Polish Energy Policy 2050 - an instrument to develop a diversified and sustainable electricity generation mix in coal-based energy system

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Abstract

Polish economy is still undergoing the transformation process and seeks to converge with the most developed economies in Europe. While many economic reforms have been made, the generating sector was left to its own devices and lack of the investments caused that electricity supply in Poland is ineffective and not secure. The coal is a primary fuel and it constitutes over 80% of the energy mix. Thus, with energy mix restructuration ahead, the ambitious and balanced energy policy is highly required.

The article aims to present the 2050 Energy Policy for Poland, which should facilitate the transformation of coal-based electricity generation system towards more sustainable and diversified energy mix. Comprehensive description and review of the current conditions of energy sector in Poland are accompanied with strengths and problems that need to be solved, taking into account European requirements. Additionally, in the paper the authors describe the development process of the Polish Energy Policy as they actively participated in the calculations of optimal energy mix for Poland. The manuscript presents the *eMix* model (energy mix optimization tool) developed by the authors, that constituted a background for Ministry of Economy to create Energy Policy. Hundreds of simulations scenarios were performed for the Ministry of Economy to provide the clear view of the electricity generation sector and to understand the impacts of all external stimuli to the mix. Assumptions for the model and results of calculations according to the policy scenarios are presented in the paper. Finally, the authors evaluate the final decisions of the policy makers, integrated in the Polish Energy Policy 2050, taking into account the challenges for the Polish power sector.

Keywords: energy policy, sustainable development, energy mix, optimization, computer modelling, transition country

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List of abbreviations

bcm - billion cubic meters
 CHP - Combined Heat and Power
 DSR - Demand Side Response
 EC - European Commission
 ETS - EU Emissions Trading System
 EU - European Union
 EUA - European Union Allowances
 GDP - Gross Domestic Product
 HVDC - High Voltage Direct Current
 IEM - Internal Energy Market
 LNG - Liquid Natural Gas
 (n)CDGU - (not) Centrally Dispatched Generating Units
 PV - Photovoltaics
 PEP 2050 - Polish Energy Policy 2050
 PSE - Polish Transmission System Operator
 RES - Renewable Energy Sources
 TSO - Transmission System Operator

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1. Introduction

1.1 Research background

The paper provides the description of the most recent Polish Energy Policy 2050. Currently, Poland is in the middle of its economy transformation. Having one of the biggest GDP growth in Europe (3.6 % in 2015, while average in EU did not surpass 1.9% [1]), Polish economy is considered as secure and stable, even in the face of recent disturbances and financial crises (see Poland's ratings for 2015 i.e.: [2]). Nevertheless, maintaining the current development rate requires significant reforms and new strategic thinking. Energy sector is crucial for the further progress and although some reforms of the electricity markets were already made (liberalization, Third Party Access, unbundling etc.), there were little investments in the generation sector (see chapter 2.2.2.). Current situation of the Polish energy sector, particularly power sector, is not optimistic. Pol-

and faces the regular shortages of the power system reserves and missing capacity problems. In August 2015, Polish TSO limited the electricity consumption for the industry [3]. New investments are not likely to be started, because of the very low prices at the wholesale electricity markets (average price in 2015 at the wholesale electricity market was around 36.34 €/MWh [4], which was not attractive for investors). Moreover, the trend indicates further prices decrease due to the growth in renewable energy sources (RES) penetration in Poland.

Currently, the Polish energy mix relies on coal in over 80%. About 5 GW of power capacities must be commissioned until 2020, further 5 GW until 2030 and 9 GW until 2040. Currently installed power capacity in Poland reaches 40 GW, and up to 2050, almost a half of it must be replaced with the new units. Additionally, as the Polish economy is still converging, increase in electricity consumption is guaranteed and new additional assets must be constructed to cover the demand. Another problem of the Polish power system is stability and balancing issue caused by the intermittent generation. Hence, it can be said that the Polish power sector is currently in transformation and many actions must be undertaken to provide a secure electricity supply for the citizens and industry. From this perspective, the case of Polish energy mix, its energy policy and the transition to low emission economy is very interesting.

The paper presents the assumptions for the 2050 Polish Energy Policy (PEP 2050) but also describes the backstage of the policy development, as the authors of the manuscript took active part in the process. Their role was to act as consultants on the technical aspects of the power system operation and to predict the results of the Polish energy mix optimization. For that purpose, the analytical tool – *eMix programme* [5], [6] – was developed. It is an optimization model, designed by the authors of the manuscript in cooperation with the Department of Energy of the Ministry of Economy of the Republic of Poland. After the development stage, the *eMix* served for calculating dozens of scenarios to find the most optimal solutions for Poland. The manuscript presents the main assumptions and features of the *eMix* and describes the results of the energy mix optimization that formed a basis for PEP 2050 assumptions.

1.2 Paper structure

The paper begins with the motivation for its creation that shortly describes the major problems of power sector. Since Poland is a part of European Union and Polish policy must be coherent with EU policies, there is the brief description of the European power sector and European Energy policy 2030 (Section 2.1). This part also mentions the idea of Emissions Trading System (ETS) and Internal Energy Market. The section 2.2. comprehensively presents the Polish Power sector with all the challenges that need to be addressed in the nearest future. Then, there is a description of the Polish Energy Policy 2050 and its operational objectives and priority projects. Section 3 was developed to present the already existing approaches to energy system modelling used for the policy development and the *eMix* model assumptions. Section 4 starts with the calculation of the scenarios implemented in the *eMix* model with their main results: installed power structure and electricity generation up to 2050, CO₂ emissions, primary fuel consumption, total and marginal cost of electricity generation. This part is followed by the presentation of scenarios included in the Polish Energy Policy 2050. The article is summarized with conclusions and policy implications.

2 Energy Policy

The *energy mix* represents the share of particular technologies used to meet the energy demand. Energy Policy should guide to achieve the most beneficial energy mix from the energy security perspective. Although the presented Policy influences the whole economy of the country (electricity, heat, transportation etc.), the main problem addressed in the article is the electricity sector. Consequently, the following information is mostly related to the electricity production rather than whole energy sector. Polish Energy Policy 2050 was developed in accordance with the European Energy Policy 2030, thus the brief description of European Policy assumption is also presented in the article.

2.1 European Energy Policy 2030

The exploitation of the primary energy in the EU-28 countries is constantly decreasing. It is the result of the gradually shrinking supplies but also of the fact that the extraction of raw materials is uneconomical on a small scale. Almost all energy sources have decreased their production and the total production of the primary energy in 2014 equaled 770.7 million tonnes of oil equivalent, which represents the drop by 17% in ten years. The decrease in primary production is not so problematic, since the increased amount of electricity is being

produced from RES. In 2014 around 24% of electricity generation derived from unconventional sources (Figure 1) [7].

The deficiency that results from the decline of energy production must be met through the import. In 2014, 53.5% of the gross energy consumption among the EU countries was imported from the non-European countries. The EU-28's imported 881 millions toe more than exported [8]. Each EU-28 country (in spite of Denmark) must import energy to cover the demand, yet the index of imported energy was higher in the most populous countries (Germany, France, United Kingdom, Italy or Spain). Most of the imports of crude oil come from OPEC countries and Russia. The gas is mostly supplied by Russia, Norway and Algeria.

The energy security of EU-28 relies heavily on the relationship with their neighbors, mostly Norway and Russia. EU spent €300 billion in 2013 on importing crude oil and its derivatives of which one third goes to Russia. Six member countries import the gas only from Russia and three among them use the gas fired power stations to cover quarter of their total domestic demand [9]. The uncertain relations between trading or transit countries and Russia may pose a threat to the reliability of raw materials supply in Europe. The gas conflict between Russia and Ukraine in 2009 made the situation even more alarming. To mitigate the consequences of the possible suspension of supplies, the Council of the European Union released the "Directive 2009/119/EC of 14 September 2009 imposing an obligation on Member States to maintain minimum stocks of crude oil and/or petroleum products" [10]. The obligatory stocks should cover the equivalent of the higher one of the following quantity:

- Enough to cover 90 days of daily imports (average)
- Enough to cover 61 days of inland consumption (average)

The daily imports and inland consumption are converted to the crude oil equivalent calculated for the previous year (or for the obligations for the first quarter of the year for the last but one year) [7].

The dependence of European Union on the primary energy import is one of the biggest stimuli to constantly decrease the energy intensity of its economy and focus on the more ecological energy sources. Thus, the European Commission released "A policy framework for climate and energy in the period from 2020 to 2030" [11] in which it highlights the overall direction of the energy policy development for the nearest future.

The climate and energy policies overall directions assume reaching the four main objectives:

- Improved competitiveness
- Security of supply
- Sustainability
- Low emissive economy

The 2030 directive is one of the guidelines that precisely established the targets to achieve above-mentioned objectives. It was elaborated to constitute the continuation of the "20/20/20" policy. The following Table 1 presents the main goals of the 2020 and 2030 directives.

Because of the already taken measures related to the "20-20-20" policy, the target of 40% greenhouse gases reduction in 2030 is likely to be achieved. The predicted level of greenhouse gases reduction will probably reach about 32% in the 2020. Thus, there is not much investments to be made in order to achieve the established goal for 2030.

The greenhouse gases reduction and increase of the share of RES are strongly related to each other. The first target should result in the increase of the share of RES by 27%. The development of RES' share in the power sector is the easiest way to improve energy independence. The European Union is constantly exposed to the price fluctuations of the imported raw materials and fuels. Investments in this sector will not only limit the volatile expenditures on imported goods, but also stimulate the growth of innovative technologies and create new jobs. The share of RES in the energy industry is likely to exceed 45% by 2030.

The energy efficiency 20-20-20 target, although very important (is very valuable to achieve the main objectives of the energy policies), probably will not be reached by 2020.

To achieve the greenhouse gases reduction by 40% in 2030, the energy savings should be increased by 25%. This could be realized by maintaining the level of investments in the industry and passengers' vehicles and increasing investments in housing sector, transport (other than passengers' vehicles) and electrical equipment. All those expenditures will on balance lead to the cuts in the running costs. They should also prompt the development of the technology and consequently the EU will maintain the leader position in the technology sector. The costs of adaptation to the new policy will affect mostly countries with lower GPD per capita.

Those countries have usually lower energy efficiency; their energy production is based on the conventional, inefficient power generating units and thus, require greater investments in the energy sectors. It is calculated that the countries with the GPD factor lower than 90% of EU average should invest in the power sector approximately €3 billion a year more than the average EU country (from 2021 till 2030). The 2030 policy also defines the change in the ETS trading system and development of the internal energy market.

ETS trading system

The downturn of the economies during the crisis, among other reasons, resulted in the surplus of the allowances for the carbon dioxide emissions. The low price of allowances makes the whole system ineffective – it does not stimulate the investments in the low-emission energy sources and industry. To artificially increase the prices, the European Commission (EC) decided on withdrawing €900 million allowances for the years 2014-2016 and postpone them until 2019-2020 (so called backloading). Additionally, currently the phase four of the EU ETS is being discussed. Between 2020 and 2030, new rules for allowances allocation will be implemented. Free allowances will be limited only to the very specific cases, mainly to avoid ‘carbon leakage’. Any further exemptions from the European Union Allowances (EUA) purchasing will be made only if equivalent of EUA value is paid to the low or zero-emissions technologies (Modernization Fund, NER400). As the backloading or occasional cancellation of EUA is not effective measure to increase the allowances’ prices, EC decided on implementation of the Market Stability Reserve from 2021 that will cut of the surplus of allowances year by year to enhance the stability of the ETS system (increase the prices and stabilize the trends). It would also alleviate the consequences of the sudden but temporary growth of the demand that can result in carbon leakage (some high emissive companies may be interested in the assignment of its production to the countries with no ETS system).

Internal Energy Market

The conclusion of the Internal Energy Market (IEM) development is one of the highest priorities of the European Commission. The IEM would improve the energy security of European countries. First of all, it would diversify the foreign sources of primary energy for member countries. Secondly, it would require the increase in the number of interconnections and as a result allow for better management of the electricity distribution. Finally, it would reduce the growth of the electricity prices for households and enterprises. It is estimated that the fully integrated IEM could bring the savings of between €40-70 billion in comparison to current costs. The IEM will allow for terminating the subsidies for the well-developed technologies and RES after 2030. Hence, all the energy generating sources will be subjected to the equal market rules. IEM for the electricity will require significant investments in the infrastructure, mainly transmission networks and interconnectors, and implementation of new market designs including intraday markets and pan-European balancing market.

2.2 Polish Energy Policy 2050

2.2.1 Polish energy mix 2014

The average yearly electricity demand for Poland increased by 17.3% in comparison to 1990 and reached 154.9 TWh in 2014 [12]. At the same time, the electricity production increased by only 14.8% (Figure 2). During this period, the available average power reserves were satisfactory (excluding economy crisis in 2008), until 2014 when the first positive import/export balance appeared and 2.2 TWh was imported from foreign countries [13]–[15].

Over 80% of electricity in Poland is produced from hard coal and lignite. The energy mix can be considered in two dimensions. The first one relates to the structure of the installed capacity, so the share of each particular technology, according to the capacity in the whole power system. The second dimension relates to the share of each particular technology in the final electricity generation. Both of them are extremely important, as the power system operation cannot be analyzed only in one dimension. The share of particular technologies in energy production in Poland diverges from the capacity installed structure (Figure 3). The share of lignite exceeds 34.63% to cover the underproduction of other sources, mostly RES and water power plants. According to the Yearly Coordination Plans prepared by the PSE (Polish Transmission Operator), the average capacity available in 2016 will equal 34 457 MW while there will be 41 426 MW [17] of capacity installed (Figure 4).

Poland is still a developing country so the GDP is predicted to be still increasing in the next decades although with the declining pace. Despite the fact that the energy efficiency of the economy is in all likelihood going to improve (Figure), the total electricity demand will continue to grow (Figure 6).

According to all forecasts, the electricity demand will increase by approximately 50% in the next 30 years (Figure 6). Thus, the problem of *missing capacity* (see 2.2.2.6) will not decline with time and must be addressed as quick as possible to avoid blackouts [19], [20].

2.2.2 Key problems of the Polish power sector

The energy sector as being very vast and complicated structure faces a lot of problems. The main challenges are related to its infrastructure, economic and political issues – sometimes they concern more than one of those areas at the same time. In the following section the authors raised the questions of ageing and insufficient infrastructure, primary energy supplies, and basic financial problems appearing in the power sector in Poland.

2.2.2.1 Decommissioning of power plants

The recent inspection carried by Polish Supreme Audit Office released a report on the current situation of Polish energy sector and the forecasts on the future energy security. The main problem of Polish energy sector is the impending decommissioning of old units. The predicted lifetime of coal power plants is 40 to 45 years. 59% of turbo generators are over 30 years old. Next 16% are between 20 and 25 years. Only 25% of units were built in the recent 20 years. Even more alarming situation can be observed for the boilers of which over 63% is over 30 years old and only 20% is less than 20 years old (Figure 7) [23]–[25].

Figure 8 shows the historical data and the forecasts of power demand in Poland [23]. It is predicted that in 2035 the maximum demand on the power will reach 30 GW and in the next 15 years it will probably exceed 38 GW. At this time, only 5 GW of currently operating power generating units will be available. The rest of the required capacity must be covered by the new units. Between 2010 and 2014 there were declarations of building 10 units, but all of the investors withdrew their offers because of the high uncertainty of future income [26]. Reluctance to build new units may cause the deterioration of Polish energy security especially taking into account the schedule of decommissioning of currently existing units (Table 2).

Despite the emergency measures that can be taken by the PSE, the shortages of power available are predicted to appear inevitably. The first serious shortage appeared in the August 2015. High temperatures, low water levels, planned renovations and breakdowns (that in the crucial moment August, 10th constituted one fifth of predicted demand in the morning peak) resulted in power cuts for the industry [29]. Such shortages are predicted to appear also in the nearest future. According to the calculations conducted by the authors, in the most realistic scenario, if nothing changes, the 9% of required level of power reserves will not be available most times (excluding 2019 and 2020 when new generators start operation) and 18% of power reserves will not be available at all (Figure 9). What is more, the power deficits may appear in 2016 autumn and then from 2022 they will gradually deepen significantly (Figure 10). It is worth highlighting, that the analysis, which results are presented below, assumes that the TSO can still benefit from so called ‘cold reserve’. It is a type of ancillary service, introduced to maintain in the reserves of 830 MW supplied by several units that should already be decommissioned. The TSO is going to maintain this service until 2017 or even 2018 and 2019, although the reliability of this power is limited (in August 2015, when Poland faced power cuts, none of the units in “cold reserve” were able to start up).

The investors claimed that by 2028, they are going to spend over €13 billion on creating additional 10.5 GW of capacity and around €2.8 billion on refurbishing existing units [26]. Those numbers, however impressive, are not sufficient. The energy security in the nearest, as well as in the more distant future, will be maintained only if fast actions are taken. Some regulations need to be introduced, even though they may distort competition and introduce additional costs. It is predicted, that between 2020 and 2035, as a result of the energy shortages and its social implications, the total losses of losing energy security are going to reach over €16 billion. This is why even cost-generating actions taken by the government are relatively profitable [26]. Decisions about supporting the investments in the electricity sector such as capacity remuneration mechanisms should be made as soon as possible in order to avoid the giant costs of undelivered energy.

The alarming situation in the Polish energy sector was also described by numerous foreign institutions. In 2015, the World Economic Forum released a report [31] in which it evaluated 125 economies on the energy

sector impact on economy growth, environmental sustainability and security. Poland received 0.65 EAPI index, which placed it at the end of the list of well developed countries. It reflects the urgent need to improve the situation in the Polish energy sector. According to ENTSO-E [32], Poland was the only European country threatened to loose adequacy in the 2015-2016 winter period. It points out the weak interconnection, danger caused by unplanned flows of energy through Poland (loop-flows) and insufficient level of power reserves in the hot, summer periods.

2.2.2.2 *Weak transmission network*

As of 31.12.2015 Polish transmission network consists of three types of high voltage lines [33]:

- 750 kV: 114 km
- 400 kV: 5984 km
- 220 kV: 7971 km
- 450 kV DC (interconnection with Sweden): 254 km

70% of transmission lines is over 30 years old, and 47% over 40 years old [34], [35]. However, the maintenance processes prolonged the period of efficient functioning of transmission lines to 70 years, so the problem of old lines have been postponed. Although the average age of Polish transmission lines is below the one in Switzerland or Germany, the transmission and distribution system must deal with many other problems. Almost 66% of transmission and distribution lines are the overhead lines that are subjected to severe weather conditions (typical to Polish climate) that often cause damages [23].

The grid's density is not equal on the Polish territory – it is more expanded on the south and less in the north. The uneven structure causes that the grid operates in the “open” configuration instead of the meshed one and the possibilities of reconfiguration are limited. Polish grid allows for only one-way electricity flows and limits the potential of distributed generation. The frequent thefts of the infrastructure constantly increase the expenses of the operators [36]. The transmission losses are very substantial in the Polish energy sector: the total loss of electricity transmission in 2011 reached 10774 GWh (7.3% of total electricity produced) which represents the loss of almost €0.5 billion [37]

Poland has 10377 MW of interconnections available with Germany, Czech Republic, Slovakia, Ukraine, Belarus, Lithuania and Sweden (Table 3). The connections with Sweden and Lithuania are made through DC Links. What is worth mentioning, in 2015, Lithuania finished the undersea 700 MW HVDC interconnection (NordBalt) with Sweden. This investment is also important for Poland, since the connections between Poland, Lithuania and Sweden create so called Baltic Ring which increase possible energy transmissions between those countries [38], [39].

Despite the large potential capacities of the interconnectors, which constitute the 25% of the installed generating capacities in the Polish national power system, the real possibilities of their utilization is strongly limited due to the loops flows. They are caused by the wind generation farms in Germany and not properly designed trading zones in the eastern and central Europe. Electricity traded by the German trading companies are executed through the Polish grid, blocking the capacities. The only fully controllable interconnectors in the Polish power system are HVDC links with Sweden (600MW) and recently commissioned interconnection with Lithuania (500MW). The shifting transformers (that are currently being installed) at a transmission line between Poland and Germany should enable the control over power flow (1500 MW for export and 500 MW for import). Nevertheless, the transformers are to be installed only on one connection with Germany, while effective control can be obtained only by installing them at the entire synchronous connection and removing bottleneck in the western part of Polish transmission system.

2.2.2.3 *Gas uncertainty*

All scenarios of the polish power system development, considering increase of the prices of CO₂ allowances, indicate the need for transformation towards gas-fired conventional units. Such power plants are able to balance the intermittent generation, since CHP gas-fired units are fully switchable (electricity only or heat only operation is possible) and emit moderate amount of CO₂. Additionally, the investments costs are the lowest among currently known technologies and a unit can be constructed within two years, what limits the financial costs. The crucial problem is gas availability and its prices.

Polish natural gas fields are estimated to have proven reserves of 140 059 billion m³ (as of December 2012) according to [24] and 0.1 trillion m³ (for 2014) according to [42]. The proven reserves allow for over 23 years of extraction, if production were to continue at current rate. Polish gas consumption (mainly for heating and chemical industry) in 2014 equaled over 16 bcm of which almost 4.47 bcm derived from domestic sources and 11.65 bcm were imported [43]. The share in the primary energy balance is growing - in 2011 it constituted 11.1% and it increased to 13% in 2015, this tendency is likely to continue [21], [24], [42].

Estimates of the Polish resources of technically recoverable shale gas vary from 38.1 billion m³ [44] to 768 billion m³ [24], [45], or even very optimistic 4188 billion m³ [46]. So extreme discrepancy makes relying the Polish gas security on this doubtful source very risky. In addition, as of today, those deposits are impossible to economically extract with available technology and there is no proof that they will be in the foreseeable future. Another problem results from the use of controversial but the least expensive technology for the shale gas extraction - hydraulic fracturing. Investors' initial interest and optimistic approach to concessions and exploration of the Polish shale gas are becoming more and more cautious. Most of them have already delayed exploration activity to the unspecified future [47], [48]. Thus, Poland can solely rely on the domestic deposits and gas imported.

Although the gas prices in Europe are constantly declining, Polish expenses on gas imports are relatively high. Poland in 2010 prolonged the Yamal contract with Russia on gas imports, that obliged Poland to buy 10.2 billion cubic meters of gas a year (till 2022) of which 85% is contracted in a take or pay system. Additionally, the price contracted is one of the highest price in Europe (on average 23% higher than the one in western countries [49]). The prices of gas across the Europe decreased significantly recently, because of the decrease of crude oil prices. Although the details of the gas contracts are classified, it was revealed that the Russian gas price for Poland equaled 227.4 USD per 1000 m³ in the last quarter of 2015 [50]. The price discrimination results from overusing market power of monopolistic Gazprom. In past, most of the Polish gas imports were coming from Polish natural supplier – Russia. Although Polish gas transmission system is still oriented on importing gas from east, the situation is constantly changing due to deeper and deeper liberalization of the gas sector and expansion of gas market. Although the gas exchange in Poland is developing, the liquidity of the market is still insufficient.

Poland is a transition country for Yamal-Europe pipeline with transition capacity of 33 bcm per year (Figure 11). Given to the new infrastructure in Wloclawek and redevelopment of Mallmow metering station on the German side, Poland may import gas from the west through the virtual and physical reverse (5.5 bcm of fixed flow and additional 2.7 bcm of interruptible flow). Additionally, there is a possibility to import 1.5 bcm through Lasow and 0.5 bcm from Czech Republic. In case of suspension of gas supplies it is already possible to cover about even 90% of demand. The recently opened and soon to be exploited LNG gas terminal in Swinoujscie makes it possible to import additionally up to 5 bcm of LNG a year (with perspective of extension to 7.5 bcm a year) [51]. Poland has already signed in 2009 a contract for 1.5 billion m³ of LNG for 20 years with Qatar. Although the price for Qatar's gas is higher than Russian, it is still beneficial to differentiate the sources of this fuel. Furthermore, in Poland there are nine storage facilities owned by one company PGNiG. Seven of them store high-methane natural gas (over 2.5 bcm) and two of them store nitrogen-rich gas (0.23 bcm) [52]. Given all the opportunities available, the actual dependence on Russian gas is decreasing and Polish prospects to negotiate terms of Yamal contract are becoming more and more real.

2.2.2.4 *High price of domestic coal*

Polish reliance on coal (hard coal and lignite) as the primary fuel for electricity and heat production is not unjustified. Poland has large own supplies of those fuels. As of 31.12.2013, the total geological resources of coal are presented in Table 4.

In 2015, according to data supplied by Agency of Industry Development [54], Polish mines produced 72.2 Mt of coal (0.3 Mt less than in 2014), sold 73.6 Mt (3.3 Mt more than in 2014) and 5.8 Mt were stored (3.6 Mt less than in 2014). Despite the increase in sale and significant decrease of employment (over 10 thousand employees less than in 2014 with almost the same level of output) the financial results of the sector were still dramatic. It is estimated, that in 2015 Polish mining sector lost out over €460 million [55]. It is caused by high cost of coal production and the uneconomical structure of employment. In 2013 51.2% of cost was incurred on the employment and 17.6% on external services [56], [57]. Because of this high inefficiency, since last quarter 2015 the price of extraction of a tone of hard coal was around 240 PLN - around 61 USD. Neverthe-

less, the average world-market hard coal prices in January 2016 was around 46 USD/t in Amsterdam-Rotterdam-Antwerp and 50.25 USD/t in Richards Bay in RPA [58] (approximately 25 % lower than the previous year). The decrease of the coal prices is caused by the reduction of coal consumption in China and warm winters that recently can be observed [59].

The situation of Polish mining sector is not going to improve in the nearest future. The market price of coal will constantly decrease as well as domestic consumption (because the efficiency of electricity generation gradually increases, and part of the share of coal in Polish energy mix must be replaced by low emissive technologies). Thus, the cost reduction is essential if Poland does not want to close its mines or constantly subsidize this sector.

2.2.2.5 *Energy from RES*

In 2014 14.8 % of capacity was installed in RES (6028 MW). As a result, RES were responsible for 8% of total electricity production (13 388.26 GWh). The structures of capacity installed in RES and their electricity production are presented in Figure 12 [60], [61].

64% of power production from RES fell to wind energy and next 17% to solid biofuels (Figure 12). For many years, cofiring of biomass became a cheap and easy way to increase revenues (because it was subsidized by a mechanism of ‘green certificates’ – a kind of guarantee of origin system) and reduced the theoretical CO₂ emissions (because it was treated as ‘zero emissive’ fuel). It was predicted that it would trigger large investments in biomass production in Poland, which was supposed to develop the agriculture sector, but despite high potential [62], it turned out that it is more profitable to import biomass from abroad [63]. In 2014 11.7% of solid biofuels consumption was imported (mainly from eastern Europe countries but also from Germany, Spain, Greece, Indonesia, Liberia, Togo, Ghana and others [64]–[66]), as a result, instead of supporting Polish economy, huge amount of money was transferred abroad. In addition, cofiring of biomass decreases the efficiency and lifetime of boilers that were primarily designed for coal-only combustion [67]. As a result, it is possible, that in the nearest future the decommissioning of old units will cause the decrease of total domestic energy production from RES which may result in not fulfilling European Union’s recommendations [68].

2.2.2.6 *Missing money and missing capacity problem*

As it was described in the Section 2.2.1, Polish power system needs immediate investments in new generating units. Existing conventional power plants have high fixed and variable costs (in comparison to subsidized wind energy with almost no variable costs). At the same time, the low prices of energy on the wholesale market (Table 5) and highly variable generation of those units (that are not designed to operate in such conditions) (Figure 13) cause that the generators are facing so called missing money problem (inability to cover their costs).

Their decreased time of operation does not allow for covering all expenses from the revenues from energy only market. The unpredictability of revenues deters potential investors, or even lead to closure of existing, inviable units, so the Polish power sector in the nearest future is going to face *missing capacity problem* – the situation in which not enough capacity is installed in the system to cover the demand [70]. First power outages appeared in August 2015 when high temperatures and low water levels on top of planned and unplanned outages (that exceeded 20% of predicted energy consumption in the morning of 10 August) caused the reduced available electricity supply for industrial users [71]. In the consecutive years, the power unbalances are likely to appear continuously [26], [72].

2.2.3 *Policy assumptions 2050*

The main targets of Polish Energy Policy 2050 (PEP 2050) were intended to create conditions for constant and sustainable development of the energy sector that should contribute to the economy growth, provide energy security in Poland and meet the energy demand of Polish enterprises and households. Proposal of the PEP 2050 was developed with assistance of the Advisory Team, which part were the authors of the manuscript.

The proposal consists of (a) Polish Energy Policy 2050, (b) Assessment of the PEP 2030, (c) Action Plan for 2015-2018, (d) Environmental Impact Assessment of PEP 2050 and (e) Perspective View for the Polish Energy Sector in 2050 – conclusions from the simulation analyses. The part “e” consists of the analyses prepared by the authors of this manuscript.

To achieve the main targets of the Policy, three separate operational objectives have been established (Table 6). The energy security, competitiveness of Polish economy and environment protection are the most important issues that must be taken into consideration while thinking about power sector development.

The operational objectives are very general and just point the imprecise measures (such as ‘limiting pollutions’) to achieve them. More detailed guidelines are presented in the nine priority projects that are listed below:

I. Effective utilization of domestic solid fuels sources

Since Poland has its own resources of hard coal and lignite – the energy generation must be based on those fuels to increase independency on foreign supplies.

The decreasing prices of hard coal in the world have reduced the competitiveness of Polish supplies. There is an urgent need for reducing the costs of Polish mining sector, otherwise Polish coal supplies would not translate into energy security. It is predicted that the development works of new ways of using coal for energy production will be intensified, what would ensure the availability of different technologies such as coal gasification or liquefaction. Gasified coal could constitute a substitution for the natural gas imports. Simultaneously, there are many works connected with development of better technologies for using the byproducts of coal extraction such as methane, water and heat.

II. Improvement of energy efficiency (including CHP)

The overall energy efficient index will be increased thanks to new highly efficient power generating units that will consequently replace older assets. It is also important to maximize the time of the operation of the efficient units during the year. Additionally, the grid losses should be minimized. Current grid losses in Poland reach 6.9%, while the average EU losses do not exceed 5.7%. Grid losses can be reduced through modernization and replacement of currently existing lines, replacement of electrical substations by more efficient ones, development of distributed generation and increase of the efficiency of final energy use.

The improvement of energy efficiency can be carried through the change in heat production and distribution. 75% of energy for the heating should be coming from CHP power stations, otherwise 50% of it should come from RES or waste heat. The district heating modernization or replacement in some cases and building insulation would contribute to the energy efficiency through the limitation of the heat losses. In the long-term perspective it is important to increase the popularity of low-energy buildings and household appliances.

III. Building nuclear power plant

According to PEP2050 part of the capacity installed in the Polish power sector will be covered by the nuclear power plant of minimum 6000 MW [74]. Although the project works have been already launched, the final rated power has not been yet finally specified, and the start of operation is constantly being postponed (according to different sources is scheduled for 2029 or even 2031) [75], [76].

IV. Unconventional gas

In the long-term perspective, the unconventional deposits of natural gas can play a crucial role in increasing the competitiveness of Polish economy. Thus, the works on searching the shale gas in Poland should be continued.

V. RES penetration

The increase of share of RES in the energy mix in Poland should be maintained. However, it is important to limit the impact of RES on the stability of energy sector. Thus, the techniques of energy storage or weather forecasting should be developed to make the RES generation more predictable and controllable. All subsidies for RES should be withdrawn by 2035. Polish energy sector by this time should develop a technique of renewable electricity generation that would be perfectly adjusted to Polish conditions and potential.

VI. Prosumers

Thanks to the further deregulation of energy sector as well as increasing accessibility and affordability of micro power plants, the resell of excessive electricity produced by private households will be possible. This phenomenon should be followed by the development of smart grids, that are adjusted to the distributed generation.

VII. Smart grid

The development of the transmission and distribution systems should also consider introducing smart grids and smart metering systems. It would allow for better communication between energy recipients and providers. Real time price signals would also increase the potential of DSR. The smart grid would allow for better management of grid, which result in increasing its security and reducing the costs of exploitation.

VIII. Interconnections

The development of the interconnections should be carried on three fields:

- Diversification of sources and directions of import of crude oil,
- Development of transmission grid interconnections,
- Diversification of sources and directions of import of natural gas. In the short-term perspective it is connected to finalizing the Swinoujscie LNG Terminal, in further perspective it is planned to construct the gas pipelines (provided for in the trans-European networks program).

IX. Development of power generating assets

Current analyses indicate the urgent need to increase the available capacity in the power system. The financial and regulatory incentives allocated to RES and cogeneration units, the need of purchasing CO₂ emission allowances and relative stabilization of electricity prices resulted in the reluctance of the investors to build new assets. Thus, to avoid missing capacity problem some mechanism to mitigate investment risks and increase the profitability of the investments in conventional and nuclear energy sector must be implemented.

One of the appendices to PEP 2050 [24] describes the Action Plan to achieve policy targets. It directly settles the tasks to achieve three main targets of PEP 2050 (operational objectives). Nevertheless, the action plan covers only the period 2015 – 2018 and it lacks the long-term strategic vision. The time constants in the energy sector are much longer than for other industries and therefore its problem cannot be solved or planned to be solved only in short-term perspective.

3 Mathematical modelling for development of energy policy

In the entire economy almost all sectors depend on each other (directly or indirectly). In order to assess the impact of any policy it is important to analyze its impact on the sector itself and then on the whole economy. In most cases both tasks: sector analyses and cross-sector analyses, the economics provides tools that can be successfully used. However, there are some sectors of the economy, that cannot be analyzed and for which the policy impact cannot be assessed only on the basis of econometric tools. These are the very technical branches such as energy and power sector. Primary objectives of these sectors operation relate to the technical standards and requirements, while the market rules are the secondary issue. Therefore, while assessing the impact of energy policy it is essential to properly investigate the sector operation and the effects of the policy on the sector itself. The second step may relate to impact assessment of the policy on the other sectors and entire economy. Analyzing the PEP 2050, the authors of the manuscript developed the sector model to define the directions of the energy policy for the power sector.

This chapter consists of a brief summary of the existing approaches to this task, that were considered in the development of model for optimization of Polish energy mix and description of the model itself.

3.1 Different approaches

Until now there have been many models developed for energy system modelling. Nevertheless, the need for appropriate model that would be able to represent the important technical details of the power system operation and face the challenges of twenty-first century energy systems (with high RES penetration) has not been satisfied yet [77]. It is essential for such models to link long-term energy planning with consideration of short-

term variability of intermittent generation [78]. Connolly et al. made a review of models created to analyze the future operation of energy systems with renewable generation [79] and many scientists around the world are continuing researches on this topic.

Some of them are carrying researches over satisfying all energy needs from renewable generation in particular areas. The Ostegaard et al. analyze the possibility of covering 100% of energy needs of Aalborg Municipality in Denmark from renewable energy sources with commercial EnergyPLAN model (deterministic, input-output model) [80]. The same was done for whole Denmark [81], Ireland [82] and Macedonia [83]. Other researches examined the 100% RES penetration with other computation tools e.g. in [84] the authors are using H₂RES software (model for energy planning in isolated regions – further description in [85]) for Portuguese [84] power system or Mathlab for New Zealand's power system [86].

Other optimization models are used for power systems with mixed conventional and renewable generating assets. Tolis and Rentizelas [87] created quadratic programming optimization model for energy system planning (for case of Greece power sector) maximizing total Net Present Value subjected to social, and technical constraints taking into account electricity and emission allowances pricing. In [88] there is a linear programming model for electricity generation planning in Greece taking into account life cycle external cost. Tahir and Banares-Alcantara [89] used linear programming energy mix optimization model with knowledge representation module that transforms energy policy assumptions into equations representing technology preference. In [90] there is a description of Chinese power sector planning model minimizing the accumulated total cost with consideration of CO₂ emissions mitigation. Pina et al. [91] developed hybrid modelling method for electricity systems development planning with high RES penetration (e.g. Portugal) using long-term TIMES and short-term EnergyPLAN. In [92] the authors decided on least-cost energy planning of United Arab Emirates energy system using linear MARKAL optimization model. MARKAL model was also used in [93] for energy system optimization to examine the impact of shale gas supply and energy policy on the USA system. In [94] the authors presented two-stage stochastic energy planning model taking into account financial risk related to over and underproduction (case study - sub sector in Ontario). [95] shows a MILP model for electricity generation optimization taking into account life cycle cost and environmental aspects. Another MILP model for transmission expansion planning (using Benders decomposition) is showed in [96]. MILP modelling was also used in [97] for generation expansion planning with sensitivity analysis (for Greece case study) calculating total electricity demand, total cost composition, power and electricity production structure, investment cost for newly-built, total CO₂ emissions and electricity flows between zones. In [98] there is a multiperiod disjunctive optimization model presented for planning investments in energy sector by total Net Present Value maximization. The model takes into account technical and economic aspects of power system operation and is applied to Argentina.

Most times the MILP programming is used for small, distributed generation systems such as in [99], [100]. In [101] authors used MILP model for distributed storage coordination (that can be used for: price arbitrage, active/reactive power control, profit maximization and balancing services) that maximizes storage's net profit. The review of micro-grid planning systems is made in [102].

3.2 Model description and assumptions

The authors, for the purpose of PEP 2050 development, designed a technical optimization model – *eMix*, representing the generation expansion planning in the Polish power sector. In the contrast to the economic approaches (general market equilibrium etc.) it focuses on the technical aspects of the power system operation linked with its operation costs. The model incorporates representation of every single unit in the power system and calculates the optimal energy mix to 2050 with one year interval. Single unit representation requires application of Mixed Integer Linear Programming and makes the model unique among other this kind models. It was already widely discussed not only in the energy sector (e.g. Government administration, Transmission System Operator, Distribution System Operators) but also in academic journals [5], [6], [103]–[105]. Below, only essential summary of the model assumptions is presented.

The objective function (1) represents the total costs of units construction and operation consisting of fixed costs $CF_{u,t}$ and variable costs $CV_{u,t}$. Fixed costs include construction cost with financial and fixed operation and maintenance costs. Variable costs consist of variable operation and maintenance costs and cost of fuel and CO₂ emission allowances. The *eMix* calculates the annual financial burden for the power plants. It provides better approximation of the power sector operation, where investments are made thanks to the banks' loans

and external funds. Such formulation enables the implementation of bank loan and interest rate that lead to more reliable results.

Index u in formula (1) represents the particular power unit and t stands for the year in assumed horizon. Component $P_{I_{u,t}}$ denotes the installed power capacity of generating unit, X_u is the binary variable that represents the unit's presence in the energy mix and $E_{u,t}$ is the real variable representing electricity generation of unit u in year t .

$$\min \sum_{u \in U} \left(\sum_{t \in T} (X_u \cdot P_{I_{u,t}} \cdot CF_{u,t} + E_{u,t} \cdot CV_{u,t}) \right) \quad (1)$$

subjected to:

$$\forall u \in U \quad X_u = 0 \text{ or } 1 \quad (2)$$

$$\forall u \in U, \forall t \in T \quad X_u = 1 \Rightarrow E_{u,t} > 0 \quad (3)$$

$$\forall u \in U, \forall t \in T \quad X_u = 0 \Rightarrow E_{u,t} = 0 \quad (4)$$

Formula (2) defines the binary variables. When X_u equals "0" it means that unit u does not exist in the mix, when it equals "1" the unit is constructed and is able to operate. More detailed formulation of binary variables is presented in [106]. Equations (3)-(4) present the relation between binary and continues variables. They denote that power unit can only produce energy if it exists in the power system in particular year t .

Main constraints of optimization model are presented in equations (5)-(7).

$$\forall t \in T \quad \sum_{u \in U} P_{A_{u,t}} \geq P_{D_t} + K_PRESERVE_t \cdot P_{D_t} \quad (5)$$

$$\forall t \in T \quad \sum_{u \in U} E_{u,t} = E_{D_t} \quad (6)$$

Unlike majority of existing models, *eMix* optimizes both power and energy balance that are defined exogenously. (5) represents that in each year t total available power of generating units $P_{A_{u,t}}$ (it is usually lower than installed power) has to cover the prospective annual peak load P_{D_t} with required power reserve (usually 18% of average annual demand). Formula (6) presents the energy balance where total electricity generation in each year has to be equal to planned energy demand E_{D_t} . The assumed values of power and energy demand in long-term perspective are presented in Table 7. According to the peak load, the authors decided to follow the prognosis prepared by the Department of Strategic Analyses of Chancellery of the Prime Minister of Poland [22] presented in Figure 8.

The electricity generation from particular unit has to be between minimal and maximal level (7). In *eMix*, the upper limit $E_MAX_{u,t}$ results from technical parameters of unit u . The minimal electricity generation $E_MIN_{u,t}$ means the volume of energy that has to be generated and sold to cover the fixed costs of the unit.

$$\forall u \in U, \forall t \in T \quad E_MIN_{u,t} \leq E_{u,t} \leq E_MAX_{u,t} \quad (7)$$

eMix includes the large power units (CDGUs), RES and nCDGUs (CHP and industrial plants) with their typical technical and financial parameters (database of type series). The CDGUs are implemented as individual units using MILP, while RES are optimized linearly considered as a group of units that is brought together according to technology.

4 Scenarios for the energy mix development for Poland

Scenarios analysis, which part is presented in the manuscript, is included in part "e" of the PEP 2050: (e) *Perspective View for the Polish Energy Sector in 2050 – conclusions from the simulation analyses*. It presents the case study carried out for the Polish power system to estimate the prospective energy mix up to 2050. The calculations were carried out using *eMix* optimization model and results constituted a basis for the assumed final scenarios of Polish energy mix development (see Section 4.4).

4.1 Calculation scenarios

Authors upon request of Ministry of Economy, calculated dozens of simulation scenarios in order to verify the impact of particular decisions and external requirements to the final energy mix. In the manuscript, the authors' selection of the scenarios is presented as the most valuable and interesting. The scenarios differ in the aspects that highly influence the prospective shape of the power system in Poland, i.e. European Emission Allowances (EUA) price, the required level of the electricity generation from RES and the construction of the first Polish nuclear power plant according to Polish Nuclear Power Program see Section **Error! Reference source not found.**). As the future of the Polish power system also depends on the gas price, Table 8 presents the assumed gas price (350 \$/1000m³) that is equal for all scenarios. It is higher than current price (see Section 2.2.2.3), but the uncertainty of a gas prices and their dependence on the political decisions do not provide reasons for very low estimations for prices. Especially, that prices for Poland in last decades was the highest in Europe. Moreover, the scenarios differ in the implementation of the learning rates for the RES.

Reference scenario is S1. It assumes the increase in the EUA price starting from 15 €/tCO₂ in 2020 to 40 €/tCO₂ in 2050. Although the current price of CO₂ emissions allowances is around 9 €/tCO₂, such an increase is highly expected due to regulations overtaken in the EU ETS, especially introduction of the market stability reserve (MSR) [108]. The RES requirement is kept at the 19% of the total electricity generation. It is a transformation of the EU requirement of 15% share of RES (for Poland) in total energy consumption to the requirements for RES share in electricity consumption.

S2 assumes the implementation of the Polish Nuclear Power Program, i.e. the construction of 4x1600 MW nuclear power plant with a 2-year interval between each unit, beginning from 2029. It is considered as the political decision. The scenario S3 introduces ultra-high CO₂ emission allowances prices growing up to 90 €/tCO₂. Verification of the energy mix with high RES share is made within scenario S4. It assumes the linear growth of the minimal share of RES penetration starting from 19% in 2020, then 27% in 2030 (EU Energy Policy 2030) and 50% in 2050.

To address the increasing expansion of the RES in the global power systems, the scenarios S5 and S6 have been introduced. They assume the prospective development of the technology that will lead to the cost reduction of the RES in the presented time horizon. The S5 and S6 introduce the learning rates for the RES that represent the decreasing construction cost. In S5, the input parameters are assumed as in reference scenario, while the S6 represents high EUA price as in S3. Additionally, in the S5 and S6 there is no requirement for the minimum RES electricity generation and the PV potential is unlimited.

4.2 RES potentials and learning rates

The important input parameter that determines the maximum capacity of particular technology is the capacity potential. The value of this parameter is strictly related to the modelled power system and is particularly important for the RES development. It depends on the legal regulations (e.g. Polish law that imposes the minimum distance requirement between new wind turbines and buildings or natural protected sites) and the geographical location of the country that defines the wind speed or the sunlight exposure. In eMix the assumed potentials for the RES in Polish power system are presented in Table 9. Moreover, the presented model imposes the maximum, annual amount of the capacity for particular technology that can be commissioned in one year. This parameter is the result of the economic and technical constraints, e.g. the investors capital capacity for new investments or the restrictions to integrate new power units to the grid. The only way to implement such a limitation is direct cap put on the power capacity potential and its allowable annual increase.

Table 9 also presents the learning rates for the RES that denote the annual, relative decrease of the construction cost. The value of this parameter has been assumed according to [22] for PV, wind turbines and biogas units.

4.3 Results of optimal energy mix

The presented simulation results cover: installed power capacities: Figure 14-Figure 19, electricity generation: Figure 20-Figure 25, CO₂ emissions: Figure 26, primary fuel consumption: Figure 27, Figure 28 total cost of electricity generation: Figure 29, Figure 30 and marginal cost for electricity generation: Figure 31.

In all scenarios, the beginning of the optimization horizon is determined by the existing (before 2020) structure of the Polish power system. Therefore, the starting point for the optimization is high coal based power system with the 25GW power capacity installed in this type of technology. However, the capacity of lignite and hard coal units in all scenarios is decreasing over the years and reach 5.5 GW in 2050.

In S1, after decommissioning of majority of coal-fired units, the dominant technology the gas become. Due to increase in the EUA price, the capacity of gas-fired power units reach 33 GW that is over a half of total installed power in the system. Among the RES, the largest share belongs to wind turbines, as it is the least expensive RES technology. Wind onshore units reach their maximum capacity limit (16 GW) in 2035. In consequence, the second least expensive RES technology is developed – PV. It is worth to be noticed, that there are no learning rates for RES in S1. Therefore, the only reason, for which RES enter the mix, are the external requirements coming from policy options. RES themselves are too expensive in comparison to other conventional technologies. The installed power in S2 corresponds to this in the S1 but the construction of nuclear power plants (derived from the political decisions) causes the downturn in expansion of new gas-fired units. The high EUA price, as in S3, changes the installed power in the system dramatically. At the beginning of the optimized period over 6 GW of gas-fired capacity is constructed. The nuclear power units do not appear in the power system, until the EUA price is very high. According the results obtained within the *eMix*, EUA must cost around 80-90 €/tCO₂ to justify investment in nuclear technology. It is caused by very high overnight costs and high costs of the capital with long construction period (Scenario S3). Despite high CO₂ emission allowances price, the RES still enter the mix only to fulfill the energy policy requirements. Scenario S4 presents how the Polish energy mix would look like in case of high share of renewables. The structure of RES is diversified and the order of technologies entering the mix depend on overall costs of electricity generation. The reason why more expensive technologies appear, instead of the least expensive, is the hosting capacity of the national power system to accommodate particular technology and renewable energy resources that are implemented in the model. It can be seen that wind onshore and PV units reach their maximum potential of 16 GW.

The scenarios S5 and S6 represent the energy mix with learning curves for the RES that decrease their construction cost (see 4.2). It should be noticed that these scenarios do not include the forced requirement for RES electricity generation. Therefore, the commissioning of each unit in the system (including RES) is the result of cost minimization. Moreover, the authors decided to remove the cap for the PV technology when the limits for other RES are maintained at the same level as in S1-S4. In S5 the input parameters are as in reference scenario. Therefore, the installed capacity of conventional power plants is at similar level as in S1. The difference can be seen in the RES capacity that in S5 is even lower than in S1. The only technology among RES that is cost effective is wind onshore but it reaches its cap of 16 GW after 2040. The decreasing construction costs of PV and biomass units do not make these technologies profitable. The situation is different in S6, where the high EUA price causes the large development of RES. The wind onshore reaches its cap in 2025 and is kept at this level to the end of the time line. After 2035 the large development of PV units is observed. The total capacity of PV reaches the level of 30 GW in 2050.

Figure 20 – Figure 25 present the electricity generation among scenarios as a percent of a total electricity generation. The red line denotes the assumed annual energy demand that increases annually by 0.9%. The results of scenarios S1, S2, S4 and S5 show that before 2030 there is a sharp drop in the energy production from coal technologies caused by the increase of EAU price. According to obtained results, if price is higher than 40 €/tCO₂, the gas-fired units are more competitive than coal-fired ones, even for the baseload operation, regardless the high variable costs. In scenario S2, the introduction of nuclear power units denotes a decrease in the electricity generation from gas units because of lower variable cost of nuclear technology than the other conventional units. In scenarios S3 and S6, from the very beginning the energy production from gas units is high and reach almost 20% of total electricity generation. The expansion of nuclear power units causes that in 2050 almost 40% of energy is produced by these units. In scenarios S1-S4, the energy production from RES is not higher than required levels but in S5 it is the lowest among all scenarios. In S5 the share of RES in total electricity generation is lower than 10% before 2030. Then it grows to about 15% in 2050. It is a result of the lack of the minimum requirement of RES electricity generation. Only wind onshore technology is commissioned even though the construction costs of other RES are decreasing with time. The S6 shows that the other RES technologies are cost effective when there is a high EUA price. The large development of PV units after 2035 causes that the share of the RES equals over 30%.

Figure 26 presents that every scenario results with a decrease in the CO₂ emissions. In almost every scenario the imposed requirement by EU of 43% CO₂ emissions reduction after 2030 is fulfilled (in Poland it means -40% in ETS sector in comparison do 2005 and the emissions below 103 million tCO₂). Surprising is the fact that the highest emissions occur in scenario S4 (high RES share). This situation is due to large share of biomass technology in the total electricity generation. Depending on approach, emissions from biomass are not considered in carbon dioxide final balance, however emissions during burning the wood pellets occur. The lowest CO₂ emissions are in scenario S6 where there is a large development of both nuclear power units and carbon-free RES technologies (wind onshore and PV).

The primary fuel consumption presented in Figure 27 and Figure 28 shows the gradual switch from the lignite and hard coal consumption to the gas. The gas use only for electricity generation in S1 or S5 equals 43-45 billion m³, what stands for a great challenge for the Polish economy to ensure such a large gas volumes, which in majority has to be imported. However, commissioning of nuclear power units as in S2, S3 and S6 denotes the gas consumption at the level of 13-25 billion m³. The similar effect is triggered in S4 by the high development of renewables. Execution of any scenario will required large effort for the economy to adjust associated sectors especially for providing new sources for the gas import, strengthening the gas transmission system, increasing liquidity of a gas market and establishing the base for the nuclear industry, which in Poland does not exist.

The structure of total costs of the power system divided into: financial, fixed and variable O&M, fuel and CO₂ emissions allowances costs is presented in Figure 29 and Figure 30.

The need for the new investments in the Polish power system causes the capital and financial cost of almost every scenario is increasing. Only in S5 the financial cost slightly decreases after 2040. In S1, with high investments in gas-fired units, the main costs' component is the fuel. In other scenarios, the financial cost dominates, due to a construction of nuclear power plants or renewables with high CAPEX. The impact of the high CO₂ prices on the total costs in the power system is highly evident in S3 and S6 in 2020. To mitigate this impact in the following years, the structure of the power system has changed to low-emissive technologies. Finally, the marginal cost for electricity generation (Figure 31) presents the possible impact on the energy prices for the energy consumers. Due to transformation needs towards more sustainable energy mix, every development scenario is associated with increased marginal cost of electricity. In the long-term perspective, prices at the markets converge to the costs of production. Hence, electricity price for the final consumers will go up in the future. Electricity sector must be transformed and it cannot be achieved at current costs.

4.4 Final 2050 Policy Scenarios for Poland

The final shape of the energy policy for Poland will depend on administration and government actions. On the basis of results presented, final shape of the energy policy (actual for the April 2016) were developed and scenarios for energy mix were assumed. Policy makers must take into account the following issues:

- The pursuit of constraining the negative impact of energy sector on environment
- Already accepted European Union policies that concern particular elements of energetic sectors
- Current state of discussion on the further development of situation in particular areas of power system in Poland that involve:
 - The costs and range of using the domestic supplies of hard coal and lignite
 - Possible development of nuclear energy sector in Poland
 - Potential of unconventional gas supplies extraction
 - Potential of unconventional energy sources

Energy policy assumes three competitive scenarios for the energy mix development. The first one is a reference scenario that assumes that the current trends in energy sector will remain the same. The next two scenarios are auxiliary scenarios and constitute analytical variants. The auxiliary scenarios are embedded on the existing structure of generating assets and its probable change.

4.4.1 Common assumptions

For all scenarios it is assumed, that the transmission and distribution grid will expand. In 2050 perspective, all grids will be the smart-grids. As a result of implementation of internal energy market in Europe, the interconnections will be strongly developed – their capacity will constitute a significant percentage of capacity in-

stalled in the system. After 2035, the subsidizing for RES will be withdrawn and those technologies will have to be able to achieve economical independency. The Program of Polish Nuclear Energy in the accepted shape will be realized. Each of the scenarios assumes the continual increase of energy efficiency be it the efficiency of energy sector or heating, housing and final use of energy. The energy market will also change drastically. Those changes will result from:

- The increase in number of prosumers (mostly those with micro generation) – their expansion will be facilitated thanks to the limited restrictions related to the integration with distribution lines
- Incentivizing the DSR – the industrial consumers will be providing their DSR services for operators directly, while the household consumers through the integrators
- Rationalization of energy consumption that can be accomplished given to the Advanced Metering Infrastructure – the real-time electricity pricing will encourage the electricity recipients to become more active and responding consumers. It will be also possible to store energy in the electric vehicles.
- Increasing flexibility and diversification of offers of electricity sellers that will be having access to the data from abovementioned meters. It is expected to introduce the possibility of demand reduction and prepaid offers that would be functioning similarly to the pay-as-you-go mobile offers.

4.4.2 Sustainable scenario

This scenario is a most probable scenario and is very close to the calculated within the *eMix S2* scenario. In the sustainable scenario, the Polish energy balance in 2050 will be comparable to the one established in 2035. This scenario also assumes the maintenance of the significant (however limited in comparison to present situation) role of coal and crude oil and a moderate growth of importance of natural gas. The RES will expand their share in the energy mix. It would among other things result from:

- European energy policy that assumes the 10% of RES share in production of transport fuels and 15% in primary energy balance (up to 2020)
- Targets concerning reductions of CO₂ emissions
- Construction of two nuclear generating units of total 6400 MW that would constitute 12% of primary energy.

The RES expansion could be nevertheless more profound than it has been predicted. EU and global resolutions on environmental issues are very important stimuli, and their precise impact hard to predict. The sustainable scenario assumes:

- The sustainable extraction of solid fuels including extraction of new deposits at the lowest possible costs but with regard to future generations' needs. The mining sector must undergo a change that will increase its productivity. This can be achieved through reorganization of the existing assets and alternatively through the development of new technologies of mining. Because the already being exploited deposits are becoming exhausted or more and more problematic to make use of, some new mines will have to be created.
- Realization of nuclear energy plan. Polish nuclear energy sector needs specialized staff and investments in the research and development branch.
- Realization of subsidizing plan for RES and cogeneration as well as development of prosumers sector and micro-generation.
- Increase of the share of gas in energy production. This target can be accomplished through: education of the staff that would coordinate the LNG terminal, subsidizing the use of natural gas in transport and doing researches on the shale gas extraction.
- Increasing the energy efficiency of economy (industry and final consumers).
- Investment in new conventional power plants that would take advantage on domestic natural supplies. The share of coal in energy production should be followed by the development of clean coal technology.

This scenario allows for fulfillment of European Energy Policy goals as for the reduction of greenhouse gases emission thanks to the increase in share of RES, implementing the nuclear power plant, increase of the energy efficiency of energy production, transmission and use and the use of clean coal technology.

4.4.3 Alternative nuclear scenario

The nuclear scenario assumes the expansion of nuclear power energy that would constitute up to 60% of total energy produced. This scenario involves huge long-term investment on the realization of nuclear plan, but

those expenses could be compensated by the low nuclear fuel prices, independence from liquid fuel imports and the reduction of costs resulted from the need of buying CO₂ emission allowances.

The share of particular technologies in energy production is predicted to be as follows: nuclear energy 40-60%, hard coal and lignite 10-15%, crude oil 10-15%, natural gas 10-15% and RES 15%. The scenario requires the construction of more than one nuclear power plants. Their allocation should be profoundly considered and take into account the allocation of conventional units. The growth in electricity production from uranium will result in the reduction of use of liquid fuels in transportation and the extraction of coal. The RES will be limited to the distributed micro-generation for prosumers purposes.

4.4.4 *Alternative gas+RES scenario*

The gas+RES scenario assumes the combined share of those two technologies to reach 50-55% in 2050. Those two technologies complement one another, since gas units are flexible units and can be launched in short notice when the intermittent generation does not produce. The share of particular technologies in energy production is predicted to be as follows: gas+RES 50-55% (at least 20% of RES), hard coal and lignite 15-20%, nuclear 12%.

The gas supplies would be extracted from conventional and unconventional deposits in Poland, but also from LNG terminal, Yamal pipeline and interconnectors. The growing share of gas fueling in transportation would also limit the dependence on imported crude oil. Gas would also become more popular among individual consumers – both households and industries. This scenario requires further development of gas transportation infrastructure and storage systems since the demand for the gas increase sharply in the winter periods.

5 Conclusions and Policy Implications

The paper analyses the situation of the Polish energy sector – underinvested and coal-based – which has to face EU energy and climate policy and undergo a transformation to more sustainable and diversified one in a very short time. Policy makers in Poland, being aware of the challenges, started to implement actions towards energy sector and especially power system reforms and the effect of those actions is proposal of the Polish Energy Policy 2050, described in the paper. Authors of the manuscript had an opportunity to support a development of the policy as the part of advisory board, being responsible for the modelling and analyzing the impact of various assumptions for the future energy mix in Poland. Decisions about the final policy assumptions are left to the politicians.

In the manuscript, authors presented selected scenarios for the Polish energy mix transformation, driven by the assumed decisions concerning the sector, fulfilling the ideas of EU energy and climate policy - mainly decarbonizing. Generally, scenarios can be divided into two groups: without any learning rates and with learning rates for the RES. Moreover, the scenarios with learning rates for renewables include no limit for PV potential that can be found as a technology with high possibilities to develop in the Polish power system. According to the obtained results, the highest reduction in CO₂ emissions provides energy mix based on nuclear power plants. The lower decrease in emissions provides scenario with high share of renewables without any learning rates. It is a result of the potentials imposed on the RES technologies. When carbon-free technologies (mainly wind turbines and PV) reach their capacity limit, the biomass and biogas units are commissioned. While the nuclear investments are activated by the very high price of EUA (90 €/tCO₂), the highest cost of the electricity production occurs in energy mix with high share of renewables without any learning rates. It shows that investing in renewables with current capital costs and limited potential of particular technologies is although environmental friendly, also the most expensive and provides the least reduction of CO₂ emissions. However, the scenario with high EUA price and learning rates for RES shows that the decrease in the capital costs of RES and increase of PV potential will give the lowest CO₂ emissions among all scenarios. It indicates that in future, and with some additional measures (high EUA prices) RES units may become fully competitive to the conventional electricity sources. In fact, assuming subsidies for RES it could be earlier that results indicates, as the optimization model does not consider subsidies, but only pure investment costs (with credits). All of this alternative scenarios are very dangerous for Polish economy, because of being most expensive. In addition, they would require high expenditures in the electricity sector up to €20 – 25 billion annually in 2050 and would result in growth of electricity prices above 100 €/MWh. BAU scenario, assuming aligning with the EU policy at the least costs is a very interesting scenario. Assuming the EUA prices at 40 €/tCO₂, this scenario provides over 30% reduction in CO₂ emissions in 2030 in comparison to 2020, and keeps the electricity prices below 80 €/MWh. Nevertheless, this scenario would require switching the power sector to gas, which taking into account the unpredictable gas supply and its prices is very risky. Additionally,

this scenario would require expansion of the gas transmission system and searching for new gas suppliers, as a gas consumption only for power sector would grow from 1 mld m³ (2020), 26 mld m³ (2030) to 46 m³ (2050). It can be achieved observing continuous development of LNG infrastructure and gas market in Europe.

Results of the analysis summarized above are reasonable and clearly indicate, that it is not possible to integrate all the possible technologies in the Polish power sector. As the current basis is coal and lignite technology, any other will require not only the investments in power plants but also investments in the auxiliary sub-sectors dedicated to them. For example, switching to gas – investments in gas infrastructure, switching to nuclear – development of the entire nuclear industry as Poland never used this technology. Providing the high penetration of RES would require back-up capacities, grid extensions and maybe development of own technologies to prevent from transfer all funds abroad to the technologies suppliers. Therefore, it is highly important to indicate the path, which Poland would follow in the future. This path must be clear, stable and fully supported by the government to provide good framework for the operation for the sector's actors.

Unfortunately, proposal of Polish Energy Policy 2050 does not fulfil described requirements. PEP 2050 only briefly diagnoses the problems of energy sector in Poland but does not provide any solutions. It does not define the clear path for development and transformation, which could be used for construction of adequate mechanisms and measures to achieve the objectives. Three alternate scenarios described in the proposal of policy are only hypothetical and the policy is not followed by any important decisions. In the policy it is even stated “the future shape of the energy mix is dependent on the decisions that were already made”, what means that at the moment there is no clear plan for the future of Polish energy sector transformation. Moreover, the Execution Plan, being a part of a policy, do not enter the long-term perspective and focuses only on the three following years. It does not indicate any tools or mechanisms that should be incorporate to support the energy sector operation.

Policy does not investigate:

- a. any actions towards new market design, suitable for the RES and conventional units,
- b. actions towards secure and predictable operation of electricity interconnectors to suppress the loop flows and transit flows,
- c. problems relating the prosumers development,
- d. innovative approach to local energy balancing, increasing the responsibility of Distribution System Operators in power system balancing,
- e. opportunities to use the energy sector as a leverage for the economic growth and increase of the GDP,
- f. Supporting the national technologies for electricity generation (RES and conventional) and preventing from transferring all expenditures to foreign manufacturers,
- g. Social problems, connected with very large mining industry, which would not be needed if Poland leave the electricity generation based on coal,
- h. High prices of electricity that is extremely dangerous for energy intensive industries.

Polish energy sector based on inefficient usage of coal must be transformed according to the requirements of EU energy and climate policy. Nonetheless, strong attachment to the coal causes that transformation cannot be achieved overnight and requires a series of responsible decisions. Development of these decisions should involve multidisciplinary analyses indicating not the least expensive and the easiest solutions but those which will have the best impact on the entire economy.

Acknowledgements

The authors would like to thank the Department of Energy at the Ministry of Economy for invaluable remarks from perspective of government administration and policy makers during process of development of Polish Energy Policy 2050.

The authors would like to express the gratitude to the FICO® corporation for programming support and provision of academic licenses for Xpress Optimization Suite to Institute of Electrical Power Engineering at Lodz University of Technology.

The authors would like to thank Prof. Władysław Mielczarski, also involved in the consultation of the Energy Policy 2050 for Poland, for his supervisory and the paper review.

The authors would like to thank the Lodz University of Technology Computer Center as the calculations mentioned in this paper were performed using the PLATON project's infrastructure.

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Figure 1 Gross power generation in EU-28 in 2014 [7]

Figure 2 Domestic energy production and consumption in GWh for 1990-2014 [13], [16]

Figure 3 Capacity available in 2014 (left) and energy production (right) [13], [16]

Figure 4 Capacity installed in 2014 (left) and capacity available (right). CDGU - Centrally Dispatched Generating Units, nCDGU - not Centrally Dispatched Generating Units [17]

Figure 5 GDP growth and electricity intensity of Polish Economy [18]

Figure 6 Future electricity demand in Poland according to ARE, Department of Strategic Analyses and assumptions in PEP2050 [21], [22]

Figure 7 Age of boilers and turbo generators in Poland [23]

Figure 8 Historical data and forecast of power demand in Poland according to Ministry of Energy, Department for Strategic Analyses and own study [22], [27], [28]

Figure 9 Reserves and power deficit (own development based on Polish TSO data [30])

Figure 10 Power deficits (own development based on Polish TSO data [30])

Figure 11 Gas interconnections: black – existing; grey – planned/under construction[109]–[111]

Figure 12 Structure capacity installed in RES (left) [60] and electricity generated by RES (right)[61]

Figure 13 The electricity generation in January 2016 (own development based on [73])

Figure 14 Installed power [GW] – S1

Figure 15 Installed power [GW] – S2

Figure 16 Installed power [GW] – S3

Figure 17 Installed power [GW] – S4

Figure 18 Installed power [GW] – S5

Figure 19 Installed power [GW] – S6

Figure 20 Electricity generation [%] – S1

Figure 21 Electricity generation [%] – S2

Figure 22 Electricity generation [%] – S3

Figure 23 Electricity generation [%] – S4

Figure 24 Electricity generation [%] – S5

Figure 25 Electricity generation [%] – S6

■ 2020 ■ 2030 ■ 2040 ■ 2050

Figure 26 CO₂ emissions [mln t CO₂]

Figure 27 Primary fuel consumption [mln t] for lignite and hard coal; [mld m³] for gas – scenarios S1 – S3

Figure 28 Primary fuel consumption [mln t] for lignite and hard coal; [mld m³] for gas – scenarios S4 – S6

Figure 29 Total annual cost of electricity generation [mln €] – scenarios S1 – S3

Figure 30 Total annual cost of electricity generation [mln €] – scenarios S4 – S6

Figure 31. Marginal cost for electricity generation [€/MWh]

Table 1 Comparison of energy policies for 2020 and 2030 targets [9].

20-20-20 (enacted in 2009)	Energy policy 2020-2030
20% of greenhouse gases reduction in comparison to 1990	40% of greenhouse gases reduction in comparison to 1990
20% of share of RES in energy consumption (15% for Poland)	27% of share of RES in energy consumption
20% improvement in energy efficiency	27% improvement in energy efficiency compared to the projected efficiency for 2030 if the situation would not change

Table 2 Schedule of CDGU power plants decommissioning (own development)

2013-2020		2021-2030		2031-2040		2041-2045	
	MW		MW		MW		MW
Adamow	600	Jaworzno III	1350	Belchatow	1870	Belchatow	1850
Belchatow	740	Kozienice	675	Dolna Odra	908	Opole	763
Dolna Odra	454	Laziska	905	Kozienice	1570	Turów	522
Kozienice	660	Ostroleka	447	Opole	769	Lagisza	460
Lagisza	360	Polaniec	450	Patnow 1	880	Siersza	306
Laziska	250	Rybnik	900	Polaniec	1125		
Ostroleka B2	200			Rybnik	875		
Patnow 1	400			Turow	966		
Siersza	360						
Skawina	440						
Stalowa Wola	240						
Zeran	244						
Σ	4 948	Σ	4 727	Σ	8 963	Σ	3 135

Table 3 Polish interconnections [34], [40], [41]

Interconnection	Capacity
Germany	
Krajnik - Vierraden	2x408 MVA
Mikulowa - Hagenwerder	2x1386 MVA
Czech Republic	
Dobrzyn - Albrechtice	1386 MVA
Wielkopole - Nosovice	1386 MVA
Kopanina/Bujakow - Liskovec	2x400 MVA
Slovakia	
Krosno - Lemesany	2x831 MVA
Ukraine	
Zamosc - Dobrotwor	415 MVA
Rzeszow - Chmielnicka	out of order
Belarous	
Bialysto - Ros	out of order
Sweden	
SwePol DC Link	600 MW
Lithuania	
LitPol DC Link	500 MW

Table 4 Hard coal and lignite resources in Poland [53]

Hard coal	
In-balance: 51,4 billion Mg	Recoverable: 19,5 billion Mg
	Non-recoverable: 27,9 billion Mg
Out-of-balance: 19,1 billion Mg	Recoverable: 7,9 billion Mg
	Non-recoverable: 10,5 billion Mg
Lignite	
In-balance: 22,7 billion Mg	Recoverable: 1,5 billion Mg
	Non-recoverable: 21,2 billion Mg
Out-of-balance: 3,5 billion Mg	Recoverable: 0,1 billion Mg
	Non-recoverable: 1,4 billion Mg

Table 5 Average monthly prices in March 2016 in Poland [69]

	€/MWh	Description
Monthly Base Price	34.4	Contract for 1 MWh of electricity supply for each hour of a day
Monthly Peak Price	37.78	Contract for 1 MWh of electricity supply between 7:00 a.m.-10:00 p.m.
Monthly Offpeak price	28.02	Contract for 1 MWh of electricity supply between 0:00-7:00 a.m. and 10:00 p.m-0:00

Table 6. Key operational objectives of PEP 2050

I	Providing energy security	<p>According to Polish law, the energy security is a state of economy that allows for covering the long-term demand on fuels and energy in a technically and economically grounded manner.</p> <p>To improve the energy security, it is important to focus on:</p> <ul style="list-style-type: none"> - Diversification of primary energy sources and their import directions - Providing adequate capacity installed and diversification of the structure of final energy generation - Effective utilization of domestic solid fuels sources (and their conservation to enable their extraction in future) - Stimulation of DSR development - Preservation and development of transmission and distribution systems - Defense of critical infrastructure
II	Increasing competitiveness and energy efficiency of Polish economy	<p>To improve the competitiveness and energy efficiency of Polish economy, actions must be taken to:</p> <ul style="list-style-type: none"> - Rationalization of primary energy cost - Development of the competitive electricity and gas markets in accordance with EU policies - Improvement of energy efficiency in enterprises, heating systems and final energy use
III	Limiting the impact of energy sector on the environment	<p>Limiting the impact of energy sector on environment can be achieved through:</p> <ul style="list-style-type: none"> - Limiting the greenhouse gases emissions - Limiting the air, water and soil pollution - Increasing the share of RES

Table 7. Prospective energy demand and peak load, own study based on ([22], [27], [107])

Years	2020	2030	2040	2050
Energy demand [TWh]	172.7	188.9	206.6	226.0
Peak load [MW]	27 562	30 748	34 303	38 268

Table 8. Scenarios definition

No	Description	EUA price [€/tCO ₂]	RES requirement	Execution of nuclear program (political decision)	RES learning rates
S1	Reference scenario – Business as Usual	15-40	19% (all horizon)	NO	NO
S2	Polish Nuclear Power Program	15-40	19% (all horizon)	YES	NO
S3	High EUA price	90	19% (all horizon)	NO	NO
S4	High RES share	15-40	19%, 27%, 50% (2020, 2030, 2050)	NO	NO
S5	Reference scenario with learning rates	15-40	NO	NO	YES
S6	High EUA price with learning rates	90	NO	NO	YES

Table 9. The potentials and learning rates for RES [22]

Parameter	Hydro	PV	Biomass	Biogas	Wind onshore	Wind offshore
Potential [MW]	3 000	16 000*	15 000	7 000	16 000	8 000
Max. annual capacity increase [MW]	1 500	2 000	1700	250	2 000	500
Learning rate [-]	-	2.2%	-	0.9%	1.2%	0.3%

* for scenarios S5 and S6 PV potential is unlimited