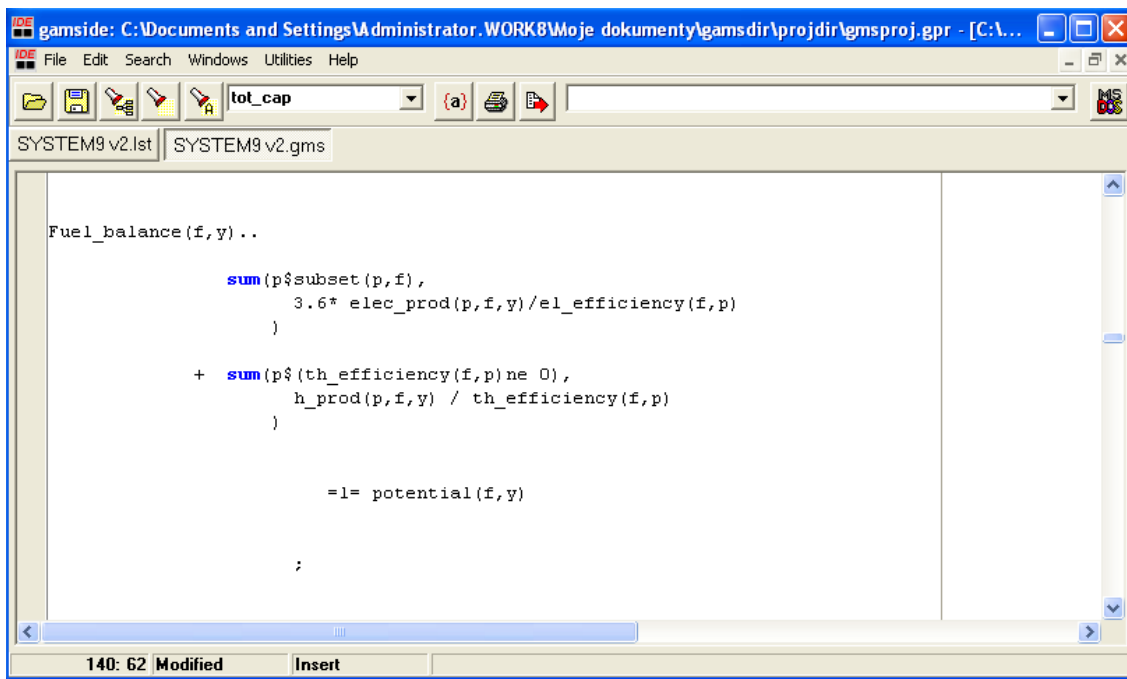
Electricity and heat demand: For each year of the modeling period, electricity production is calculated according to final electricity consumption and different losses in the process of electricity production and transportation. Electricity production has to meet this demand, which is increasingly growing. As a consequence existing plants are not always sufficient to provide it. Then the model is able to decide the implementation of new plants in the most economical way.

In addition, renewable energy sources production has to fulfill annual EU quotas globally increasing during the modeling period. This constraint has a major influence on the implementation of new capacity, since a simulation run without renewable quota showed that no renewable sources power plant would be built in this case.

Technology and capacity constraints: In order to meet electricity demand, the model is able to make a choice between keeping exploiting existing capacity or reducing it and building new plants, regarding the most cost-efficient option. Nevertheless, this choice is essentially determined by the EU energy policy scenario which is under study.

Fuel constraint: Even if available hard and brown coal potential in Poland is assumed to be enough, other sources such as gas are constrained by an upper limit on imports. In addition, natural constraints are potential limits for renewable energy sources.

Figure 5: Example of equation implementation in GAMS: fuel consumption ruled by constraint

In order to summarize model working and to visualize interactions between the different inputs, the model structure is presented below:

Figure 6: Model structure
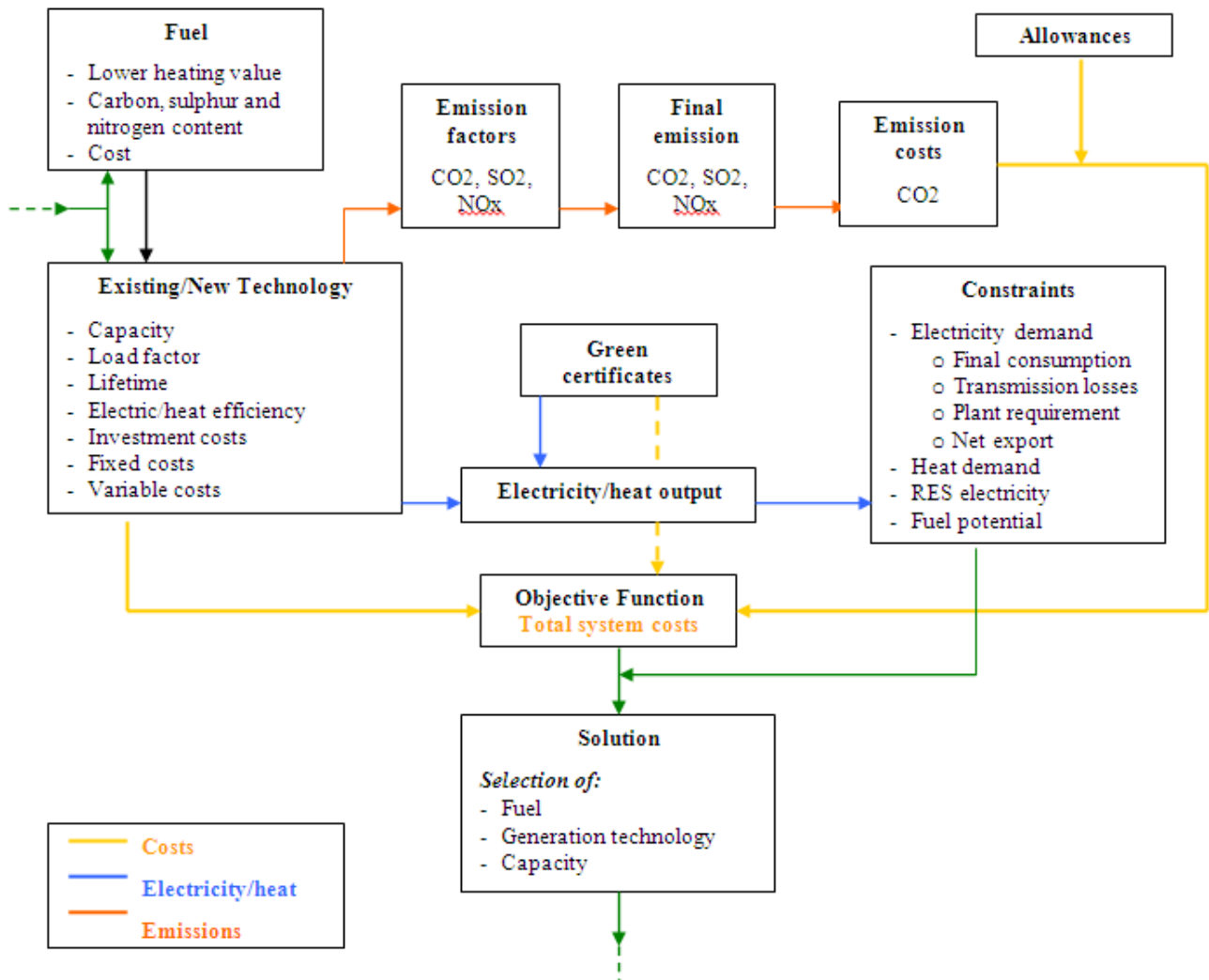
Scenarios

Two scenarios were defined to analyze the consequences of implementing EU ETS on Polish energy sector.

First scenario, called Reference Scenario (Ref_Sc), assumes that even after 2012, 100% of CO_2 allowances will be granted for free. There is no emission cap but quotas about electricity production from renewable sources must be provided. Nevertheless, no financial help to support renewable energy development is taken into account.

Second scenario is called CO_2 Scenario (CO2_Sc) and takes into account the price of allowances (20 € per ton between 2013 and 2020 and 50 € per ton then). To balance this substantial increase of production cost due to CO_2 allowances and to promote the use of

renewable energy sources, Poland chose to implement the RPS/TGC strategy (Renewable Portfolio Standard/Tradable Green Certificates). To make renewable energy competitive facing cheaper fossil fuel energy sources, green certificates are granted (70 € per MWh produced from renewable sources). However, simulations were run without green certificates in order to visualize the real costs of the evolution of Polish power sector.

III.   ARTICLE

In order to present the results of this study, I wrote an about fifteen pages article entitled "Impacts of the implementation of European Union policy Emission Trading System on Polish power sector". The whole analysis of the results is available in the appendix "**Results analysis, extract of the article "Impacts of the implementation of European Union policy Emission Trading System on Polish power sector"** ".This article is going to be suggested to a Polish scientific magazine in order to be published.

The main conclusions of these simulations showed that the implementation of non free CO_2 allowances in Poland will lead to the major development of renewable energy sources. Whole potential would be exploited for wind and hydro power, rising green electricity generation to more than 23% in 2030. In addition, CO_2 taxes would tend to reduce coal plants working as much as possible since they remain high polluting technologies in spite of important emission improvement. In order to replace coal technology, nuclear power should be used. The mix of renewable and nuclear sources should lead to a major decrease of CO_2 emissions by 60%. Even if CO2 Scenario does not seem to be efficient economically, according to huge changes it would generate (62 063 M€ for CO2 Scenario against 42 832 M€ for Reference Scenario), the implementation of green certificates would create subsidies about 12 055 M€ which would enable to balance the majority of these investments and to make these new technologies competitive compared to traditional coal technologies.

However, it is important to keep in mind that these results are the fruits of simulations. They do not rule future development of Polish power sector, but they can give the tendency these different scenarios would lead to. It is clear that Poland will not close coal plants and build nuclear plants so easily. Nevertheless, it is very interesting to understand that Poland should move towards green and nuclear technologies in order to cut CO_2 emissions efficiently in an economically optimal way.

In addition, I wrote a small article about the impacts of CO_2 price on Polish CO_2 emissions. This article presents the results of a sensitivity analysis aiming at studying the evolution of CO_2 emissions according to the price of CO_2 allowances during the two periods of CO_2 payment implementation (between 2013 and 2020, and after 2020). This analysis showed that European Union policy (20 € per ton of emissions between 2013 and 2020, 50 € per ton then) was one of the best efficiency-price ratios. This policy would enable to cut efficiently CO_2 emissions by 22% while limiting the risks of carbon leakage.

This article is available in the appendix "**Impacts of the implementation of CO_2 price on Polish CO_2 emissions**".

Finally, at the end of my internship I worked for a couple of days on the writing of a Germano-Polish project proposal about a feasibility analysis of biomass and biogas development in Poland.

IV. BIBLIOGRAPHICAL RESEARCH

All along my work period, I had to do bibliographical research in order to familiarize myself with new concepts, about European Union energy policies or financial engineering, and to find reliable data to base the model and the article on. But the main part of my research concerned the points which embarrassed my tutor and me, that are cost and electricity production discount.

1. Cost calculation methodology

In order to take into account the inflation effect on money devaluation, costs were discounted according to a base year (in this case, the first year of the modelling period) and a discount rate. The discount rate, also called real interest rate, is the nominal interest rate corrected according to inflation, the relative increase of energy price, and other possible relative price increases.

For the majority of costs, discount only intervenes in the model to calculate annual costs. However, it was more complicated for construction costs, which needed more research. Indeed, instead of paying whole construction costs in the first plant years, it was decided to split these costs equally all along plant lifetime. In order to calculate this annual payment and after bibliographical research, I used the Capital Recovery Factor (CRF) method. This methodology is described in the appendix "**Cost calculation methodology**".

2. Cost of MWh generation

The second point that embarrassed us was the calculation of MWh generation cost. As different costs are discounted annually in the model, it was not possible to divide this amount by annual electricity production (at the end of the modelling period, thanks to the important discount, MWh would have cost almost nothing). That is why we wondered about the methodology we should use. After productive research, it was decided that electricity production would also be discounted. This methodology, based on a report of the International Energy Agency, is described in appendix "**Calculation of MWh generation cost**".

TECHNICAL KNOWLEDGE AND PERSONAL IMPRESSIONS

This internship has been a real source of technical education, but most of all, I learned a lot about myself from this experience.

Technical knowledge

As a researcher assistant, I had to develop my own study, which had not been carried out before. First, I learned how to use new software, GAMS, which is a very useful tool for mathematical programming and optimization. It enabled me to apply the lessons I was given during core program about optimization methods. I realised that resolution methodology was the same, except that it was solving far bigger systems than I used to do manually. As I had to develop a whole model, I became more familiar regarding programming and simulations, which were not really parts of my strengths before. This has unquestionably been a major asset of this internship.

Furthermore, I mainly worked in autonomy, carrying out my own study. This led me to take my own initiatives about model development. In addition, during the meetings we had with my supervisor and with Mr Pluta sometimes, I had to explain my choices and to defend them. Moreover I had to suggest axes of evolution for several issues we faced. We had to find answers to these problems, and then I had to validate these theories, by bibliographical researches (for MWh generation cost for instance) or by running a simulation (as an example, for the implementation of green certificates).

In addition, I had to learn a lot about EU energy policies to develop this model: their aims, their implementation and hindrances that countries had to overcome in order to fulfil them. For example, I studied both REFIT and RPS systems in order to understand their advantages and drawbacks. It was also interesting to see that these systems are not suitable for all European countries policies, which lead them to implement one or the other policy. It was also rewarding to work on Polish power sector since it is totally different as French one. Polish energy sector is essentially based on coal, which is a real issue regarding greenhouse gas emissions for instance. Whereas France succeeded in dropping coal, replacing it by nuclear technologies, Polish power sector tends to turn itself firstly to renewable energy sources. This makes energy sector management very different and it was very interesting to learn from that.

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Besides, working in another language was a rewarding experience. On top of improving my English register, I understood essential things also valid for French work but even more when both interlocutors do not obviously master the language perfectly. Thus, understand and above all being understood were more important than usually. Things that could be evident are not obviously for everyone. This asked me lots of rigour, while I was presenting my results to the whole team or simply explaining my advances to my supervisor.

Personal impressions

As I said it, this internship allowed me to learn about myself and to think about my professional project.

I wanted to do this work placement in order to complement my formation with an in-depth experience in university research, as I worked last year in an engineering office. In addition, since I am decided to get specialized in building energy management, I wanted to have an experience in another field in order to widen my abilities.

I really enjoyed this internship, thanks to its topic which interested me a lot. Carrying out this study was rewarding because only few people had worked on this topic before. Consequently, I had to manage on my own since it was almost something new. In addition, passing down my results with scientific community by potentially publishing my article seems extremely rewarding since it would contribute to public awareness about energy issues.

However, I did not feel at ease with several aspects of university research. First, this type of study requires a share of uncertainty. Since this analysis had not been carried out before, I had to choose some hypothesis but I had not comparison elements to refer to be sure of the relevancy of my choices. Moreover, this is a forecast of future evolution of Polish power sector. As a consequence, these are just speculations on what is possible to happen but nothing can prove that these assumptions are correct. This fact of not being able to evaluate my own job tended to puzzle me. In addition, I was a bit disappointed by the fact that this study and the model could always be improved, taking into account new parameters. It made me realized that I needed goals to work, with quality criteria in order to evaluate it and to make it as perfect as possible.

These reflections confirmed my will to work in an engineering office, meeting a clarified need and reaching an evaluable goal. In addition, comparing with the technician internship I did last year, I think that I could work more efficiently carrying out many projects instead of only one.

Anyway, this internship was a very great experience and I was really pleased to work with such a pleasant atmosphere. In addition, it enabled me to travel throughout Eastern Europe and to experience a new culture. It was interesting to understand several aspects of a country which had known such a different past. Both visiting and talking with Polish people, it was impressive to see how much Poland had been marked by Second World War and Communism. Considering all the museums or monuments dedicated to the war, without citing concentration camps, it is not hard to understand that Polish people have gone through this trauma with high difficulty. But fortunately, the darkest periods of Poland past are not the only ones that can be experienced and it was with a great interest that I could visit beautiful cities full of impressive architecture, very different from what can be seen in France.

This internship made me wish to come back to Poland in order to visit areas I could not see and to travel throughout other Eastern Europe countries, that I would not have planned to do before.

APPENDICES

MODEL ELEMENTS

Input

Sets:

Types of Fuel	Technologies	Modelling Period
Hard Coal (HC)	Combined Heat and Power (CHP)	2006 - 2030
Brown Coal (BC)	Pulverized Fuel (PF)	
Oil	Coal Fluidized Bed (CFB)	
Gas	Power Plant (PP) for non-coal fuels	
Wind		
Hydro		
Biomass		
Nuclear		

Parameters:

Electricity and Heat generation	Plant characteristics	Market characteristics
Electricity demand	Lifetime	Fuel price and potential
Heat demand	Load factor	CO2 price
Renewable quotas	Construction cost	CO2 Free allowances
Electricity and thermal efficiencies	Fixed and variable costs for operating & maintenance	Price of green certificates
	CO2, SO2 and NOx emission factors	Discount rate

Equations

- Electricity, heat and renewable electricity production ruled by constraints
- Fuel consumption ruled by potential constraint
- CO2, SO2 and NOx emissions
- Costs of electricity generation
    - o   Construction cost
    - o   Fixed and variable costs
    - o   Fuel consumption cost
    - o   CO2 cost

- Goal function: optimization of total costs

Output

- Evolution of existing and new energy capacity
- Cost distribution
- Emissions
- Fuel consumption
- Distribution of electricity production
- Cost of MWh generation

RESULTS ANALYSIS

Extract of the article "Impacts of the implementation of European Union policy Emission Trading System on Polish power sector"

Aiming at analyzing the influence of RPS system on Poland energy sector, the study focuses on the evolution of electricity generation, fuel consumption, gas emissions, cost distribution and the evolution of MWh generation cost.

Electricity generation

Reference Scenario

In this scenario, total installed capacity increases from 29 GWe in 2006 to 33 GWe in 2030. The details of this evolution are presented below:

Table 3: Ref_Sc Generation capacity [GWe]

Technology	Fuel	2006	2010	2015	2020	2025	2030
PF	HC	12,73	11,34	11,315	10,891	9,77	9,325
PF	BC	4,91	4,91	4,91	4,91	4,91	4,91
CFB	HC	0,81	0	0	0	0	0
CFB	BC	2,11	2,11	2,11	2,11	2,11	2,11
CHP	HC	6,944	6,944	6,944	6,944	6,944	6,944
PP	WIND	1,483	3,426	3,703	5,681	8,418	8,418
PP	HYDRO	0	0,74	1,19	1,19	1,19	1,19
SUM		**28,987**	**29,47**	**30,172**	**31,726**	**33,342**	**32,897**

The most striking result of the Reference Scenario is the constant importance of coal in electricity generation. With 97.8% of production in 2006, electricity generation from coal remains the highest share of total production (84.8% in 2030), except for hard coal which use decreases by

21.5%, and particularly for hard coal used with pulverized fuel technology (decrease of 26.8%). But this decrease is only due to quotas about renewable energy sources production (a simulation run without RES quotas shows that no investment in green technologies would be made). Thus, instead of keeping exploiting hard coal plants, small share of wind and hydro plants are developed.

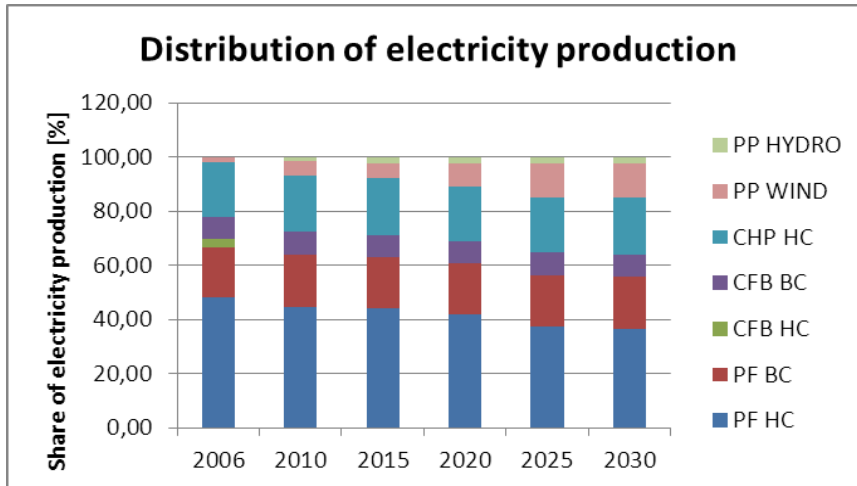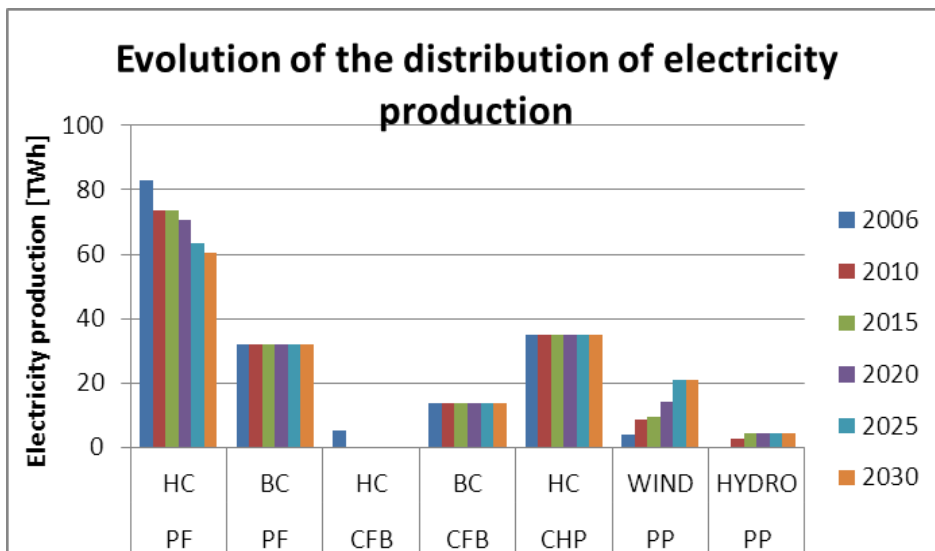**Figure 7: Ref_Sc Distribution of electricity production [%]**

Figure 8 highlights the evolution of electricity production and the minor proportion of green production. With less than 11% in 2020, renewable energy sources production hardly increases until 15.2% in 2030.

**Figure 9: Ref_Sc Evolution of electricity production [TWh]**

In addition, *Figure 4* presents the evolution of total electricity production. The peak in 2006 is certainly the result of the fact that existing plants are enough to provide necessary electricity.

However, according to renewable energy sources quotas and the constraint about closing existing plants progressively, there is consequently a slight overproduction in 2006.

Then, electricity production is firstly rising according to electricity demand but from 2022, production is slowly decreasing whereas final consumption keeps growing. In fact, this decrease of production is linked with technology improvement which progressively limits losses in electricity generation process.

**Figure 10: Ref_Sc Electricity production [TWh]**
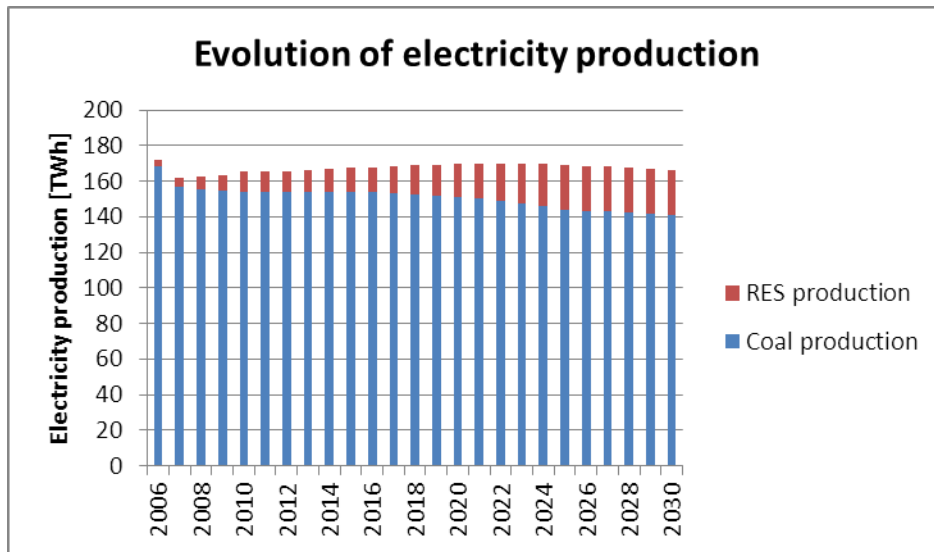
CO2 Scenario

In this scenario, installed capacity remains stable all along modeling period. From 2006, maximal needed capacity is reached as shown in *Table 4*.

Table 4: CO2_Sc Generation capacity [GWe]

| Technology	Fuel	2006	2010	2015	2020	2025	2030
PF	HC	12,73	11,243	11,243	6,593	1,593	0
PF	BC	4,91	4,91	4,91	3,91	0	0
CFB	HC	0,81	0,039	0,039	0,039	0	0
CFB	BC	2,11	2,11	2,11	1,11	0	0
CHP	HC	6,944	6,944	6,944	6,944	6,944	6,944
PP	WIND	1,483	3,576	3,789	14	14	14
PP	HYDRO	0	0,633	1,19	1,19	1,19	1,19
PP	NUCLEAR	0	0	0	3,059	13,05	14,198
SUM		**28,987**	**29,455**	**30,225**	**36,845**	**36,777**	**36,332**

This overproduction from the beginning of the modeling period enables to close progressively existing plants in order to replace them by new technologies. Since CO_2 emissions are taxed in this simulation, renewable energy sources production are extremely developed while coal plants are closed.

Figure 11: CO2_Sc Evolution of electricity production [TWh]
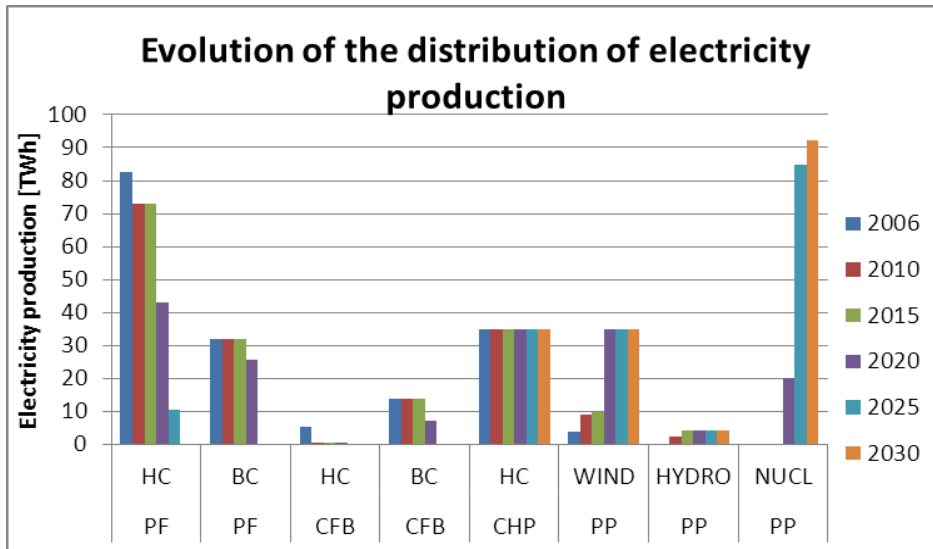
As shown in *Figure 5*, the closing of coal plants is very quick except for Combined Heat and Power plants which are needed to meet heat demand. Indeed, electricity from coal which was 97.8% of electricity generation in 2006 represents only 20.9% of electricity production in 2030. At the same time, proportion of green electricity is increasingly growing from 2.2% of electricity production in 2006 to 23.6% in 2030, with a 23.1% level in 2020 which reaches EU goals of "20-20-20" target.

Figure 12: CO2_Sc Electricity production [TWh]
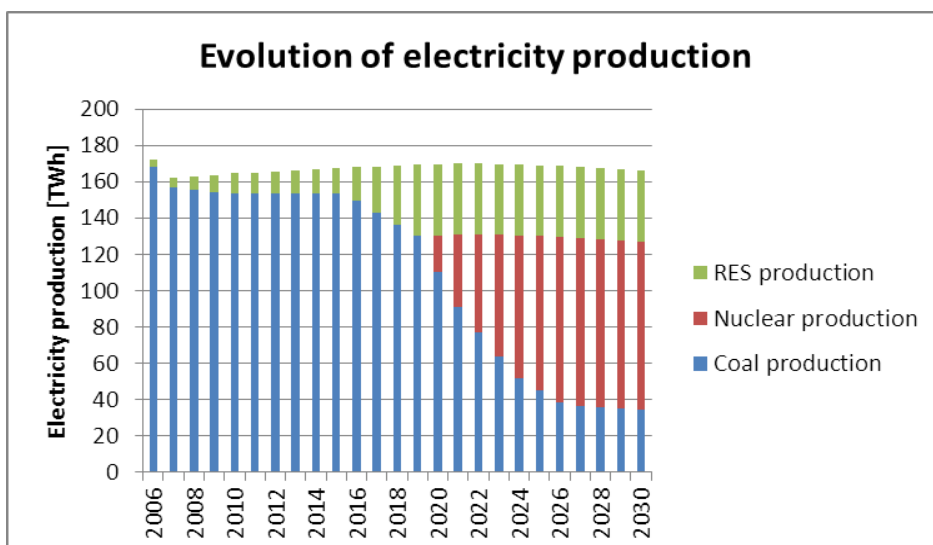
In addition, wind and hydro technologies are so developed that their maximal potential is quickly reached (from 2015 for hydro and 2020 for wind). In order to provide the rest of the electricity demand, nuclear plants are built. These technologies are used instead of new coal technologies because even if major improvements have been done to limit emissions in new coal plants, CO_2 allowances remain very expensive. Since nuclear technologies do not produce greenhouse gases, they seem more interesting regarding cost-efficiency.

Figure 13: CO2_Sc Distribution of electricity production [%]
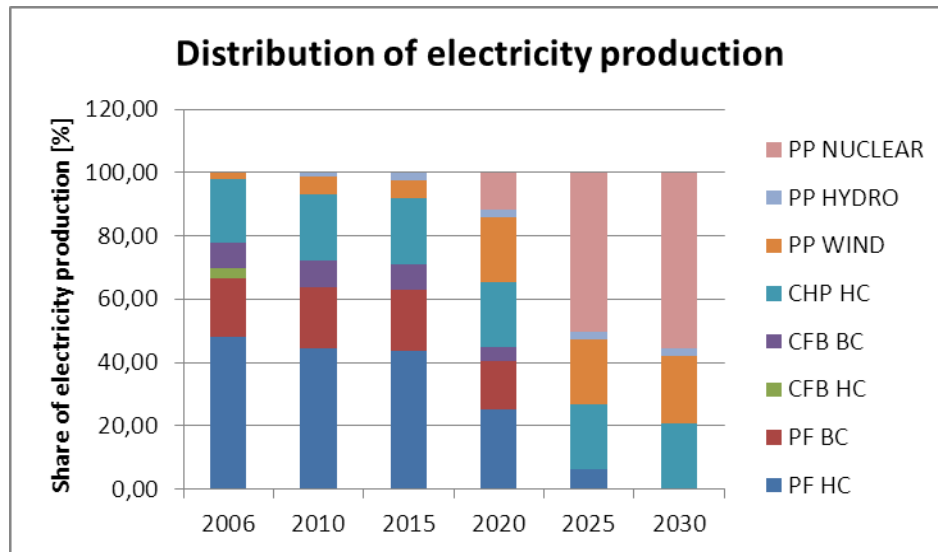
Furthermore, the development of nuclear plants is quite impressive since a 14 GWe capacity is built for only ten years. In 2030, nuclear technology provides 55.5% of electricity demand.

## Fuel consumption and Emissions

Reference Scenario

In the Reference Scenario coal remains the main fuel to produce electricity. As it provides 98% of electricity generation, coal represents 99% of total fuel consumption in 2006. This consumption decreases regularly during the modeling period (8.3% between 2006 and 2030) because of the improvement of technology efficiency and loss cutting.

Table 5: Ref_Sc Energy needs [PJ]

Fuel	2006	2010	2015	2020	2025	2030
HC	1320,75	1206,35	1205,07	1183	1124,69	1101,58
BC	365,04	365,04	365,04	365,04	365,04	365,04
GAS	0	0	0	0	0	0
OIL	0	0	0	0	0	0
WIND	13,35	30,83	33,33	51,13	75,76	75,76
HYDRO	0	9,32	15	15	15	15
BIOMASS	0	0	0	0	0	0
NUCLEAR	0	0	0	0	0	0
SUM	**1699,14**	**1611,54**	**1618,44**	**1614,17**	**1580,49**	**1557,38**

As a consequence, greenhouse gas emissions remain high. Indeed, existing capacity plants are mainly fueled with hard or brown coal and do not reach nowadays standards about greenhouse gas emissions. Nevertheless, a gentle decrease is observed for CO_2 emissions which are reduced from 164 Mton in 2006 to 143 Mton in 2030 (12.5% decrease). This level is still very high and the decrease by 8% in 2020 is far from reaching the 20% target set by EU. However SO2 and NOx emissions are cut more efficiently because existing plant level of emission is gradually improved all along modeling period.

Figure 14: Ref_Sc Gas emissions
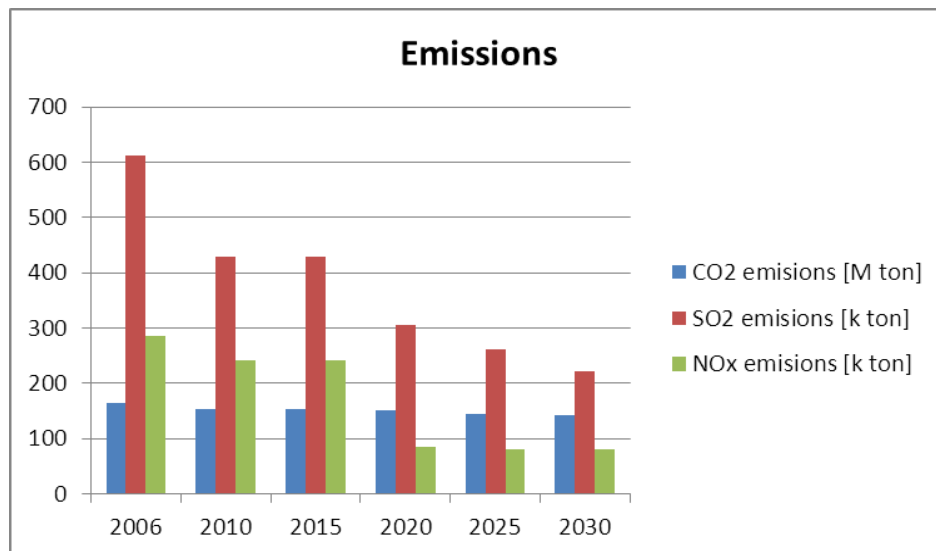
CO2 Scenario

In this scenario, electricity generation from coal decreases from 97.8% in 2006 to 20.9% in 2030. This fact explains the cut of coal consumption during modeling period (from 99% in 2006 to 36.7% in 2030). Moreover, total fuel consumption is first decreasing between 2006 and 2020 by 8% because of the improvement of existing technologies and the building of green technology plants which efficiency is higher than plants fueled with coal. However, general fuel consumption increases then because of nuclear plant construction which efficiency is lower than coal and green plants.

Table 6: CO2_Sc Fuel consumption [PJ]

Fuel	2006	2010	2015	2020	2025	2030
HC	1320,75	1203,35	1203,35	961,56	699,51	616,67
BC	365,04	365,04	365,04	261,04	0	0
GAS	0	0	0	0	0	0
OIL	0	0	0	0	0	0
WIND	13,35	32,18	34,1	126	126	126
HYDRO	0	7,97	15	15	15	15
BIOMASS	0	0	0	0	0	0
NUCLEAR	0	0	0	198,82	908,42	922,89
SUM	**1699,14**	**1608,54**	**1617,49**	**1562,42**	**1748,93**	**1680,56**

Furthermore, with a highly emission-taxing scenario, existing plants are quickly closed in favored of environment-friendlier technologies. This is why CO_2 emissions are cut by 27.5% between 2006 and 2020 and by 64.8% all along modeling period. In addition, SO2 and NOx emissions are also cut drastically thanks to emission improvement and closing of existing plants which were the most polluting.

Figure 15: CO2_Sc Gas emissions
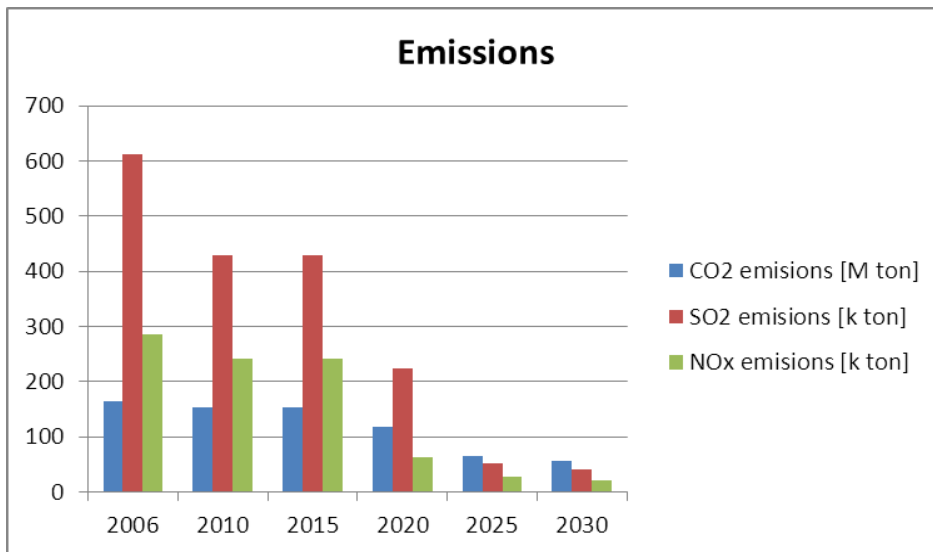
Cost of electricity generation

Reference Scenario

The total costs generated by this scenario come to 42 832 M€. This amount is essentially used to maintain existing capacity and particularly to feed them with fuel. Fuel costs represent 80.8% of total costs whereas costs for construction of new plants in order to meet RES quotas only reach 8.9% (these costs are the second higher amount). This is reflected in the MWh cost. As *Figure 10* shows it, the main part of MWh cost for coal technologies is the cost of fuel while construction costs are the most important for green technologies.

**Figure 16: Ref_Sc Distribution of electricity generation costs [€]**
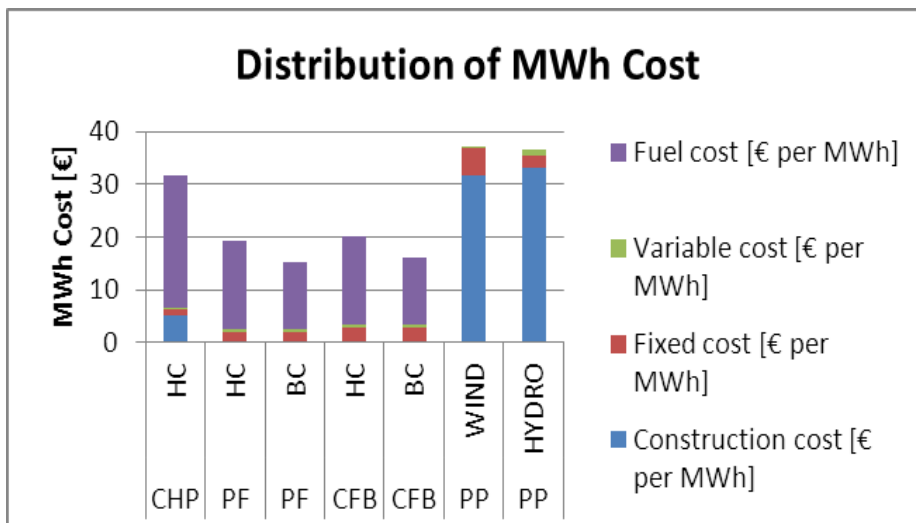
For the reference scenario, MWh cost from green technologies remains far more expensive than for coal technologies.

CO2 Scenario

For CO_2 Scenario, total costs generated by the evolution of Polish power sector reach 62 063 M€. This amount represents 1.45 times the total costs generated by the Reference Scenario. However, implementing green certificates of 70 € per MWh of electricity produced by renewable sources can generate subsidies reaching 12 055 M€, which makes this scenario competitive compared with Reference Scenario.

For CO_2 Scenario, three types of costs share the main part of total costs: fuel costs (34.8%), CO_2 costs (30%) and construction costs (27.5%). Important amount of fuel costs is used for the maintenance of existing coal plants but also for the consequent consumption of nuclear plants due to their major installed capacity. In addition, since existing plants are rather quickly closed to be replaced by environment-friendlier technologies, it seems normal that construction costs, which are the biggest costs for green technologies, represent an important percentage of this scenario. Finally, the elevated percentage of CO_2 costs is due to the price of allowances that remaining coal plants have to buy. These costs for CO_2 allowances accelerate impressively the closing of coal technologies.

Figure 17: CO2_Sc Distribution of electricity generation costs [€]
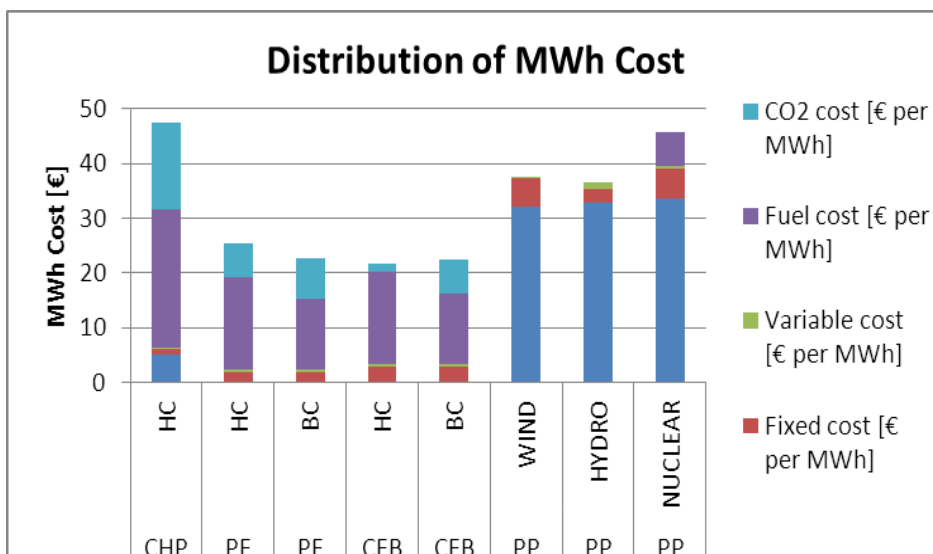
As it is visible in *Figure 11*, CO_2 costs become rather important with ETS system. Even if MWh cost from green technologies remains still higher, especially due to their construction costs, the implementation of not free allowances enables green technologies to be more competitive facing cheaper fossil fueled technologies.

IMPACTS OF THE IMPLEMENTATION OF CO_2 PRICE ON POLISH CO_2 EMISSIONS

The implementation of the European Union energy policy Emission Trading System (ETS) is about to institute non free allowances for CO_2 emissions in order to cut them. This tax is on the verge of changing deeply Polish power sector, essentially based on coal, because of the substantial increase of electricity production cost it is going to lead to. ETS proceeds in three stages: firstly, until 2013, CO_2 allowances will be granted for free; secondly, between 2013 and 2020, CO_2 price will be implemented and finally, after 2020, CO_2 price will be higher.

The aim of this study is to analyze the consequences of ETS implementation on CO_2 emissions of Polish energy sector.

In order to understand general evolution of CO_2 emissions a first analysis was run, keeping constant CO_2 price between 2013 and 2020.

Figure 18: Evolution of CO_2 emissions depending on CO_2 price
(CO_2 price is constant between 2013 and 2030)
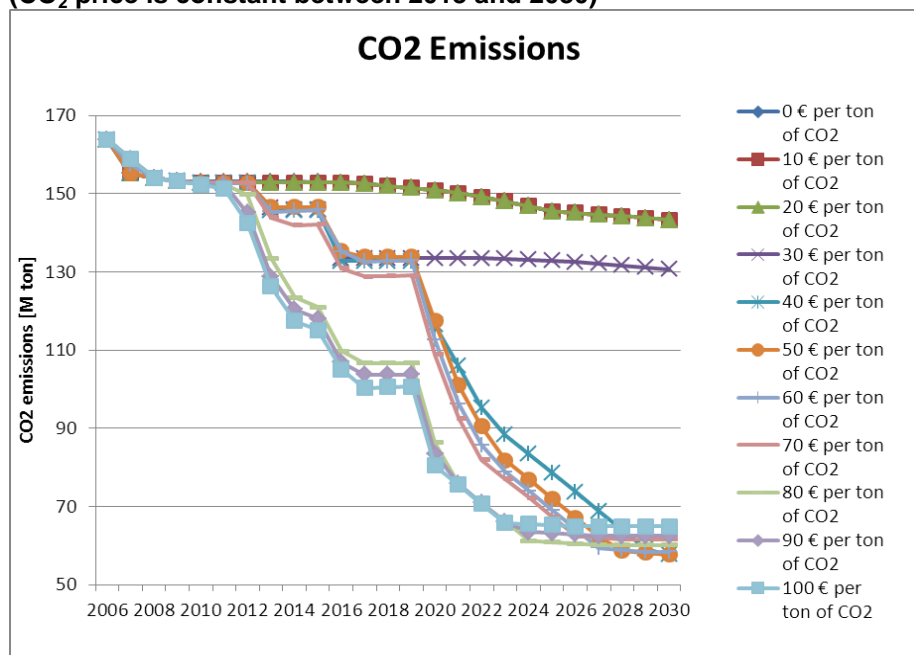
This first analysis enables to highlight global behavior of CO_2 emissions.

The first observation which can be done is that cutting substantially CO_2 emissions requires a minimal price for CO_2 allowances. A price lower than 20 € per ton of CO_2 emissions only enables to decrease emissions by 0.04% whereas with a 30 € CO_2 price, decrease hardly reaches 6.6%. On the contrary, as soon as CO_2 price exceeds 40 € per ton, emission decrease can reach 31% with the lowest emissions in 2030, since in this scenario coal plants are replaced by emission cutting technologies (green and nuclear).

In addition, three periods of emission evolution can be identified. During the first period, between 2006 and 2013, CO_2 emissions slightly decrease thanks to the implementation of quotas about electricity generation from renewable sources.

The second period, from 2013 to 2020 (implementation of CO_2 price), shows a cut of CO_2 emissions by stages. The first important decrease appears between 2013 and 2016 and can be explained by the implementation of CO_2 allowances cost. The second decrease step occurs in 2016. This is due to an important increase of wind potential which is multiplied by a 2 factor. Consequently, this potential is made the most to replace emitting coal plants.

Finally, the third period occurs between 2020 and 2030. During this time, emissions seem to decrease exponentially. This is due to the implementation of high potential of nuclear technology, which can be used only from 2020 according to current Polish power sector.

Nevertheless, ETS will implement different prices for CO_2 for the second and the third period. In order to study the influence of each period on CO_2 emissions, analyses were run keeping constant CO_2 price for one period.

Figure 19: Evolution of CO_2 emissions
(CO_2 price is 0 € per ton between 2013 and 2020)
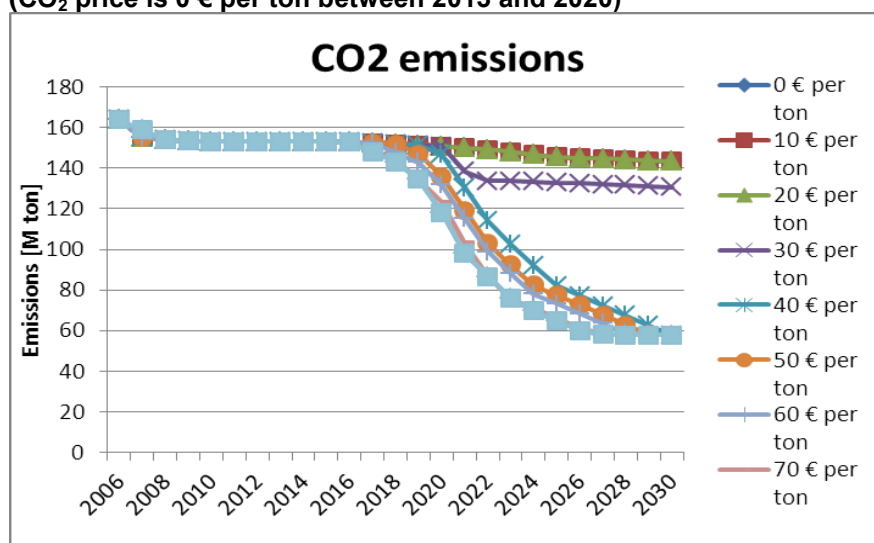
This analysis confirms the need of a minimal price for CO_2 allowances to cut emissions efficiently. With lower price than 40 €, emission improvement is not satisfying. On the other hand, beyond 40 € per ton, results are quite similar. Paying 100 € per ton of CO_2 only enables to decrease emissions by 6% comparing to 40 € per ton scenario.

Moreover, the analysis of CO_2 price aftermaths during the 2013-2020 period is interesting, as emissions vary very differently according to the fixed price of CO_2 for the third period.

Figure 20: Evolution of CO_2 emissions
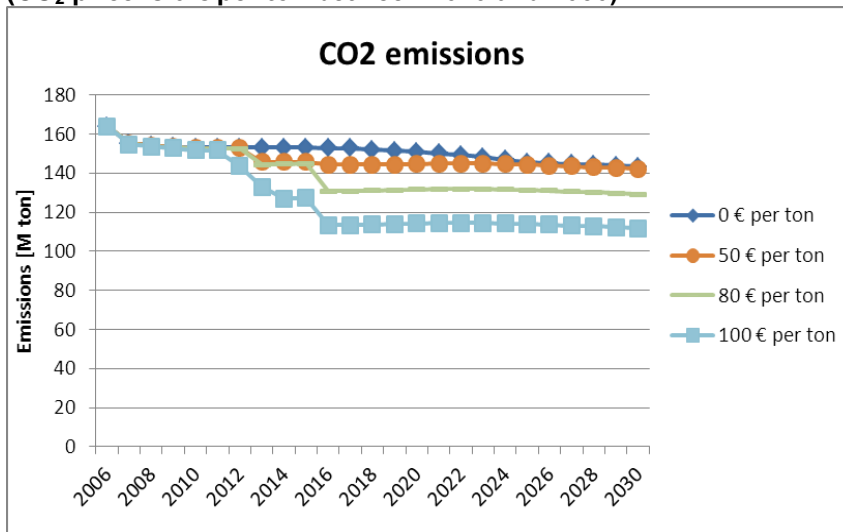(**CO_2 price is 0 € per ton between 2020 and 2030**)

Figure 21: Evolution of CO_2 emissions
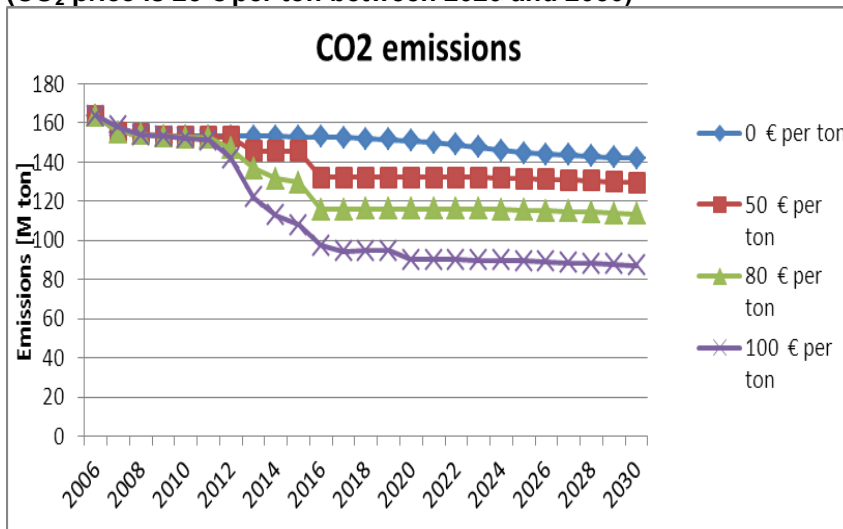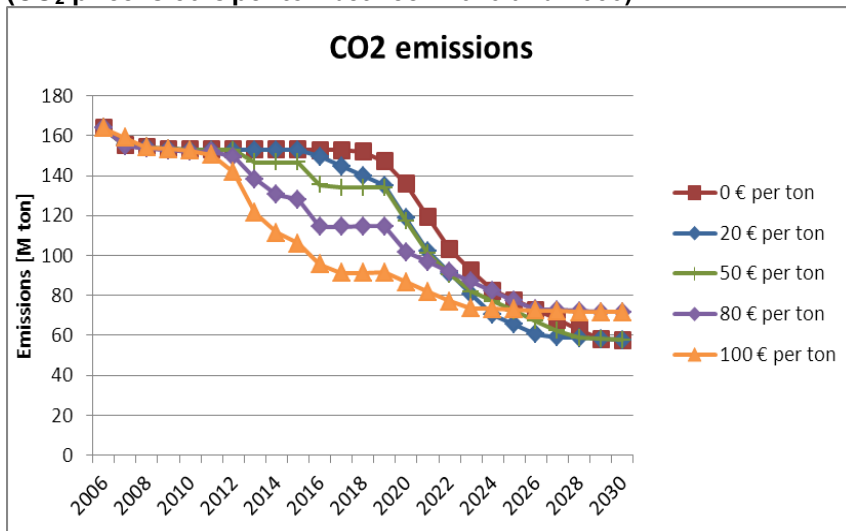(**CO_2 price is 25 € per ton between 2020 and 2030**)

Figure 22: Evolution of CO_2 emissions
(CO_2 price is 50 € per ton between 2020 and 2030)

Once again, it is visible that in order to reduce emissions after 2020 but also between 2013 and 2020, 40 or 50 € per ton at least are necessary after 2020.

In addition, with high CO_2 price, two scenarios can appear (it is visible in *Figure 23*). For CO_2 prices higher than 60 € between 2013 and 2020, biomass and gas technologies are implemented. With such high price, the cheapest scenario seem to close all coal plants as quickly as possible, developing green technology at the top of its potential (wind, hydro and biomass). In order to meet the demand before 2020, gas technology is used too, reducing by this way the final share of nuclear electricity generation. Even if this type of scenario can reduce global CO_2 emissions, emission standards in 2030 are higher than cheaper scenario. Indeed, gas plants are more efficient about CO_2 emissions than coal plants, but they still emit more than nuclear plants. Consequently, the development of nuclear power after 2020 is closely linked to CO_2 policy implemented between 2013 and 2020.

Besides, gas is a source of CO_2, but also SO_2 and NO_x emissions. The global emission decrease this scenario seems to generate can be interesting in short-term, but it may not be the optimal scenario regarding a longer period.

Furthermore, it is important to keep in mind that 90 or 100 € per ton of CO_2 would be huge costs for companies who could then be tempted to relocate their plants out of the European Union in order to evade CO2 taxes.

In order to sum up these observations, cutting CO_2 emissions efficiently requires at least a price of 40 € per ton of CO_2 emissions after 2020 (which is the most efficient period to decrease

CO_2 emissions), and lower than 60 € per ton between 2013 and 2020 to prevent carbon leakage. In addition, nuclear power is developed provided a CO_2 price higher than 40 € per ton after 2020, but its share of electricity production is above all determined by CO_2 price between 2013 and 2020, as shown in *Table 7*.

Table 8: Evolution of nuclear share according to CO_2 price

CO2 price 2013-2020	CO2 price after 2020	Share of nuclear electricity in 2030 [%]
100	50	15
80	50	32
60	50	54
50	50	56
0	50	56
20	30	0
20	40	56
20	50	56
20	80	56

Finally, the best CO_2 scenario would implement CO_2 price about 50 € per ton after 2020 according to *Figure 24*. According to this, *Figure 5* shows that an optimal scenario would use CO_2 price between 20 and 40 € for the 2013-2020 period. However, a scenario 20-50 € per ton would cut emissions by 22% whereas 40-50 € would only reach an emission decrease of 23%, increasing costs by 55%.

As a consequence, the best CO_2 policy efficiency-price ratio would implement a tax of 20 € per ton of CO_2 between 2013 and 2020, and 50 € then. This would lead to an important development of nuclear power enabling to cut CO_2 emissions until 65% in 2030 considering emissions in 2006 as a reference, and decreasing global CO_2 emissions between 2006 and 2030 by 22%.

COST CALCULATION METHODOLOGY

Even if majority of costs in the model (fixed costs, variable costs, fuel costs and emission costs) are calculated regarding year by year payment according to annual needs and emissions, construction costs (equal to unit costs multiplied by capacity to be installed) are split all along plant lifetime.

Instead of paying entire construction costs at the very beginning of plant service, they are divided into annual equal investments until plant dismantling. This method, regarding the modelling period, is more favourable economically because a plant lifetime is not obviously wholly included into this period. In this case, whole construction costs are not considered as paid by the simulation, but they are converted into salvage costs. In addition, splitting construction costs enables to homogenize total costs between years, since construction costs are one of the main share of total costs for a plant in service.

Methodology

The aim of this method is to split construction costs equally all along plant lifetime.

Firstly, we could think that we just have to divide unit costs by plant lifetime to get the annual constant payment value. But this would not take into account the inflation effect on money devaluation. This is why the factor r is introduced, the real interest rate, which enables to calculate the base year value (or present value) of a future investment.

In the same way as you can forecast how much an investment in a bank would yield after n years according to the investment rate, it is possible to estimate the today's value of a future investment. If B_n represents a future investment, n the number of years between present year and investment year, r the interest rate and B_0 the present value of this investment, we have:

$$B_0 = \frac{B_n}{(1+r)^n}$$

Where $\frac{1}{(1+r)^n}$ is called "Discount factor" or "Present Worth Factor".

As a consequence, whole construction costs representing the present value (worth of a series of future payments) are the sum of the discounted present worth of each individual payment.

In the model case, construction costs have to be split equally. So if future payments are called A, A will be a constant annual value for all n. Discounting this sum of constant payment gives us:

$$Construction\_costs = A.\left(1 + \frac{1}{(1+r)} + \frac{1}{(1+r)^2} + \frac{1}{(1+r)^3} + \cdots + \frac{1}{(1+r)^{n-1}}\right)$$

So

$$A = \frac{Construction\_costs}{\left(1 + \frac{1}{(1+r)} + \frac{1}{(1+r)^2} + \frac{1}{(1+r)^3} + \cdots + \frac{1}{(1+r)^{n-1}}\right)}$$

$$A = Construction\_costs.\left[\frac{1 - (1+r)^{-1}}{1 - (1+r)^{-lifetime}}\right]$$

$$A = Construction\_costs\,.CRF$$

with

$$CRF = \frac{1}{\left(1 + \frac{1}{(1+r)} + \frac{1}{(1+r)^2} + \frac{1}{(1+r)^3} + \cdots + \frac{1}{(1+r)^{n-1}}\right)} = \left[\frac{1 - (1+r)^{-1}}{1 - (1+r)^{-lifetime}}\right]$$

and is called Capital Recovery Factor.

_N.B:_ *For this model, the base year is the first year of the modelling period. This is why the first term of CRF expression is 1 (there is no discount for the base year). However, the base year is not usually included into the modelling period. This explains the fact that in many bibliographical researches, I found the following expression for CRF:*

$$CRF = \frac{1}{\left(\frac{1}{(1+r)} + \frac{1}{(1+r)^2} + \frac{1}{(1+r)^3} + \cdots + \frac{1}{(1+r)^n}\right)} = \left[\frac{r}{1 - (1+r)^{-lifetime}}\right]$$

Now that annual construction costs are determined, annual total costs can be calculated. Finally, they are discounted to be considered in present value.

$$Total\_costs(y) =$$
$$\frac{[Construction\_costs(y) + Fixed\_costs(y) + Variable\_costs(y) + Fuel\_costs(y) + Emission\_costs(y)]}{(1+r)^{ord(y)-1}}$$

Or :

$$Total\_costs(y) =$$
$$\frac{[A + Fixed\_costs(y) + Variable\_costs(y) + Fuel\_costs(y) + Emission\_costs(y)]}{(1+r)^{ord(y)-1}}$$

with $ord(y)$ the ordinal number of the considered year in the modelling period.

Using the exponent "$ord(y) - 1$" enables to get a discount factor equal to 1 for the first modelling year (base year).

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CALCULATION OF MWh GENERATION COST

To calculate the cost of 1 MWh, the notion of Levelised Cost Of Electricity (LCOE) was used. The advantage of this tool is that it makes possible to compare energy generation cost of different technologies all along their lifetime. This method is based on the balance between expends and receipts generated by electricity production. The cost of 1 MWh, according to this tool is consequently the minimal price the investor should sell electricity to break even. This equivalence is however based on two assumptions: discount rate and electricity price remain stable and constant all along plant lifetime.

Methodology

According to the report "Projected Costs of Generating Electricity" written by the International Energy Agency and Nuclear Energy Agency Ad hoc Expert Group on Electricity Generating Costs, LCOE is defined as follows:

"With annual discounting, the LCOE calculation begins with equation (1) expressing the equality between the present value of the sum of discounted revenues and the present value of the sum of discounted costs. The subscript "t" denotes the year in which the sale of production or the cost disbursement takes place. All variables are real and thus net of inflation. On the left-hand side one finds the discounted sum of all benefits and on the right-hand side the discounted sum of all costs. The different variables indicate:

$Electricity(t)$: The amount of electricity produced in year "t";

$PElectricity$: The constant price of electricity;

$\frac{1}{(1+r)^t}$: The discount factor for year "t";

$Investment(t)$: Investment costs in year "t";

$O\&M(t)$: Operations and maintenance costs in year "t";

$Fuel(t)$: Fuel costs in year "t";

$Carbon(t)$: Carbon costs in year "t";

$Decommissioning(t)$: Decommissioning cost in year "t".

(1):

$$\sum_t \left(Electricity(t).PElectricity.\frac{1}{(1+r)^t} \right) = \sum_t \left(\begin{bmatrix} Investment(t) + \ OM(t) \\ + \ Fuel(t) + \ Carbon(t) \\ + \ Decommissioning(t) \end{bmatrix} . \frac{1}{(1+r)^t} \right)$$

From (1) follows (2):

$$PElectricity = \frac{\sum_t \left(\begin{bmatrix} Investment(t) + \ OM(t) \\ + \ Fuel(t) + \ Carbon(t) \\ + \ Decommissioning(t) \end{bmatrix} . \frac{1}{(1+r)^t} \right)}{\sum_t \left(Electricity(t).\frac{1}{(1+r)^t} \right)}$$

which is, of course, equivalent to (2)':

$$LCOE = PElectricity = \frac{\sum_t \left(\begin{bmatrix} Investment(t) + \ OM(t) \\ + \ Fuel(t) + \ Carbon(t) \\ + \ Decommissioning(t) \end{bmatrix} . \frac{1}{(1+r)^t} \right)}{\sum_t \left(Electricity(t).\frac{1}{(1+r)^t} \right)}$$

[In this explanation, the discount of Electricity production by the factor $\frac{1}{(1+r)^t}$ can be surprising. Nevertheless, the reason is easy to see]. Equation (2)' seems to discount each year's physical value of output measured in MWh by the exponentially rising time preference factor $(1+r)^t$. Discounting physical values, however, does not seem to make intuitive sense, since physical units neither change magnitude over time, nor do they pay interest. This intuition, however, needs to be qualified. While it is true that an MWh of electricity does not pay interest, its only economic function is to produce a revenue stream that does pay interest. From today's point of view, an MWh produced this year thus does not have the same economic value as does an MWh produced next year. What is discounted is the value of output that is the physical production times its price, PElectricity in the above formula, and not output itself. It is only after mathematical transformation that it appears as if physical production was discounted."

As a consequence, this formula was used in the model, but since costs are paid from the first year of the modelling period (considered as the base year, so without discount), the exponent "t" was just replaced by "t −1" (this enables to obtain a discount factor equal to 1 for the first modelling year).

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