CO_2 emissions – fissioned, flushed or gone with the wind?

Comparative study of cost-effectiveness of different electrical capacity development scenarios in Poland

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Preface

The following is a Master's level graduation thesis for the department of Energy Planning, prepared and written July-October 2009 as part of the Sustainable Energy Planning and Management programme by B.Sc. Jan Henryk Wiśniewski under the supervision of Assist. Prof. Morten Boje Blarke.

I hereby state that the work presented in this paper is my own and no one else's intellectual property.

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Credits

I would like to offer my thanks to Assist. Prof. Morten Boje Blarke for all his advice in increasing the quality and structure of this project.

Nomenclature (in order of appearance):

LPC – Levelized Production Cost

BAT – Best Available Techniques

m_{CO2} - mass of emitted CO_2 [t]

m_C - mass of combusted coal [t]

p – ash content [%]

s – sulfur content [%]

w – water content[%]

$\frac{44}{12}$ – Carbon to CO_2 mass conversion ratio

E – amount of produced energy [GJ]

O – Lower heating value[GJ/t]

η- process efficiency[%]

n – investment period [yrs]

p – discount rate

t – investment lifetime [yrs]

Z – base income [PLN/MWh]

H – no. of full load hour equivalents per year [h]

P – power [MW]

O&M costs – costs of operation and maintenance including fuel costs

k – constant, k = 1032048

d – depth [m]

V_a – average yearly wind speed at rotor height [m/s]

V_0 – average yearly wind speed at anemometer height [m/s]

h_w – rotor height [m]

h_0 – anemometer height [m]

z – wind shear factor

T_i – A percentage of time for which V_i is achieved [%]

V_i – Given wind speed [m/s]

k – shape parameter

r – constant, r = 0.89

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Section I: Methodology & Research Question

"The squeaky wheel gets the grease"

– English proverb

Context description

Poland runs on coal. It is this country's greatest natural resource and the basis for a working economy. In year 2008, 93% of electrical energy in Poland was supplied by coal power plants (Barzyk et al., 2009).

After year 1945, abundant energetic resources, along with roughly 38% of the country's value destroyed in WWII, have caused the country to embrace heavy industry in order to rebuild cities, roads, homes and provide people with basic goods. The situation progressed slowly – Poland has been forced to abstain from taking part in the European Recovery Program (ERP), Technical Assistance Program (TAS) and Mutual Security Program (MSP) based on threats from Joseph Stalin. For the first five years after the war not a single coal power plant was built due to the horrible state of the economy and infrastructure, but afterwards the electricity production began to grow at an accelerating pace: 3.7 GW electrical capacity were installed in the 1950's and 6.65 GW el. in the 1960's. In the 1970's due to Poland taking on large loans from Western Europe, as much as 11.4 GW electrical capacity were installed .(WNP, 2009).

Figure 1. ERP modernist poster (rare-posters.com, 2009)

As the loan-money used up, growth decelerated – 6.66 GW el. in 1980's, 2.6 GW el. in 1990's. In the year 2000, 34.5 GW el. capacity were available – peak yearly use was at 22.3 GW – no coal power plants have been installed since.

Year	1946	1950	1960	1970	1980	1990	2000
Connection with	None	None	Soviet Russia, Chechoslovakia, East Germany				UCPTE countries
Net energy export [TWh]	X	X	-0.3	-0.1	0.3	1.1	6.4

Figure 2. Poland's yearly electricity balance (WNP, 2009)

Along with implementing system changes, Poland dropped most of its heavy industry in years 1989 to 1992, developing a large capacity surplus. After joining the Union for Co-ordination of Production and Transmission of Electricity (UCPTE) in 1995, Poland started exporting electricity onto the European market, and was, in year 2006, Europe's second biggest energy exporter after France – the World's biggest electricity exporter (Kuźniarski, 2009).

As of 2008, Poland is officially planning to adapt nuclear technologies for electricity production purposes. The goal is to prevent global warming by reducing CO_2 emissions within the currently very coal-dependant electricity production sector. Preparing the Polish society, infrastructure and legislation system will be an over a decade long process that will consume vast resources. The Polish plan is to start operations within the first nuclear power plant by the end of 2020.

The decision to introduce nuclear power generation to the Polish system was announced by Prime Minister Donald Tusk on November 9, 2008 (Jamroż, 2008). In the following months a National Atomic Agency (PAA) has been founded by the Ministry of Economy, under the direction of Hanna Trojanowska – the vice-minister of Economy. The scheme is still in an early part of the planning phase and the current goal is to develop the necessary legislation regarding rules concerning the level and scope of safety measures for nuclear plant operation by the end of year 2010 (Ciepela, 2009).

The European Comission has set the goal for cumulative CO_2 eq. emissions up until the year 2050. It is officially assumed that if the world emission targets are not reached by then, the global mean temperature growth will exceed 2°C and climatic feedbacks will cause an out of control global mean temperature rise. Newer studies (Meinhausen et al., 2009) indicate that due to a higher level of climatic response than previously anticipated, there is a strong possibility that the EC global mean temperature growth targets will be exceeded by the year 2030. These two dates set possible time horizon for emission reductions. The lenght of time necessary for implementing a certain CO_2 emissions reducing system affects the system's significance in terms of preventing catastrophic climate change.

One of the possible solutions to the global warming threat is a large scale shift from fossil fuels towards nuclear technologies. Nuclear power plants have been the topic of a heated discussion in Poland for over half a century. In the 1950's it was seen mostly as a revolutionary new technology, a sign of progress and man's unlimited potential.

This enthusiasm for progress was expressed in various art forms, such as the "Robots' tales" – gallant stories of atomic-powered robots in asbestos armor questing for their fair-steel maidens, probability demons, cyber-dragons, titanium-tyrants etc., published in 1964 by one of Poland's two finest SF writers of all time – Stanisław Lem, a theorist of science influenced by his wife - a medical radiologist. His idyllic approach embraces all new scientific discoveries, showing how they make for a more interesting, colorful and exciting world.

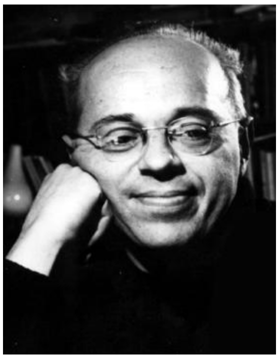


Figure 3. Stanisław Lem – 1966 (Raińczuk, 2008)

The problems of atomic-waste disposal have fueled a different discourse – one dealing with the safety risks of nuclear power in a Western European regime and visions of slowly treading the path towards self-obliteration by gradually arming the whole world with weapons of mass destruction. These problems have been toggled by the other most-famous Polish SF writer of all time Janusz A. Zajdel – a moralist, using the excuse of writing about far-away places and times to escape censorship and interest the readers in the grim truths he had to offer. In addition to being the greatest SF writer after Lem's retirement, Zajdel spent his time working at the Central Laboratory for Radiological Protection as an expert in atomic-core physics. After a lab accident, Zajdel died of lung cancer in 1985 at the age of 46. It is interesting to note that whenever Zajdel wrote about nuclear energy it was always on earth in a very near future, that the reader might live to experience.

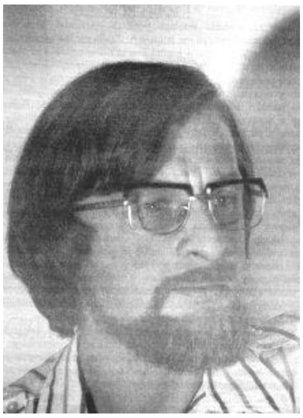


Figure 4. Janusz A. Zajdel (fantastyka24, 2009)

One of his many post-morti published stories tells the tale of an old man keeping watch over a closed quarter of a once revolutionary atomic-waste dump. The high investment made the local communities bloom for a short period of time, but after a few decades, increasing death rates among children and cancer cases among a grown-ups have caused the local populace to move, leaving the old man and his guard dogs to a long life of duty and solitude. Finally, when due to a very slow but steady increase in radiation, all the young pups are born dead and his last two faithful dogs, Saturn and Neptune die, he puts their bodies in marked barrels, and uses a special machine to fill them with resin, lock and move to a designated space with many other such barrels. Afterwards, with grim humor symbolizing what his life has become, he labels the last barrel as Pluto and before getting inside, turns the machine on.

In truth, both of the aforementioned artists portray visions of destruction coming from improper use of technologies. The opposition of approaches sprouts from the fact that Lem seems to believe in teaching people by entertaining their minds – showing them behaviors and traits that should be avoided so that all could be fine and any technology could be employed. Zajdel is haunted by real-life examples of how Eastern European countries actually develop, as opposed to theoretical plans full of grandeur presented in the media by socialist leaders – as he is unable to believe in the wisdom of societies, his stories portray atomic energy as a slow path towards doom.

Nonetheless, Poland has atomic energy to thank to for developing the minds of its most famous and world-renowned SF writers.

The debate between enthusiasts of an incredible and fascinating technology and the people afraid of potential catastrophes of human hubris has raged for decades. Partly due to the tendency of setting up many of the nuclear power plants next to country borders, and partly due to accidents such as the one in Chernobyl, very high safety standards have been passed within the EU. It is believed that proper investments in safety devices and fail-proof mechanisms will be able to prevent any peace-time disasters.

Possible approaches

Adapting nuclear technologies influences many sectors from water supply and farming through international trade and waste production to military power, with interactions between.

National safety approach

A national safety approach could potentially devaluate any considerations of economic feasibility if a high enough priority was given to increasing military strength. Using plutonium – one of the waste products of electricity generation in nuclear power plants for weapons production would limit the amount of radioactive waste the energy producer is liable for and introduce two kinds of storage facilities for radioactive electricity production byproducts with different procedures and access limitations. A nuclear power plant's dome is constructed in a way as to effectively prevent pollution spread in case of an incident and is able to withstand a blast from within. The only possibilities for radioactivity to spread over a large area are either a strong earthquake – not a threat in the area of Poland, or an outside attack damaging the plant. The attractiveness of nuclear power plants as terrorist targets, necessitates keeping airplane routes and nuclear plants far apart. The possibility of a missile attack from a wartime enemy keeps nuclear power plant localizations far away from big cities therefore most of the heat produced by nuclear power plants usually remains unused and has to be emitted into the atmosphere using up water resources that are also necessary for farming, fish breeding and industry.

Biodiversity approach

Waters at temperatures approaching 36℃ being pumped into nearby bodies of water are a standard procedure for nuclear core cooling. Long period rises in water temperatures cause loss in biodiversity in cold waters. The water habitat becomes dominated by cyanoses (Cyanophyta) and algae which lower the level of oxygen in the water and also generate hepatotoxins and anatoxins. Investing in atomic energy limits the need for new coal mines –

as most of Poland's unused coal resources are located in pristine natural locations, creating new mines causes destruction of entire ecosystems mainly due to lowering water levels by as much as hundreds of meters which prevents plant growth and drains lakes. Some bird species e.g. pigeons don't evade wind farm rotors. Big hydroelectric power plants have proven to be harmful to natural water ecosystems, changing water regimes and obstructing fish migration. Basing on these facts, switching to nuclear plants could both endanger and protect biodiversity. A study investigating biodiversity loss due to implementing versus not implementing nuclear power plants in Poland would be interesting but results for each technology could change by an order of magnitude based on location, therefore such studies would probably prove more useful during the localization phase, as part of an Environmental Impact Assessment.

Human health approach

Substituting coal with nuclear power reduces the amount of PM2.5 particulate matter in the air – an important cause of asthma, lung cancer and premature death (NRDC, 2005).

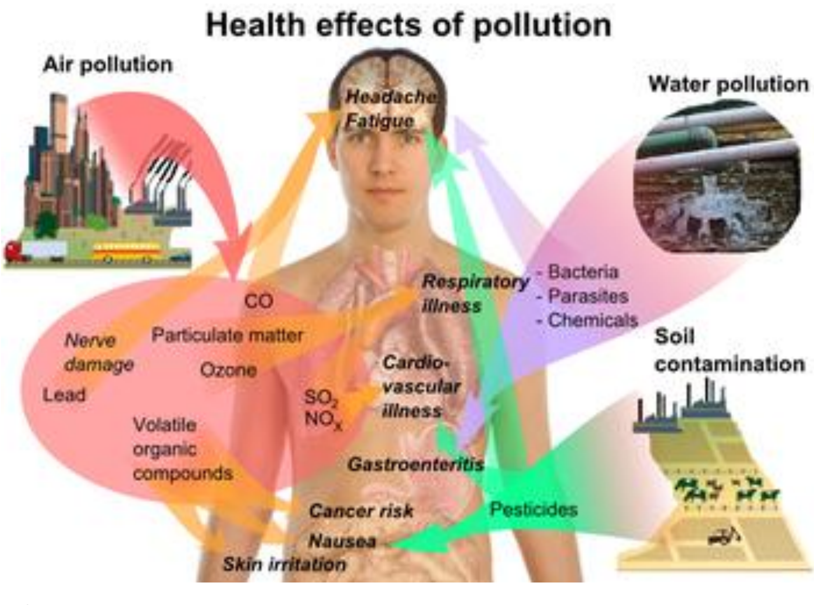


Figure 5. Health effects of pollution (West, 2009)

On the other hand nuclear power plants are suspected of causing i.e. pancreas cancer: after the 1986 accident of Chernobyl, many cases of pancreas cancer were diagnosed – it is scientifically not proven whether this was caused by the accident because mass scoping of the Ukrainian society for pancreas cancer has never been done before.

A human health approach can be part of a macroeconomic approach – comparing the costs of energy internalized by the costs of additional necessary healthcare, and value lost due to citizen deaths and the costs of energy including costs of eliminating health impacts from emissions.

Energy independence approach

Poland has no exploitable uranium resources and would be fully dependant on import of fuel. Assuming that Poland would otherwise keep using coal or substitute the planned production of nuclear power plants with renewable energy, the impact on energetic independence would be negative. Assuming however that in order to limit CO_2 emissions Poland would substitute the planned production share of nuclear power plants with oil or natural gas power plants, investing in nuclear power plants would be an option less harmful to Poland's energy independence, because of lesser possibility of conflict with Poland's potential uranium suppliers e.g. Australia and harder to cut-off supply routes in case of an armed conflict with any other country.

SEA approach

A Strategic Environmental Assessment approach combines environment, health, biodiversity approaches with social and economic consequences. It is a proper way to address all large-scale technology changes planned in a country, but doing a proper SEA for introducing nuclear power plants in Poland would require more methodologically consistent data than is currently available as well as time and experience.

LCA approach

A Life Cycle Assessment is necessary for evaluating ‘cradle to grave’ emissions from different energy generation systems. Based on obtainable data and the category we can distinguish:

- Process LCA – offering a bottom up approach, process LCA gathers information about emissions from single processes through the products life-cycle. The emissions and impacts of a product are quantified by summing up the emissions and impacts from all analyzed processes. This method is most useful for analyzing emissions from a specific factory or exact product. The method’s weak point is the need for delimitation which creates the possibility of omitting a part of the environmental effect.

- Input-output LCA – Top-down method. Best for entire groups of industries, input-output LCA possesses complete emission data at a country level per monetary value of existing product. Its use for specific products is limited to very homogenous industries but it offers ready to use emission tables.

- Hybrid LCA – a special form of LCA using both process and product data to minimize the disadvantages of both methods and combine available data of both types in an optimal way.

An approach focusing on viewpoints within a culture, and how society views technologies based on its history, culture as well as political and economic regimes.

Figure 6. Soviet promotional poster „Smoke – breath of Soviet Russia" (West, 2009)

In the 1970s whenever an important delegation arrived in Poland, the visitors would be driven to their destination through the industrial district, with special orders to all power plants and factories to make plenty of gray smoke from every stack as a necessary symbol of hard work and the progress that sprouts from it. The 1990 system change brought a division within society: industry workers – glorified and treated as heroes by the old system – now tend to treat new technologies as threats to their work and social status, while most white collars – ridiculed and humiliated by the old system for not doing any physical work believe in changing the structure of energy supply to incorporate new technologies.

Figure 7. Statue of Wincenty Pstrowski – a miner, who did 293% of his position's average (Halmer, 2009)

System preferences are only one of many factors influencing views on energy supply structures, different pollution categories, global warming and nuclear power – many books could be written on the social and historical context of people’s views on energy generation system implementation in Poland.

Techno-economic approach

Once desired goals are formulated, techno-economic analysis can be used to find the most profitable investment (from the point of view of investor or society) that fulfills these goals. More widely, techno-economic analysis compares various ways of obtaining the same results to find the most profitable ones. A very strong point of techno-economic analysis is that it operates exclusively within the field of monetary figures, necessitating no comparison and evaluation of different impacts, which would introduce subjective factors e.g. the value of human life in comparison to value of fish populations or monetary value. It offers clear and precise results, however it fails to fully incorporate impacts to ecosystems, biodiversity, human health and quality of life.

Choice of approach

In an ideal world, a holistic approach would have been adapted – one incorporating all possible aspects of development of different available electricity generation technologies and giving a clear and fully objective result. Sadly, such a method has not been invented yet. The author will pursue a techno-economic approach because it addresses key issues for policy-makers and very importantly, because there is currently a lack of papers comparing Levelized Production Costs of implementing different technologies in Poland for CO_2 emission reduction purposes.

The proper problem for the project was formulated using a part of Vagnby's Logical Framework Analysis Method (Vagnby, 2000), a problem tree – one of the tools that aim to present data about a project's key components in a clear, concise and systematic way in order to find a focal point for the thesis (BOND, 2003).

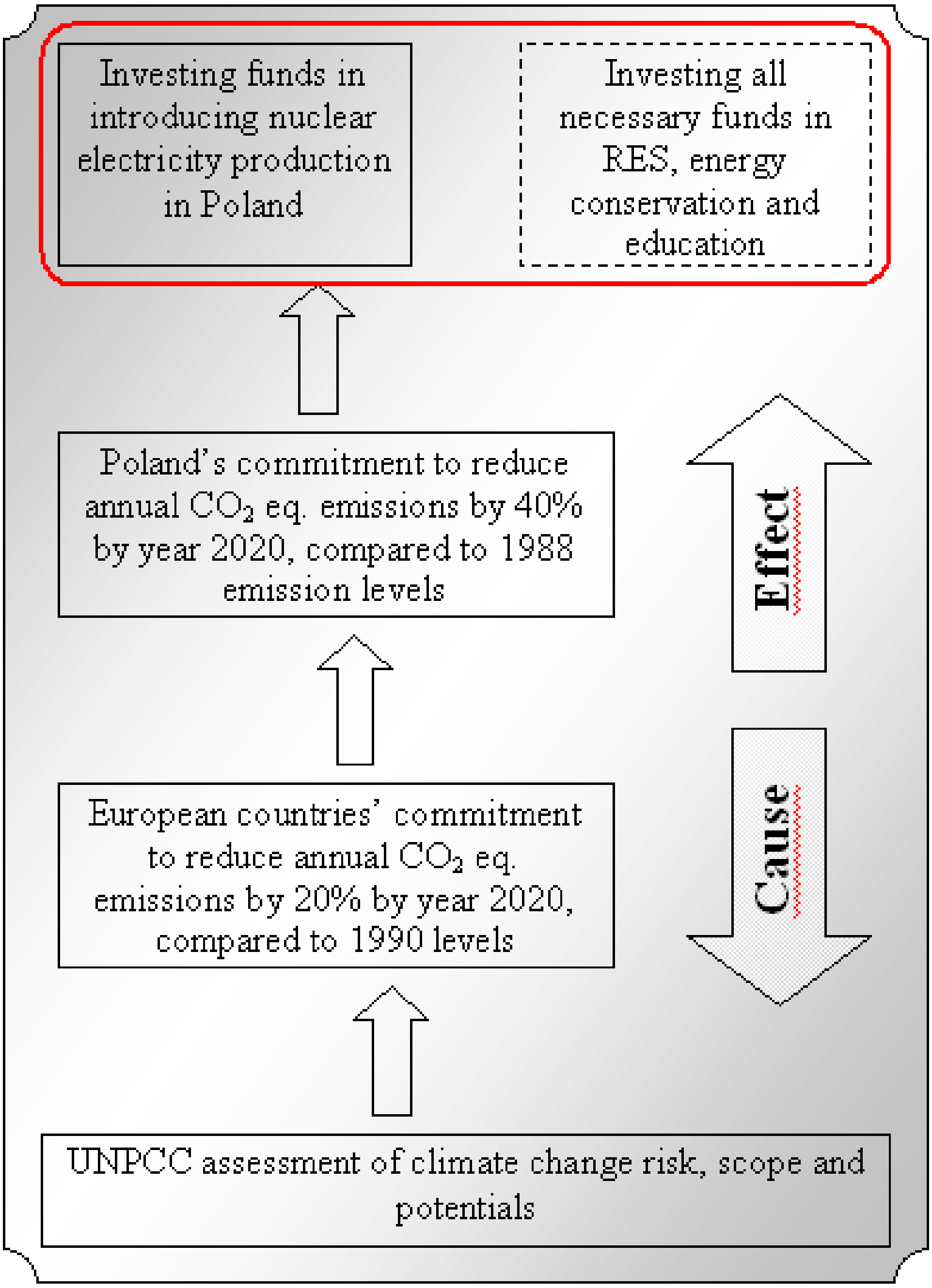


Figure 8. Project problem tree

The base for the problem tree is a scientific assessment of the risk, scale and strength of threats related to climate change. It has led to a commitment by most European Countries and Russia to limit their yearly CO_2 emission levels by 20% by year 2020, compared to year 1990. Based on this fact, Poland has adapted a personal goal of limiting its CO_2 emissions by 40% by year 2020 compared to year 1988. In November 2008 Polish Prime Minister has made a surprise announcement that at least two nuclear power plants will be built in Poland (Jamroż, 2008) and that necessary steps in order to create proper administrative and legislative changes will begin to be taken immediately and that campaigns for popularizing nuclear technologies and changes in educational system will follow. This sudden and surprising decision, as opposed to the previous plans to achieve the necessary climatic effect purely by means of energy conservation, popularize education and renewable energy generation systems (RES) has so far met with much criticism but not much economic comparison, at least using the same methodologies for all kinds of energy systems. Therefore the current situation in Poland generates a necessity for projects that that will prove that Poland either does or doesn't have economic interest in building nuclear power plants, and with regard to available data, will do so scientifically.

Research question

Poland has officially committed itself to reducing its CO_2 emissions and increasing its share of electricity from renewable sources. It is logical that these goals can be pursued either together or separately and that both options should be analyzed equally without bias.

Environmental performances of all electricity generating technologies in Europe have to meet with Best Available Techniques (BAT) standards saving policy-makers most of the burden of assessing acceptable technologies. Further effects on the environment related to location have to be assessed at a Strategic Environmental Assessment and Environmental Impact Assessment stage.

The first issues to be considered by policy-makers in the initial stages of assessing a technology are national safety and economic performance. The project has chosen to follow a techno-economic approach, which offers fully measurable results and aims to present information essential to decision making on a national scale.

A techno-economic approach to a problem of choosing between electricity generation technologies in light of CO_2 emission reduction goals leads to the research question:

What is Poland's most economically feasible solution for reducing CO_2 emissions within the electricity production sector?

To assist in analyzing the problem, three sub-questions have been developed:

What are the costs of producing electricity from different technologies and technology mixes?

What is the level of competitiveness of nuclear power plants compared to other available technologies?

Based on project outputs, what path of development should Poland follow?

Structure and content

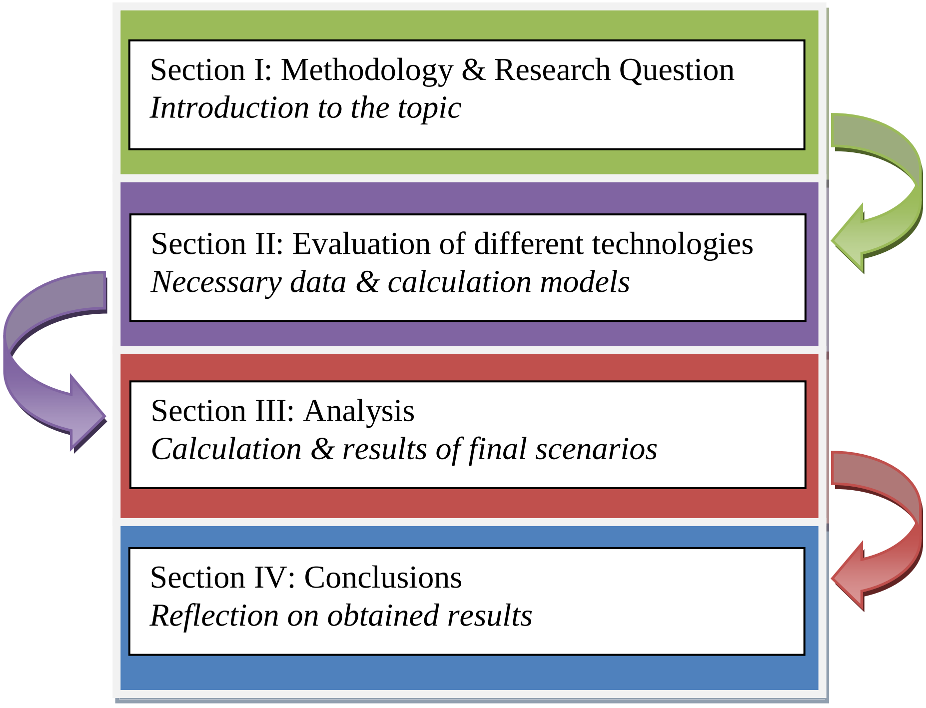


Figure 9. Project structure

Section I introduces the reader to Poland, a country with unique views on various energy resources stemming from geographic and economic conditions as well as numerous political and social interactions within the last century. It lists possible approaches to analyzing the introduction of nuclear energy into the Polish system and selects the approach most clear in its results – the techno-economic approach. It also presents the projects' methodological framework and introduces the research question.

Section II gathers data and introduces necessary assumptions for each analyzed technology to be used for calculations in Section III.

Scetion III uses inputs from Section II in order to calculate the cost of electricity production from five chosen scenarios – each providing the same level of CO_2 emission prevention, compared to coal-powered generation in the designated planning period. It then assesses the instability of energy costs for each scenatio by means of a sensitivity analysis.

Section IV puts results of the analysis into perspective, looking into connotations of results achieved in the form of economic LPC figures in a real world perspective of the Polish system. It adds economic advantages and weaknesses not included in a monetary cost analysis along with barriers to growth and suggestions for development. The section deals with the research question and deducts the logical next step ensuing from the project findings.

Necessary delimitation

Because biomass prices are unstable in Poland, are very region-dependant and have been known to change by a factor of 3 within the span of a year, calculations of electricity prices from biomass combustion plants will not be included.

Section II: Evaluation of different technologies

“The squeaky wheel doesn’t always get greased: it often gets replaced”

– John Peers

The aim of the project is to analyze the economic costs of preventing CO_2 eq. emissions to the same extent as with plans for adapting nuclear technologies in Poland using different technology mixes, and by price comparison, assessing the feasibility of the Polish nuclear scheme. This approach will allow not only for assessing the economic usefulness of introducing nuclear plants into the Polish system, but also comparing various alternatives in order to pinpoint the most profitable solution.

The project scenarios will take hydroelectric, on-shore wind, off-shore wind and nuclear power plant scenarios into consideration:

- The nuclear scenario will calculate the electricity cost of energy produced from planned nuclear power plants

- The on-shore wind/coal mix scenario will calculate the cost of producing electrical energy from on-shore wind farms up to an extent providing the same CO_2 eq. emission savings till 2030 as the Polish nuclear scheme and providing the rest of the electricity from coal-powered plants.

- The off-shore wind/coal mix scenario will calculate the cost of producing electrical energy from off-shore wind farms up to an extent providing the same CO_2 eq. emission savings till 2030 as the Polish nuclear scheme and providing the rest of the electricity from coal-powered plants.

- The hydroelectric-energy/coal mix scenario will calculate the cost of producing electrical energy from hydroelectric-power plants up to an extent providing the same CO_2 eq. emission savings till 2030 as the Polish nuclear scheme and providing the rest of the electricity from coal-powered plants.

- The equal CO_2 emission reduction from all renewable sources / coal mix scenario will calculate the cost of producing electrical energy from all renewable sources assessed in the project: off-shore wind farms, on-shore wind farms and hydroelectric-power plants up to an extent providing the same CO_2 eq. emission savings till 2030 as the

Polish nuclear scheme, redistributed equally and providing the rest of the electricity from coal-powered plants.

The reference scenario will be regarded as a frozen development scenario in which no changes to the energy structure in Poland will be made. The Ministry of Environment made an analysis on future developments within the energy generating sector as did the Ministry of Economy, Ministry of Infrastructure and Ministry of Farming (Ciepela, 2009), however there is no agreement between the four ministries as to which technologies and to what extent will be implemented.

Discount rates

A discount rate is the rate of return that a project has to achieve to be considered profitable. It is the return rate of other market opportunities of investing the money potentially available to the investor – an investment with a higher yearly return is considered profitable, with a lower one – not.

A basic input for calculations using the NPV method, discount rates for Poland have been announced annually by the European Commission since the 21st of September 2004. Since the 1st of July 2008 the European Commission only announces base rates, and discount rates are to be calculated by adding 100 base points which are equivalent to exactly 1 percentage point.

Time period	Base rate[%]	Discount rate[%]
01.06.2009-	4.53	5.53
1.04.2009 - 31.05.2009	5.62	6.62
1.01.2009 - 31.03.2009	6.78	7.78
1.07.2008 - 31.12.2008	6.42	7.42

Figure 10. Table of obligatory base rates and discount rates for Poland (Polskie Stowarzyszenie Funduszy Pożyczkowych, 2009), (Urząd Ochrony Konkurencji i Konsumentów, 2009).

Since the 1st of July 2008, the European Commission only announces base rates, and discount rates are to be calculated by adding 100 base points which are equivalent to exactly 1 percentage point.

The discount rates in Figure 8 have been designated for use on long term investments in PLN. As of June 1st 2009, the official rate is 5.33%

Because the scenarios compete with one another, they all use the same discount rate – the different levels of risk associated with the technologies will be internalized into the project using a sensitivity analysis.

Coal Power Plants

Figure 11. Coal power plant (Popkiewicz, 2009)

Traditional coal combusting plants have the highest emission level in ton CO_2 per MWh produced electricity. It is due to the fact that the energy producing process is basically an exothermic oxidation reaction of C into CO_2. The mass of CO_2 is counted using the formula:

$$m_{CO2} = m_C \cdot (1 - p - s - w) \cdot \frac{44}{12} \tag{1}$$

, where

m_{CO2} - mass of emitted CO_2 [t]

m_C - mass of combusted coal [t]

p – ash content [%]

s – sulfur content [%]

w – water content[%]

$\frac{44}{12}$ – Carbon to CO_2 mass conversion ratio

Before year 1990, Polish professional plants used to burn crude coal with a 25-35% ash content and 1.2-2.8% sulfur content. After the 1990 system change, environmental protection issues started to influence the energy production sector necessitating pollution reduction. The hard coal power plant model used for this study will use thick coal with the following parameters:

Ash content: 6.8%

Sulfur content: 0.67%,

Water content < 0.2%

Net calorific value: 29.5 MJ/kg.

(Blaschke et al., 2005)

According to the previous equation, the amount of emitted CO_2 per one of fuel has experienced a 1,25-1,45 factor growth, however due to an increase in combustible substrates and a growth in process efficiency, the TCO_2/MWh produced electricity emissions have gone down.

$$E = O \cdot m_C \cdot \eta[\%] \quad (2)$$

, where

E – amount of produced energy [GJ]

O – Lower heating value[GJ/t]

η- process efficiency[%]

, hence

$$m_{co2} = \frac{E \cdot (1 - p - s - w) \cdot \frac{44}{12}}{O \cdot \eta} \tag{3}$$

Assuming a process efficiency of 45% and annual production equaling to 6400 full load hours (Zaporowski, 2008):

Thick coal	
Full load hours eq. annually	6400
Efficiency [%]	45
Ash[%]	6.8
Sulfur[%]	0.67
Net calorific value[GJ/t]	29.5

Figure 12. Yearly CO_2 emissions from installed capacity

For the parameters presented in figure 6, producing 1 MWh of electrical energy requires emitting 0.878 tons of CO_2.

O&M costs

The costs of fuel, conservation and energy production have been abstracted from data published in tome 11 of the Polish Energy Policy (Zaporowski, 2008) by using the study's result and methodology as data and reversing the calculation process.

Time of operation [yrs]	30
Investment period [yrs]	4
Installed power[MW]	1
Capital costs [PLN/MW]	4300000
Discount rate	0,08
Time of operation [h/a]	6400
Levelized Production Cost[PLN/MWh]	196

Figure 13. Data used for calculation of O&M costs in hard coal plants (Zaporowski, 2008)

The data presented in figure 13 have been assumed for the purpose of calculating the O&M costs of a coal power plant.

The capital costs of producing energy in PLN/MWh el. have been divided into equal parts for the investment period and properly discounted:

$$\text{'Discounted capital costs'} = \sum_{i=0}^{i=n-1} \frac{\text{'capital costs'}}{n} \cdot (1+p)^{i} \tag{4}$$

, where

n – investment period [yrs]

p – discount rate

In this case the discounted capital costs have are equal to 74% of nominal capital costs.

This value has to be equal to the sum of discounted profits, which has been calcualted using the formula:

(5)

$$\text{'Discounted capital costs'} = \sum_{i=n}^{i=n+t} \frac{Z \cdot H \cdot P}{(1+p)^i}$$

, where

t – investment lifetime [yrs]

Z – base income [PLN/MWh]

H – no. of full load hour equivalents per year [h]

P – power [MW]

After substracting Z from the energy cost, the O&M costs for electricity production have been calculated at a level of **143.69 PLN/MWh**. This price will be used for further calculations, although taking into account that the market electricity price in the first half of year 2007 ammounted to 128 PLN/MWh (IEA, 2008) it is possible that the actual O&M costs are lower.

Remaining input

Even though roughly 25% of all active coal-powered plants in Poland are older than 40 years (Chojnacki, 2009), the assumed operation period will be set to **30 years** to take into account the constantly growing quality standards for electricity production.

Based on professor Zaporowski's study (Zaporowski, 2008) the capital costs are assumed to amount to **4 300 000 000 PLN/GW** installed capacity and the investment period to be **4 years**.

Nuclear Power Plants

Figure 14. Krsko nuclear power plant at night (Nagpal, 2008)

O&M costs

The costs of O&M have been isolated from the Zaporowski study (Zaporowski, 2008), using methods discussed in the 'Coal power plants' chapter.

Time of operation [yrs]	30
Investment period [yrs]	6
Installed power[MW]	1
Capital costs [PLN/MW]	7800000
Discount rate	0,08
Time of operation [h/a]	6400
Levelized costs[PLN/MWh]	234

Figure 15. Data used for calculation of O&M costs in nuclear power plants (Zaporowski, 2008)

Based on data shown in figure 15, O&M costs have been calculated at 119.68 PLN/MWh produced electricity

Other input

According to PGE – Poland's biggest energy producer and the company interested in building nuclear power plants in Poland, the construction process can start in year 2016 and it is fully possible that the first **1.6 GW** reactor will begin producing energy by the end of year 2020. The expected exploitation period is **40 years** and capital costs are expected at approximately 3 000 000 000 EUR/GW installed capacity, which amounts to a **19 680 000 000 PLN** investor cost for the first reactor.

Wind farm general info

For project purposes 200MW wind farms, consisting of 40 REPower 5MW turbines will be examined. The REPower 5 MW has been selected because of the tendency to go large-scale, as well as the fact that it functions both as an on-shore and off-shore model with some minor modifications (e.g. helicopter platform). The size of the wind farm has been selected so that using an off-shore transformer is justified, but not big enough that the transformer cost becomes negligible in electricity cost calculations. For wind farms set in specific locations rather than general calculations, a turbine should always be chosen with regard to the local wind-speed curve, resulting in more profits and a lower electricity cost.

Single turbine	
Cut-in speed	3,5 m/s
Cut-off speed	30 m/s
Nominal speed	13 m/s
Nominal power	5 MW
Tower height	90 m
Entire wind farm	
No. of turbines	40
Wind farm area	12.446784 km^2
Nominal power	200 MW

Figure 16. Wind farm assumption table

Off-shore wind farms

Figure 17. REPower 5MW deep-water wind turbine (Willis, 2008)

Turbine costs

The number used for calculations has been derived from a high-quality British study (ODE, 2007). The study, amongst other figures presents empirical costs of large turbines and a disaggregation amongst various components. Because of different sea salinization levels, average wave heights, distances from the shore and the importance of depth in the investment cost, most of these figures cannot be used for future off-shore turbines in Poland, however these data will be used for on-shore turbines. Based on the study a single 5MW turbine should cost approximately 14 440 000 PLN, hence the turbine cost of installing 200MW capacity will amount to **577 600 000 PLN.**

Foundation costs

There is a rule of thumb concerning a wind farm's distance from shore, saying that in order to mitigate visual impact, a wind farm has to be located at a distance approximately 100 time the hub height of the turbine from shore, the actual visibility from shore dependant on the height of the vantage point, weather, and general visibility typical to an area. For turbines with 90 m hub-height, the proper distance would be 9 km, but because local conditions might offer greater visibility, a distance of 10 km will be taken into calculation.

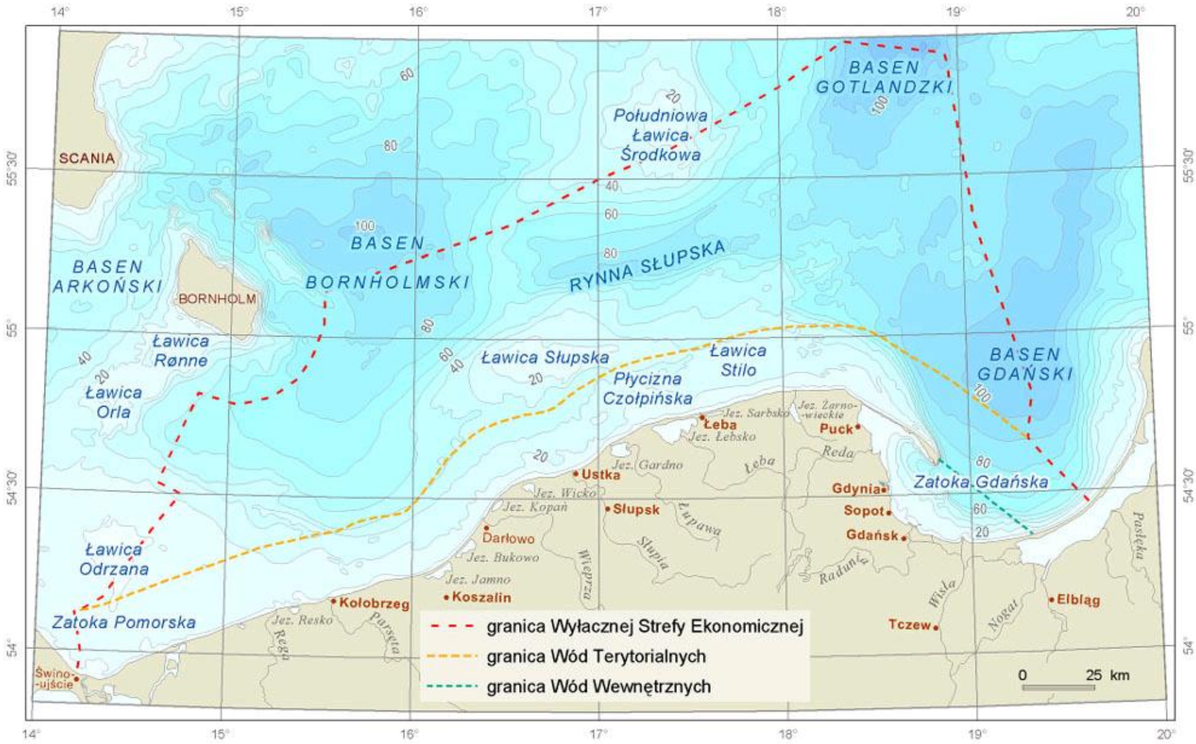


Figure 18 . Bathymetry of the south-east Baltic, along with borders of Poland's sea territory (Uścinowicz, 2003)

The locations of Polish wind farms are restricted by the brown dashed line - the border of Poland's economic sphere. The yellow dashed line in Figure 9. – the border of Poland's territorial waters, is located 12 km from shore. For a distance of 10 km the depths vary from over 15 m in the west up to over 80 m in the east. Because of an abundance of locations with a depth less than or equal 20 m, a depth of 20m shall be assumed for a typical wind-farm in Polish waters.

Monopile foundations will be taken into consideration as they are deemed to be the most economically feasible for depths between 10 m and 25 m (Nikolau, 2004).
A cost curve for foundation cost in PLN per MW installed capacity based on depth has been constructed using data on European off-shore wind farm foundation costs, gathered as part of the Long Island Off-shore Wind Project (Dale, 2007).

$$'foundation\ cost' = k \cdot e^{0.0411 \cdot d} \tag{6}$$

,where

k – constant, k = 1032048

d – depth [m]

For a depth of 20 m, a single turbine’s foundation will cost approximately 11 740 000 PLN, amounting to **469 600 000 PLN** for a 200 MW wind farm.

Transmission assumptions

Traditionally, for transmission of generated electricity to the shore and to the grid either medium voltage alternating current(MVAC) or high voltage alternating current(HVAC) has been used, although recently developments in high voltage direct current (HVDC) have made it a third possibility. Despite many benefits of the HVDC cables, i.a. low capacitance, they are not cost-effective due to the high cost of necessary electronics and transformers for distances of a magnitude of 100 km or less (Nielsen, 2003).

There are several possible options within AC cables. Power may be transmitted back to shore at medium voltage and transformed on-shore, to prevent costs of installing an off-shore transformer. This solution can cause unacceptably high losses for larger distances from shore and require several cables for larger wind farms. A MVAC cable can transmit up to 25-30 MW of power with acceptable losses for distances below 50 km (Grainger et al., 1998). The remaining question is whether installing multiple parallel 33 kV cables is an economically more feasible solution than installing an off-shore transformer. According to the Renewable Energy Research Lab (Wright et al., 2002), if more than 3 cables are necessary to transmit electricity to shore, it is recommended that an off-shore transformer should used instead.

It is assumed that the turbines will be connected to the transformer through three core 33 kV cables, and for to-shore transmission a 150 kV cable will be used.

Transformer costs

The transformer cost for the project is based on a similar transformer used for Horns Rev, a 180 MW wind farm. The transformer cost approximately 8 000 000 EUR (DEA, 2006). Assuming an increase in price as strictly proportional to the capacity of the transformer and installation costs rising from 3 000 000 EUR at a depth of 6,5 m to 5 230 000 EUR at a depth of 20 m according to the previously introduced depth to foundation-cost curve, the construction costs amount to **54 233 000 PLN**.

Cable costs

A design where each row within the turbine is connected to a single cable and the rows are interconnected by the transformer has been chosen. For a 40 turbine wind farm configured in a 8x5 array, a spacing of 7 rotor diameters from front to back (in the prevailing wind direction) i.e. 882 m, and 4 rotor diameters abreast i.e. 504 m have been used as values typically used for wind farms. Therefore the overall required length of 33 kV cable is 57 500 m for connection within the wind farm, giving a cost of approximately **22 100 000 PLN** (Morgan et al., 2003).

The cables necessary for connecting a 200 MW wind farm to shore cost 500-1500 EUR/m (de Algeria et al., 2008). To prevent the risk of underestimating the costs a value of 1500 EUR/m has been assumed. Assuming the cable leading to shore to be 11 km long – an additional 10% has been added to take changes in seabed depth into account – the cable connecting the wind farm to shore will cost **67 650 000 PLN**.

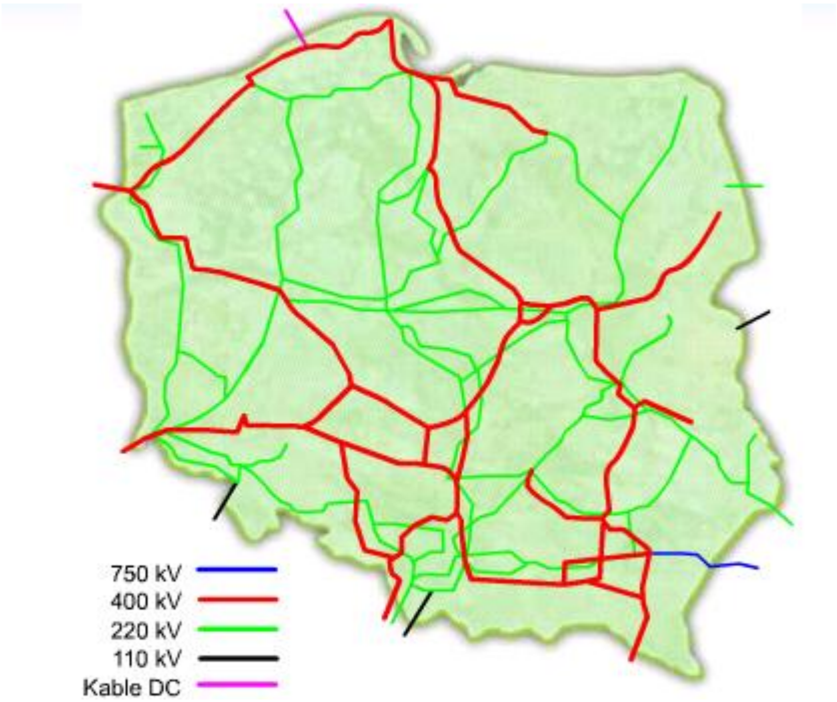


Figure 19. Map of the Polish electrical grid (PSEW, 2009)

A considerable part of Poland’s 400 kV lines is located next to the shore, hence no additional costs related to transmission on land are included in the calculation. Also, connection costs on land are not included for any technology in this report.

Cable laying costs

Taking into account that floating cables often suffer damage, mostly from anchors and fishing vessels, cables will be laid according to the state of art: 1-4 meters deep for rocky bottoms and over 4 meters deep for sandy bottoms. The cost of laying cables within the wind farm, as well as to shore is 15-100 EUR/m (Nielsen, 2003). The top value of 100 EUR/m will be used in the calculations, giving a final cost of the cable laying process at **28 085 000 PLN**.

Other capital costs

The distribution of investment costs varies from wind farm to wind farm based on localization and company employed, but for a typical, exemplary installation the costs of consultancy, electric installation and control systems to total cost ratio shouldn't vary much.

Factor	Percentage of investment
Turbines	40%
Fundations	23%
Grid connection	21%
Consultancy	10%
Electric installation	4%
Control system	2%
Total	100%

Figure 20. Average cost breakdown for an off-shore wind farm (Wizelius, 2007)

Based on data in figure 12, the costs unaccounted for previously comprise 16% of the total capital investment, so:

(7)

$$'total\ capital\ investment' = \frac{100}{84} \cdot ('turbine\ costs' + 'foundation\ costs' + 'cable\ costs' + 'cable\ laying\ costs')$$

O&M costs & production losses

TU Delft (Brekelman et al., 2003) has published an extensive study that counts O&M costs in high detail. They have calculated O&M costs for off-shore wind farms to raise the Levelized Production Cost of electricity by **39%**. After converting and discounting, the results of an ORTECH study (Roeper et al., 2005) affirm this figure.

It is also assumed that the farm's yearly production will be reduced by 5% due to maintenance and breakdowns (ODE, 2007).

Wind resources

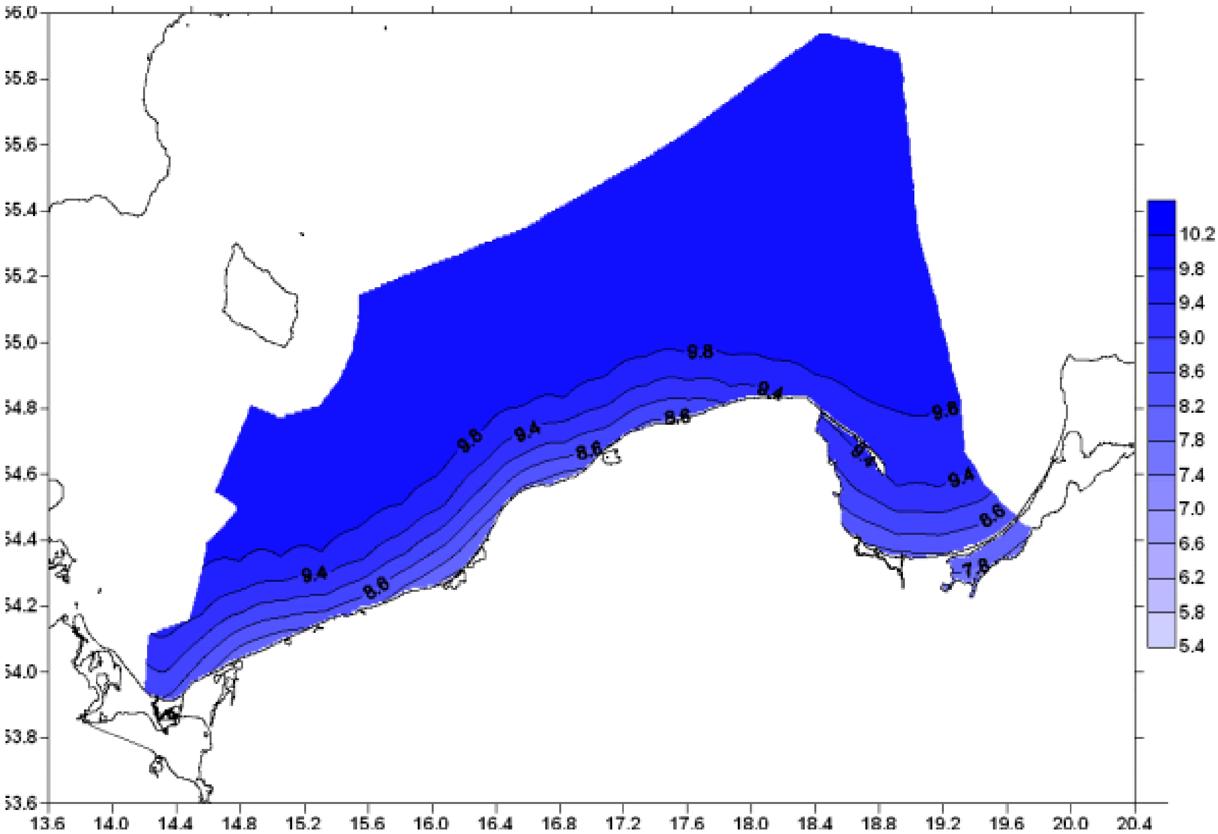


Figure 21. Wind speed isolines over the Polish area of the Baltic sea at 100m height (Szefler et al., 2007)

In agreement with previous assumptions, the future wind farm will be located 10 km from shore. According to Figure 17, each point at a distance of 10 km has an average yearly wind speed of 9.4 m/s or more, hence the 9.4 m/s at 100 m height will be used.

The planned turbines have rotors set at a height of 90 m, therefore the average yearly wind speed has to be attuned, by use of mathematical formula:

$$V_a = V_0 \cdot \left(\frac{h_w}{h_0}\right)^z \tag{8}$$

, where

V_a – average yearly wind speed at rotor height [m/s]

V_0 – average yearly wind speed at anemometer height [m/s]

h_w – rotor height [m]

h_0 – anemometer height [m]

z – wind shear factor

For the area of the Baltic sea a wind shear factor of z = 0.11 is used (Markowicz, 2006).

The calculated average yearly wind speed at rotor height **V_a = 9.29 m/s** will be used for further calculations.

Wind curve

Because empirical wind curves in Poland are only available for commercially and because the analyzed wind farms are not located in an exact specific location, the wind curves will be generated using a mathematical method. For wind curve modeling use of the Weibull Probability Density Function is one of the proper methods. A case where the function's shape parameter **k** is set to a constant is called the Raleigh distribution. Empirical data suggests that in Northern Europe wind distributions follow a Raleigh distribution and that they can adequately be used for characterizing histograms over sea areas as well as part of the land

(Kiss et al., 2007). It should be noted that for some land areas the Weibull distribution is inadequate.

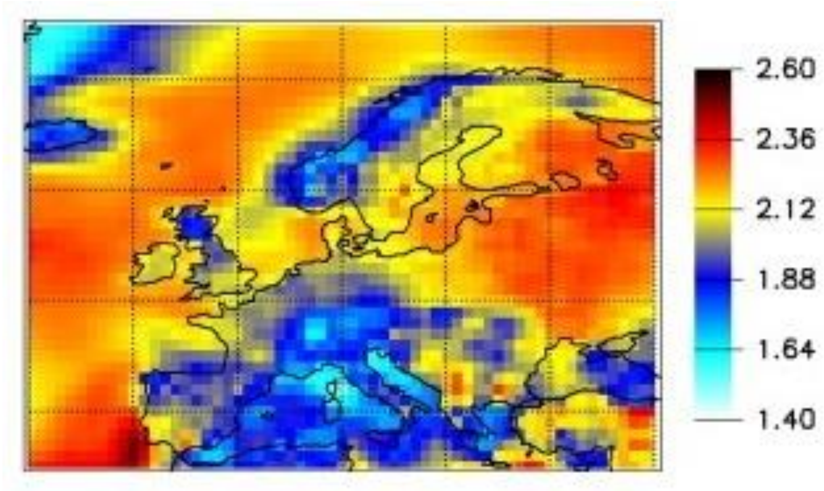


Figure 22. Map of approximate shape parameters best describing the behavior of wind distributions in Europe (Kiss et al., 2007)

For Project purposes k = 2.3 will be used for off-shore areas of Poland.

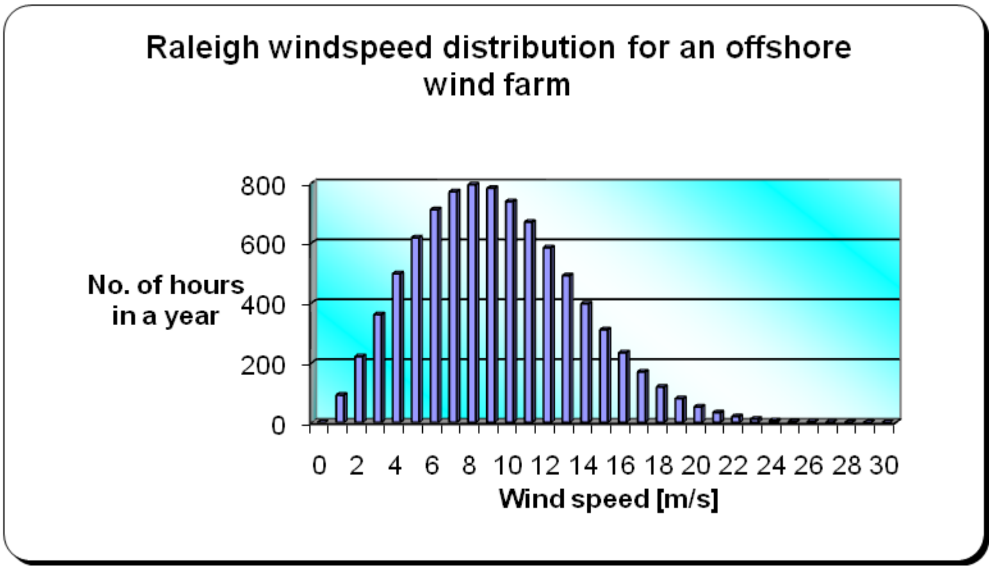


Figure . Raleigh wind speed distribution for an off-shore wind farm

Energy production

The wind turbine producer Eoltec suggests using a 10-15% turbulence factor (Eoltec, 2003). This factor is used to describe the negative effect of wind turbulence on electricity production and is subtracted from the final production value. Because turbulence is lower on greater heights and because of lower turbulence over sea areas, a turbulence factor of 10% will be used.

Input:	
Mean wind speed at anemometer height [m/s]	9.4
Shape parameter k	2.3
Height over sea level [m]	90
Wind shear factor	0.110
Anemometer height [m]	100
Rotor height [m]	90
Turbulence factor [%]	10.0%

Figure 23. Off-shore energy production model inputs

Calculating energy production by means of a Raleigh distribution is based on calculating the probability of each possible wind speed occurring. For each wind speed the shape parameter k and deviation from the mean wind speed value decide on a probability of occurring. Probabilities can be counted using this formula:

$$T_i = r \cdot \left(\frac{k}{V_a}\right) \cdot \left(\frac{r \cdot V_i}{V_a}\right)^{k-1} \cdot e^{-\left(\frac{r \cdot V_i}{V_a}\right)^k} \tag{9}$$

, where

T_i – A percentage of time for which V_i is achieved [%]

V_i – Given wind speed [m/s]

k – shape parameter

r – constant, r = 0.89

Turbulence factors, breakdowns and maintenance breaks as well as lower air density at greater heights above sea level are often forgotten in wind production studies, however they have a large impact on income and payback – in case of this study by limiting production by 17,2% – almost as if each farm had only 33 turbines instead of 40.

Output:	
Mean wind speed at rotor height [m/s]	9.29
Air density factor [%]	-1%
Yearly electricity production [MWh]	**17 954**
Time of operation [%]	92.3%

Figure 24. On-shore energy production model outputs

On-shore wind farms

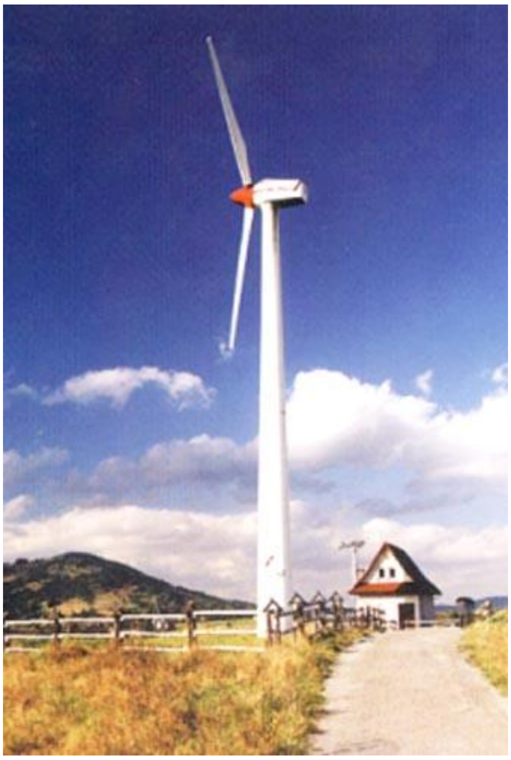


Figure 24. On-shore wind turbine located at Polish mountain town of Zawoja (Gazda, 2009)

Capital investment

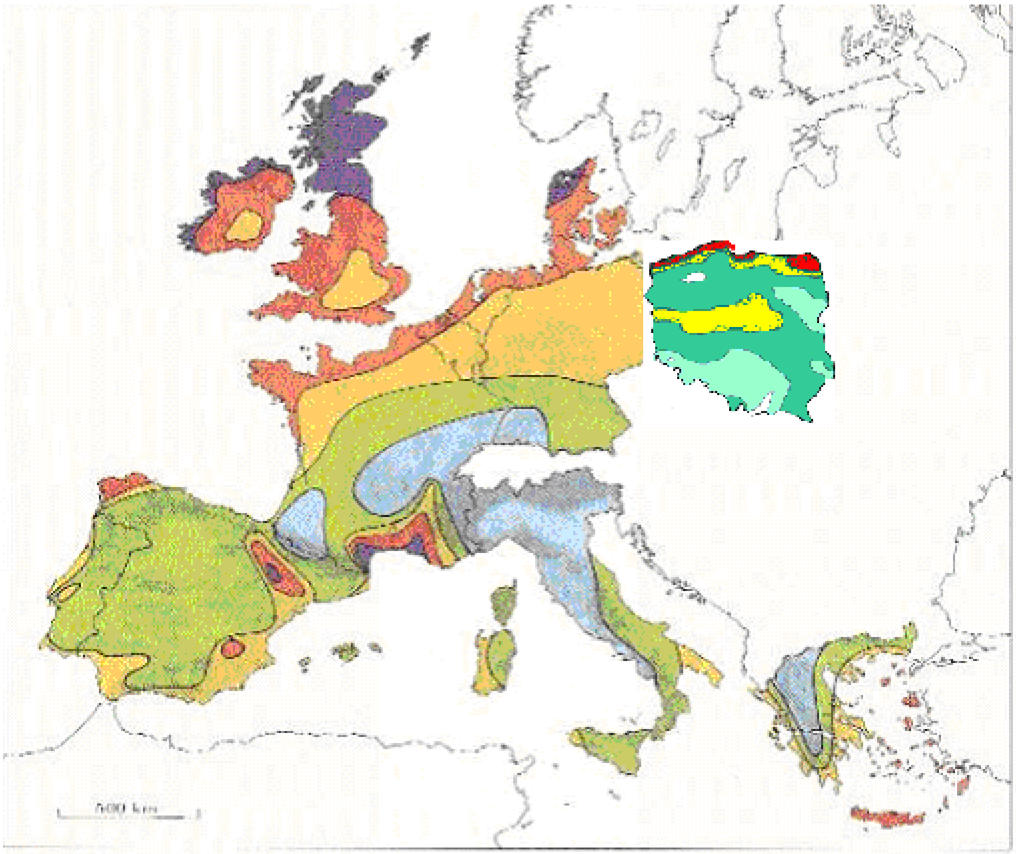
The ODE study (ODE, 2007) employed for obtaining Turbine costs for off-shore turbines also contains data on on-shore turbines including full cost of capital investments and cost disaggregation. The total investment cost amounts to 21 375 000 PLN for a single 5 MW turbine and **855 000 000 PLN** for an entire on-shore wind farm.

O&M costs & production losses

It is assumed that O&M costs will raise the LPC of on-shore wind farms by **25%**. The figure has been taken from a TU Delft study (Brekelman et al., 2003) used previously for off-shore wind farms.

It is assumed, that the farm's yearly production will be reduced by 5% due to maintenance and breakdowns (ODE, 2007).

Wind resources



Wind resources at 50 metres above ground level for five different topographic conditions

	Sheltered terrain		Open plain		At a sea coast		Open sea		Hills and ridges	
	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}
	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0-8.5	400-700
	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

Figure 25. Wind resources at 50 m above ground level (ODE, 2007), (Lorenc, 2001)

Figure 26. Wind farm locations in Poland(PSEW, 2009)

Comparing the maps of wind resources and currently operating wind farms, it is can be seen that a majority of the territory marked in yellow – with wind speeds up to 6.5 m/s is still unused by the wind industry. For potential wind farm locations a value of 6 m/s at 50 m above ground level is assumed. Assuming a wind shear factor of 0.2 for open territory (Markowicz, 2006), the average yearly wind speed at rotor level is **V_a = 6.75 m/s**.

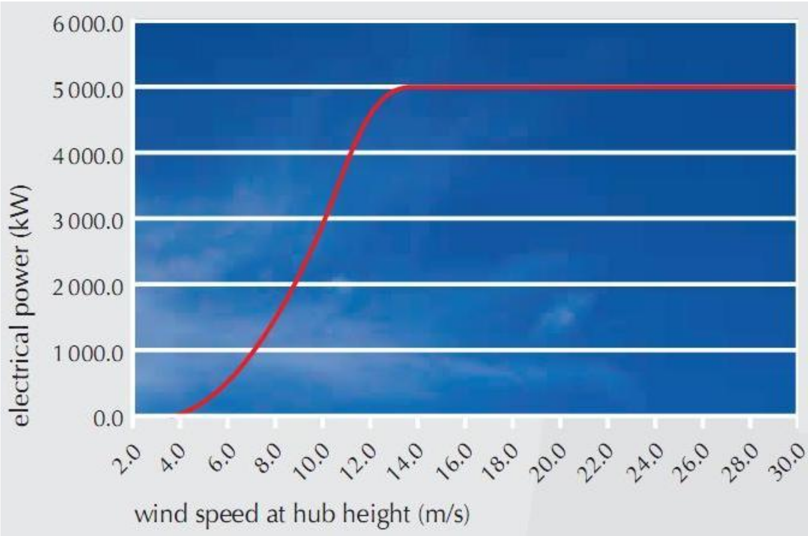


Figure 27. REPower 5MW production curve (REPower, 2007)

It must be noted that when a REPower 5MW turbine operates at 6.75 m/s it produces less than 20% of its nominal production. For actual investments in exact locations it would be more profitable to choose a wind turbine with nominal speeds closer to the average yearly wind speed of a given location.

Wind curve

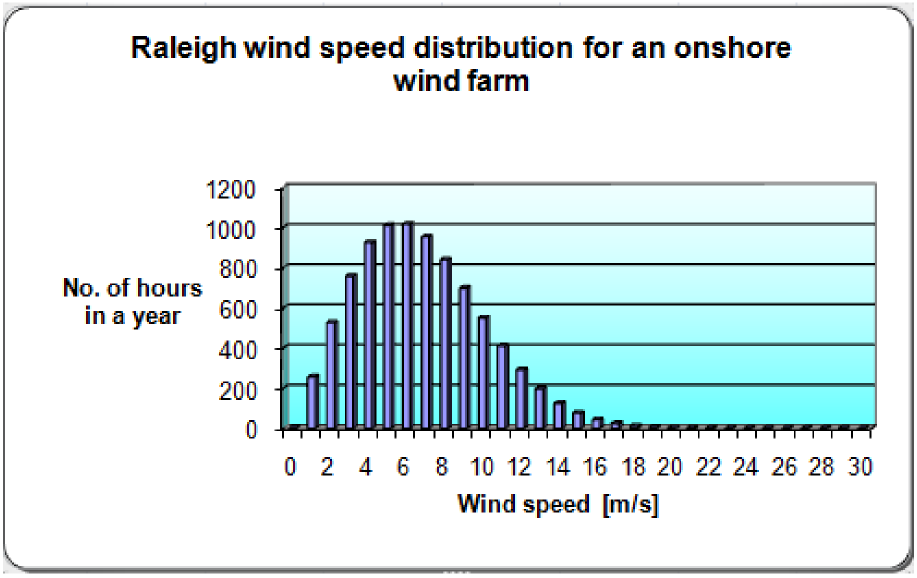


Figure 28. Raleigh wind speed distribution for an on-shore wind farm

Energy production

Based on Figure 18 potential on-shore wind farms will have a shape parameter k = 2.1.

Input:	
Mean wind speed at anemometer height [m/s]	6
Shape parameter k	2.1
Height over sea level [m]	90
Wind shear factor	0.200
Anemometer height [m]	50
Rotor height [m]	90
Turbulence factor [%]	10.0%

Figure 29. On-shore energy production model inputs

Output:	
Mean wind speed at rotor height [m/s]	6.75
Air density factor [%]	-1%
Yearly electricity production [MWh]	**9 617**
Time of operation [%]	82.3%

Figure 30. On-shore energy production model outputs

Hydroelectric power plants

Figure 31. Three Gorges Dam on the Yangtze river (Du Huaju Ap, 2006)

Profitability of a hydroelectric power plants is based on individual characteristics of each site and dependant i.a. on speed of the current throughout the year. Also, in case of hydroelectric power plants, electricity production is only the third priority – the first one being keeping the water level low enough to prevent floods and high enough to preserve wildlife and the second one keeping the water level high enough to meet the necessary intake of farming and industry situated downriver and in some cases enable outdoor recreation – swimming and sailing.

For project purposes the cost of energy from this year's investment in a 660 kW plant in the town of Rzeszów on the Wisłoka river (Gubernat, 2009) will be calculated and used as an example. Results from a single project might not be adequate for assessing energy costs for an entire industry, but they have an important quality – they represent investment costs that are fully up to date with component prices and labor cost.

Capital investment

The cost of building a hydroelectric plant is set at approximately 12 000 000 PLN, with an additional 3 000 000 PLN expense for building a 150 m long fishway and 750 000 PLN for building a tunnel for pedestrians under the plant in agreement with local populace.

The total capital investment amounts to **15 750 000 PLN**.

Energy production

The assumed yearly production is 3 000 MWh for a 660 kW plant, which equals 4546 full load hours of operation per year

O&M costs

According to data provided by Jan Pytlarz (Pytlarz, 1990) low O&M costs are typical for the hydroelectric power plant sector and in Polish plants smaller than 15 MW amount to 0.5% of the initial power plant investment costs each year, that is 60 000 PLN annually, which amounts to 2 PLN/MWh.

Analysis inputs

Technology	Coal	Nuclear	Off-shore wind	On-shore wind	Hydroelectric
Time of operation [yrs]	30	40	20	20	40
Investment period [yrs]	4	11	4	2	1
Installed power[MW]	1600	6000	200	200	0.66
Capital costs [PLN/MW]	4300000	12300000	7257548	4725000	15750000
Full load hours [h/a]	6400	6400	3591	1923	4546
O&M costs [PLN/MWh]	215.70	119.68	75.79	55.87	2.00

Figure 32. Analysis inputs table

Section III: Analysis

"Where there's a wheel, there's a way"

– Dennis Robbins

Economic costs of electricity production

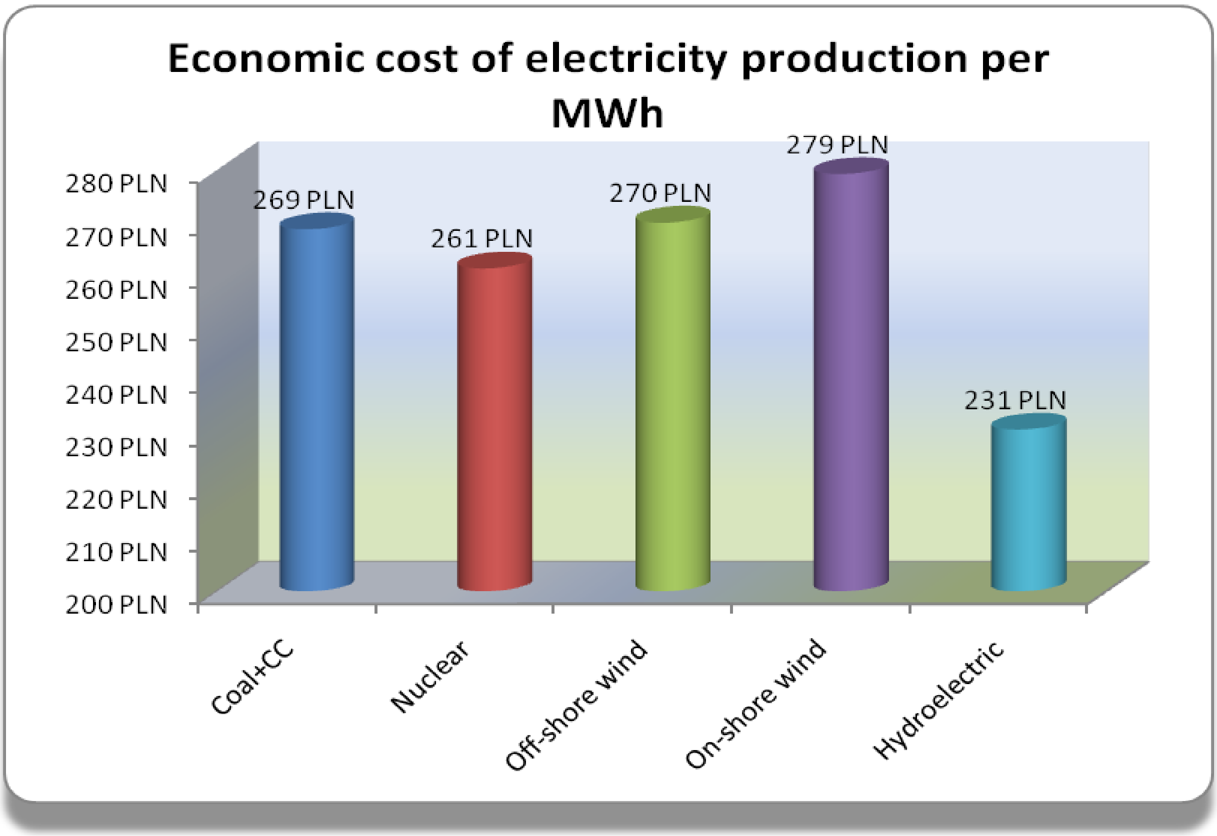


Figure 33. Economic cost of electricity production per MWh

The price for electricity from coal combusting electricity plants is increased by the price of carbon credits, at the price of 20 EUR i.e. 82 PLN, which gives an energy price increase of 72.02 PLN/MWh produced electricity. The idea behind carbon credits is that an emitter buys carbon credits from an entity which has the right to emit but is preventing its emissions in return for monetary reimbursement. Therefore, in theory, buying a carbon credit will ensure a 1 tonne CO_2 emission reduction. This inclusion is a form of internalizing external costs of CO_2 emissions in order to measure the cost of producing power, while accounting for the CO_2 market value.

Initial calculations show hydroelectric power plants to be the most profitable solution despite higher capital cost than any other analyzed technology and lower yearly load factor than either coal or nuclear power plants. The key factor influencing high profitability in this case is the O&M costs figure. The electricity producing equipment does not have to work in nearly as adverse conditions as for the other analyzed energy sources and the power plant is fueled by the kinetic energy of water – a free resource. Thanks to these factors a hydroelectric plant's main expenses are buying weather prognoses and maintaining a worker who regulates the water flow. The limiting factor for this technology is the country's hydroelectric potential. The current use of hydroelectric power amounts to 2042 MW (including 1752 MW installed in the Lower Odra hydroelectric plant), but Poland's full hydroelectric potential allows for installing approximately 12 000 MW electric generation capacity (Lewandowski, 2008), however it is a theoretical potential based on the amount of excess kinetic energy in Poland's flowing waters. The technical potential of Poland is assessed to be slightly over 50% of the theoretical potential and the current economic potential of Poland is slightly over a third of the theoretical potential, i.e. roughly 4 000 MW (Zawadzki, 2009). If a large part or all of the economic potential were to be realized, then the resulting cost of electricity would be noticeably higher.

Wind farms have the lowest yearly loads and the lowest project lifetimes of all the analyzed technologies – also their generation periods do not respond to market needs. Their main advantage over nuclear power plants lies in the fact that they can be installed sooner in the planning period, enabling for smaller emission reductions starting early instead of large emission reductions that would be necessary to achieve the same cumulative effect later. The value of this advantage against the background of wind technology weaknesses will be one of the important factors analyzed in the scenarios

Analysis scenarios

The scenarios have been cursorily educed at the beginning of Section II. Their goal is to provide a background for the economic assessment of nuclear power investments as a cost-effective way to prevent climate change resulting from CO_2 emissions.

The scenarios calculate capacities which need to be installed for any chosen technology mix in order to achieve the same level of CO_2 emission prevention as by implementing the Polish nuclear scheme along with the weighted mean price of electricity generated inside each scenario.

Assumptions

The planning period for the project is 20 years – up till the end of year 2029 – it is the final time by which Europe's emission reduction targets have to be achieved according to the the Potsdam Institute for Climate Impact Research (Meinhausen, 2009), before global mean temperatures grow by 2°C.

Calculation mechanism

The goal of the mechanism is to calculate the electricity production cost of an energy mix that offers the same level of emission reduction until the end of the planning period as building a 1 600 MW nuclear block by the end of 2020.

The capacity of renewable energy of a chosen kind that has to be installed is calculated as follows:
The amount of full load hours provided yearly by the planned nuclear plant is divided by the amount of full load hours provided yearly by the chosen technological solution, multiplied by the number of years that the nuclear plant would be able to operate within the time horizon and divided by the number of years that the chosen technical solution would be able to operate within the time horizon.

Subtracting the number of years that the nuclear plant would be able to operate within the time horizon divided by the number of years that the chosen technical solution would be able to operate within the time horizon from 1 and multiplying the result by the number of full load hours provided yearly by the planned nuclear plant gives the capacity of coal-powered plants which have to be operating to make the chosen energy mix produce as much power within the planning period as the planned nuclear plant.

The two calculated figures are enough to create percentages of yearly supplied electricity from sources within the mix.

A sum of LPCs multiplied by their respectable percentages of contribution to electricity production gives the LPC of producing electricity from a given mix.

Scenarios incorporating more than 2 technologies are based on the same calculation principle in slightly modified form.

Scenario	Amount of installed capacity [MW]				Levelized Production Cost [PLN/MWh]
	Coal	Off-shore wind	On-shore wind	hydroelectric	
Off-shore wind / coal mix	600	1782	0	0	<u>**243**</u>
On-shore wind / coal mix	711	0	2958	0	<u>**243**</u>
Hydroelectric / coal mix	711	0	0	1251	<u>**216**</u>
Equal CO_2 emission reduction from all renewable sources / coal mix	674	594	986	417	<u>**234**</u>

Figure 34. Capacity and energy price parameters of mix scenarios

All of the scenarios presented in Figure 34 provide lower electricity generation costs than nuclear power, however for some of the scenarios, the cost differences might be within the range of data risks. To determine the importance of risks affecting the LPC of possible scenarios a sensitivity analysis has been executed.

Based on available data, the option of investing in a hydroelectric / coal mix scenario has shown the lowest economic costs, however the capacity of hydroelectric power plant investments necessary to fulfill the scenario is approximately 55% of all current economically available hydroelectric capacity in Poland – a part of which is available through modernization of currently existing plants (Zawadzki, 2009). Because of that, not all available capacity offers the same level of cost-effectiveness – using up most of the available capacity will result in a rise in LPC, therefore the hydroelectric / coal mix scenario is both unrealistic in terms of actual electricity production costs and hard to achieve in practice.

To incorporate hydroelectric power plants into a scenario in which the amount of installed hydroelectric capacity does not impact potential electricity costs to the same extent, a scenario providing equal CO_2 emission reduction from all renewable sources has been created – it offers the second lowest LPC after the hydroelectric / coal mix scenario and most realistic energy costs due to consuming a lower percentage of available capacity for each respectable technology.

Sensitivity analysis

In order to assess the level of risk associated with assumptions incorporated into the project, a sensitivity analysis, enriched by an assessment of combined cost-negative and combined cost-positive scenarios has been conducted.

The sensitivity analysis includes:

- Yearly average wind speed at anemometer height change by 0.25 m/s and 0.5 m/s

- Coal, nuclear and hydroelectric yearly production change by 500 and 1000 full load hours per annum

- Annual discount rate change by 2% and 4%

In addition to readability, a low degree of unification amongst disaggregation levels of gathered data from different technologies has contributed to the delimitation of used sensitivity cases.

Firstly, the sensitivity of LPCs of single technological investments has been calculated.

Figure 35 illustrates the LPC change of single technologies based on change of yearly loads and wind speeds:

Change of yearly loads/ wind speeds [h/a]/ [m/s]	Coal [PLN/MWh]	Nuclear [PLN/MWh]	Off-shore wind [PLN/MWh]	On-shore wind [PLN/MWh]	Hydro-electric [PLN/MWh]
-1000/-0.5	207	288	295	350	294
-500/-0.25	201	273	282	312	257
0/0	197	261	270	280	229
500/0.25	193	251	260	255	206
1000/0.5	190	242	250	234	188

Figure 35. LPC change of single technologies based on change of yearly loads and wind speeds

Figure 36 illustrates the LPC change of single technologies based on change of annual discount rates:

Change of annual discount rates [%]	Coal [PLN/MWh]	Nuclear [PLN/MWh]	Off-shore wind [PLN/MWh]	On-shore wind [PLN/MWh]	Hyrdoelectric [PLN/MWh]
-4	173	187	170	185	119
-2	184	220	216	229	169
0	197	261	270	280	229
2	212	311	332	338	297
4	221	339	367	369	334

Figure 36. LPC change of single technologies based on change of annual discount rates

Figure 37 illustrates the LPC change of singular technologies based on change of annual discount rates:

Change of yearly loads/ wind speeds/ annual discount rates [h/a]/ [m/s] / [%]	Coal [PLN/MWh]	Nuclear [PLN/MWh]	Off-shore wind [PLN/MWh]	On-shore wind [PLN/MWh]	Hyrdoelectric [PLN/MWh]
-1000/-0.5/4	246	415	440	501	476
-500/-0.25/2	218	327	347	375	334
0/0/0	197	261	270	280	229
500/0.25/-2	193	251	260	255	206
1000/0.5/-4	169	178	158	154	97

Figure 37. LPC change of single technologies based on change of annual discount rates

Figure 37 presents the highest / lowest LPC of single technologies based on change of yearly loads, wind speeds and annual discount rates, overlapping each other so that the lowest price case of LPC of single technologies based on change of annual discount rates in each technology overlaps with its lowest price case of LPC of single technologies based on change of yearly loads and wind speeds in a way that the price lowering effects are further increased, the second lowest LPC case in each technology overlaps each other in the same way as do the second highest and highest LPC cases.

These figures, which provide data for a sensitivity analysis of all the singular technologies included in the report are the basis for constructing a sensitivity analysis of the energy mixes, which then need to be converted by applying rules explained at the beginning of the "Calculation mechanism" chapter.

The full sensitivity analysis incorporates 13 cases of different input data for each of the 5 existing scenarios as introduced at the beginning of the "Sensitivity analysis" chapter: 4 cases dealing with positive and negative changes in annual electricity production of all technologies; 4 cases dealing with a higher/lower discount rate than used for the standard analysis; 4 cases combining the assumptions from the previous cases - lowest production with highest discount rate, lower production with higher discount rate, higher production with higher discount rate and highest production with highest discount rate and 1 case based fully on the assumptions of the standard analysis.

Change of yearly loads/ wind speeds/ annual discount rates [h/a]/ [m/s] / [%]	Levelized Production Cost for scenario [PLN/MWh]				
	Nuclear	Off-shore wind/coal mix	On-shore wind/coal mix	hydroelectric/ coal mix	Equal CO_2 emission reduction from all renewable sources
-1000/-0.5/0	288	262	286	256	268
-500/-0.25/0	273	252	262	233	249
500/0.25/0	251	235	227	201	221
1000/0.5/0	242	228	214	190	210
0/0/4	339	312	303	285	300
0/0/2	311	287	282	260	276
0/0/-2	220	204	208	177	196
0/0/-4	187	171	179	144	165
-1000/-0.5/4	415	367	387	375	377
-500/-0.25/2	327	298	305	283	296
0/0/0	261	243	243	216	234
500/0.25/-2	251	235	227	201	221
1000/0.5/-4	178	162	160	130	151

Figure 38. Price sensitivity table of analyzed equal emission reduction options

Figure 38 presents the combined results of the 5 assessed scenarios' sensitivity analysis. For illustrative purposes these results have also been introduced in graphical form:

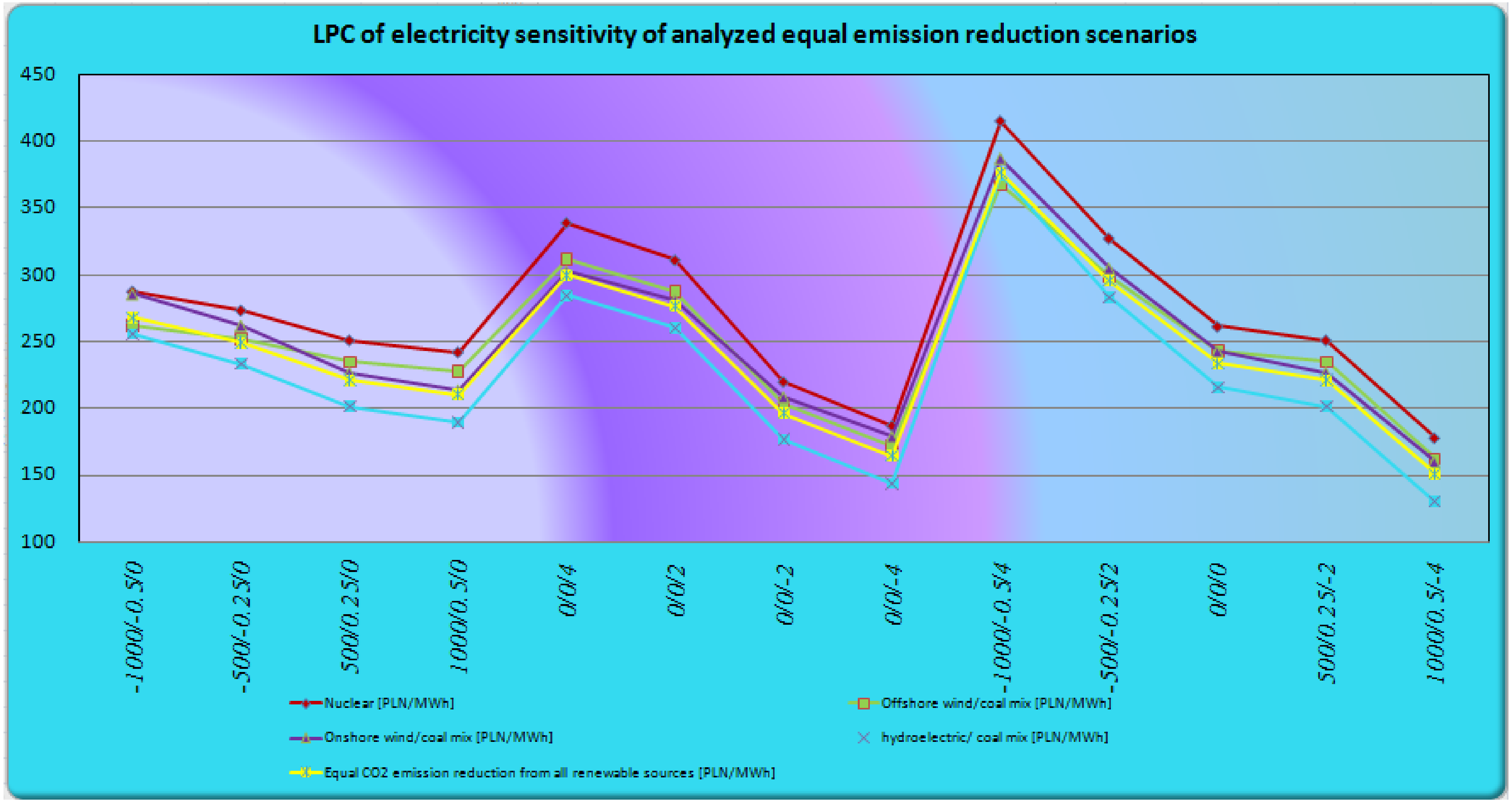


Figure 39. Levelized production cost of electricity sensitivity graph of analyzed equal emission reduction options

Each of the 5 broken curves represents one of the 5 assessed project scenarios as marked in the figure 39 legend, while each point on the horizontal axis represents a different sensitivity case. The vertical axis stands for cost values of producing electricity in PLN/MWh. Therefore, each point marked on a curve shows the economic electricity production cost according to one of the 13 different sensitivity cases included in the sensitivity analysis.

It is interesting to note that while in most cases cost of electricity from nuclear plants is not significantly higher than in the other 4 scenarios, in every of the 13 sensitivity cases the LPC of electricity production from nuclear plants is higher than from each of the other 4 scenarios. Each of the other curves intertwines with some other curves and at least once, the effect being strongest between off-shore and on-shore wind / coal mix scenarios – in the standard analysis case both scenarios have the same LPC of producing electricity, in 6 cases the on-shore wind / coal mix scenario has lower LPC of producing electricity than the off-shore wind / coal mix scenario – in the remaining 6 cases the situation is opposite. The effect results from the fact that REPower 5MW wind turbines in on-shore wind farms in Poland would operate in far more disadvantageous wind conditions than in off-shore wind farms, making the production in the on-shore wind / coal mix scenario more susceptible to periodical wind speed changes, whereas higher installation costs and electricity production of off-shore wind farms make the off-shore wind / coal mix scenario LPC values more dependent on the value of discount rates. In every case except for the case with the highest costs, the hydroelectric / coal mix scenario offers lower costs than any other scenario.

Further discussion on the sensitivity analysis results continues in Section IV.

Section IV: Conclusions

"He who puts out his hand to stop the wheel of history will have his fingers crushed"

- Lech Wałęsa, former President of Poland

Critique of objectivity

Because of the author's background (Sustainable Energy Planning and Management studies and B.Sc. in Environmental Protection) careful steps have been taken in order to prevent using spread in available input data values to the advantage of renewable technologies. Also, the decisive inputs for nuclear power plants – the capital costs – have been inserted from the investor's initial assessment presented to the government, and are far below the capital costs assumed by skeptics e.g. 56% of the capital costs presented by a Moody's study (Moody, 2008). Incidentally, the low official discount rate speaks in favor of technologies with high project lifetimes and high investment costs – hydroelectric power plants and nuclear power plants. Also, for hydroelectric power plants, merely a single case has been examined – there exists a risk it was not representative to the entire industry.

Taking these factors into account it is possible that the study results are partially subjective – in favor of nuclear power plants and hydroelectric power plants

Assessment of coal-powered plants

Despite declining profitability resulting from constantly increasing environmental standards that necessitate expenses like particle matter filters and SO_2 utilization facilities, coal-powered plants have the lowest economic cost of producing electricity when a cost increase represented by 82 PLN/t of emitted CO_2 is not included and are still economically competitive with most technologies when it is. Also, coal-powered plants have shown to be least affected by changes introduced in the sensitivity analysis.

Although in light of necessary CO_2 emission reductions it is obvious that the share of coal-powered electricity in Poland will decline, its usefulness for providing baseloads, acceptable resistance to risks and availability of abundant fuel resources within national borders ascertains that coal will remain the basis of the Polish electricity supply system for a long time to come.

Assessment of off-shore wind farms

Off-shore wind farms have proven to be the most alike to nuclear power plants in the course of the analysis. They have almost identical levelized production costs of electricity and they both have not yet been utilized in the area of Poland. Also, although 5 investments in off-shore wind farms await authority approval, the changes in Polish legislation allowing usage of an off-shore territory for more than 5 years have not yet been made, so like nuclear power, off-shore wind is so far a nascent technology, not yet tested in Polish conditions.

The possibility of a sooner investment than in the nuclear plant case – with good will from the government, is the factor that makes an off-shore wind / coal mix scenario more cost effective than a nuclear scenario. Also, although off-shore wind farms by themselves are more susceptible to both negative and positive electricity cost changes than nuclear power plants, the off-shore wind / coal mix scenario shows less susceptibility to negative or positive electricity cost changes than nuclear power plants.

The equal CO_2 emission reduction from all renewable sources / coal mix scenario, which includes installation of off-shore wind farms is assessed to be a more cost-effective way of achieving CO_2 reductions than the off-shore wind / coal mix scenario.

Poland has a developed feed-in tariff system, issuing green certificates for each MWh electricity generated from renewable sources, allowing a potential investor to break even from building an off-shore wind farm while selling electricity at 22 PLN/MWh, assuming the parameters used for the analysis.

Assessment of on-shore wind farms

On-shore wind farms have the highest LPC of all the technologies analyzed in the project. Due to a short investment period a on-shore wind / coal mix scenario shows the same level of cost-effectiveness as the off-shore wind / coal mix scenario.

On-shore wind farms have the lowest investment costs per MW installed capacity except for coal-powered plants, a factor which makes them available to a wider group of potential investors. They are included in the green certificate scheme, allowing a potential investor to break even while selling electricity at a 31 PLN/MWh price.

An on-shore wind / coal scenario is less cost-effective than an equal CO_2 emission reduction from all renewable sources scenario, which also includes major investments in on-shore wind farms.

Assessment of hydroelectric power plants

According to the model, hydroelectric power plants are the most cost-effective way of preventing CO_2 emissions during the electricity production process. They are the most beneficial technology and should be utilized in the Polish system to a larger extent. Their investor costs can be substantially subsidized by the European Union.

The funding for the plant analyzed in the project has already been ascertained. The construction of the Rzeszów hydroelectric power plant will be subsidized from EU funds based on Regional Operational Programme for the Podkarpackie region priority I innovational and competitive economy activity 1.1 – capital support of entrepreneurship, by 70% of investment cost.

The cost of building s fishway will be subsidized 100% based on Operational Programme "Sustainable development of fishery and nearshore fishing territories 2007-2013" action 3.2 – protection and development of water flora and fauna (MCG, 2009).

The unsubsidized cost of investment is equal to 15 750 000 PLN, and is reduced after subsidizing to 4 350 000 PLN, reducing production costs from 231 PLN/MWh to 65 PLN/MWh solely based on incentives from EU funds.

Electricity produced from hydroelectric power plants is further subsidized by way of green certificates sold to energy distributors at a value of 248 PLN/MWh el., meaning that for practical purposes, an investor selling energy at the economic cost of production would get an annual return rate of 36.5% and a payback period of less than 3 years.

The main obstacles in hydroelectric capacity development are high capital costs, complicated procedures for obtaining funding and permits, scarcity of qualified personnel and high monetary responsibility of the owner for not maintaining a proper balance of water quantities for fishermen, farmers, industry, wildlife and flood safety both up- and downstream from the power plant which ascertains a positive effect of small hydroelectric power plants on the environment but puts strong responsibility on the owner of the plant. Also, the available capacity is divided into small investments – excluding the Lower Odra hydroelectric power plant the average installed capacity amongst the other 683 hydroelectric power plants in Poland amounts to 0.42 MW. Developing the hydroelectric industry in Poland would require encouraging initiative at regional and local levels but introducing greater amounts of hydroelectric capacity is clearly in Poland's economic interest.

Assessment of nuclear power plants

Although the cost of producing electricity from nuclear power plants is greater than from hydroelectric power plants, the 1.6 GW capacity can be supplied from a single investment, whereas investment in small hydroelectric powered plants to provide the same capacity would be highly complicated to plan and oversee.

The cost of electricity production from nuclear power plants is significantly higher than from coal-powered plants and can only be only leveled due to assigning a high price to CO_2 emissions, in which case it is comparable.

As a scenario, the nuclear scheme is inferior to the other introduced options, due to a very long introduction period, greatly limiting its use for reducing CO_2 emissions in time to prevent cascading climate change, and the fact that as a technology it is substantially more costly than coal generation.

Also, the economic cost introduced in the study was not complete. The exact costs of introducing legislative changes, creating new administration, making changes in the educational system ,modifying local land plans and conducting social campaigns at a national scale – all enterprises foreshadowed by the government as steps to be taken in order to introduce nuclear power in the following years, have not been assessed. It is probable that these costs would greatly influence the economic cost of electricity production from nuclear power.

Addressing the research question and final observations

The project has generated substantial amount of data on the cost of generating electricity in Poland from various scenarios, all in order to address the research question:

What is Poland's most economically feasible solution for reducing CO_2 emissions within the electricity production sector?

as well as sub-questions:

What are the costs of producing electricity from different technologies and technology mixes?

What is the level of competitiveness of nuclear power plants compared to other available technologies?

Based on project outputs, what path of development should Poland follow?

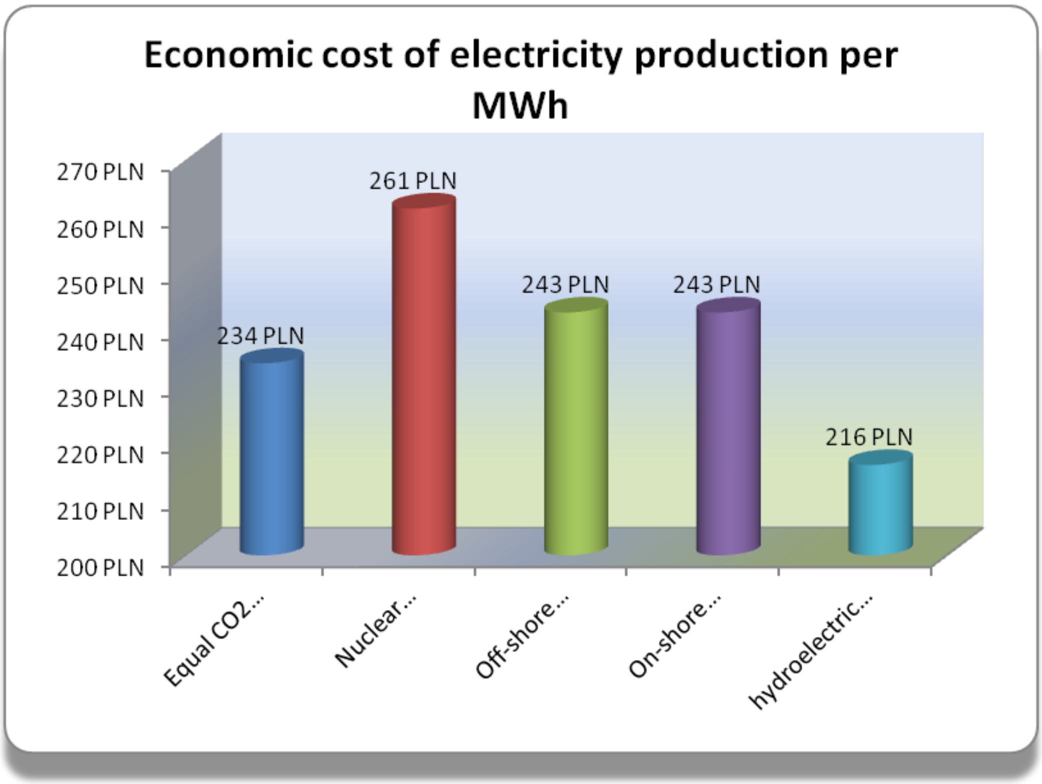


Figure 40. Economic cost of electricity production for assessed scenarios graph

The lowest figures representing economic cost have been generated for the hydroelectric / coal mix scenario as shown in Figure 40., however it has been noted throughout the project that this is related to many uncertainties, the most important relating to the rise in cost due to the scenario using 55% of Poland's remaining available hydroelectric capacity potential. Therefore the hydroelectric / coal mix scenario cannot at this point be selected as the scenario to be chosen over the rest and further study on the subject is advised.

On par with the hydroelectric / coal mix scenario, the equal share of CO_2 reductions from all technologies/ coal mix scenario – requiring the least effort on the part of the government and providing the second lowest economic cost of electricity generation should be considered. It has an advantage over the other scenarios of relying on more than two resources for energy generation, therefore the negative effects of lower winds speeds or less rainfall during a year, or possibly political instability hindering uranium supply will not have as severe effects on electricity production as in the case of other respective scenarios.

The nuclear scenario has shown to have somewhat higher economic costs of generating electricity than other scenarios both in the main analysis and in each of the 13 different sensitivity cases taken into account. The results of the study clearly show that Poland has no economic interest in developing electrical capacity from nuclear power plants.

Also, policywise, Poland has a commitment to increase its share of primary electricity production from renewable energy sources to 15% by year 2020. In January 2009 Poland has reached a 7.0% share of renewables in its electric energy mix (Barzyk et al., 2009). Basing on parameters assumed in the project and Poland's electricity use (WNP, 2009), the planned nuclear plant would supply approximately 7.4% of Poland's electrical energy use. Substituting the planned investment with any of the analyzed energy mixes would realize most of the amount necessary for meeting the 15% primary production of electricity from renewable sources goal.

Poland, with its growing national debt and existing line of policy shows very little chances of adapting both an ambitious renewable scheme and a nuclear scheme. The results of the study clearly show that on the basis of economic cost of electricity generation, either an equal CO2 emission reduction from all renewable sources / coal mix scenario or a hydroelectric / coal mix scenario would be the proper choice for future development of electrical capacity in Poland. If adapting nuclear power and one or more of the renewable scenarios would be considered, it should not be accepted before an approximation of costs associated with introducing nuclear energy into the Polish electricity generation system is made and fed into a economic cost of electricity production model.

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