Poland's 2040 Energy Transition

Energy Mix Optimization

Damian Adam Hasterok

hasterok.damian@gmail.com

Instituto Superior Técnico, Universidade de Lisboa, Portugal

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Abstract

Poland is just right on the path of Energy Transition towards a sustainable energy system. This challenge obligates urgent decisions to be made over the outlook of the national energy economy, security, and climate impact. Concerning the electrical and heating energy sector, this thesis proposes an alternative scenario for the contemporary followed by Poland – Energy Policy of Poland 2040. To determine an ideal energy mix in Poland is proposed a methodology to identify the optimal energy mix considering the total annual costs minimization. The proposed methodology has as constraints the environmental and political constraints defined by the Polish government. The considered constraints are the greenhouse gas emissions, the percentage of renewable generation in final electric consumption and the import/export balance electrical energy. A reconstruction of the prognosis was composed in EnergyPLAN tool. Firstly for a strong base definition, a model of the latest available data was constructed (2017). Relaying on a reference form, a rebuilt model of 2040 was established to apply Grey Wolf Optimizer seeking an alternative, less costly and more sustainable, energy mix. Lastly, a sensitivity analysis was carried out. The fixed costs of renewables were decreased by 20%, the carbon tax was decreased and increased by 30% and the natural gas price was rose by 20%. The obtained results allowed a reduction in the total annual costs of about 4.14%, which represents a value of 1.28 Bln. €, also guaranteeing an 8.81% reduction in emissions.

Keywords: Poland, Costs optimization, Energy transition, EnergyPLAN, Grey Wolf Optimizer.

1. Introduction

Based on BP (British Petroleum) report from the year 2020 [1], Poland produced 74.4% of electricity from coal in 2019, which represents a decrease for about 4 percentual points in comparison to 2018. However, the percentage of coal in the energy mix in Poland is four times more than the average in European countries (17.5%). The CO_2 emission reached 309 million tonnes overall and 151 million tonnes in heat and electricity sectors [2].

Poland's environmental targets to 2030 are 40% decrease of Greenhouse Gas (GHG) (from the 1990 year level), an increase of renewable energy sources (RES) in total energy consumption to 32% and an increase of energy efficiency to 32.5% [3]. In 2018, the two last objectives were adjusted to 27% [4]. Nevertheless, environmental targets are demanding challenges for Poland. In the European Union Parliament, they are much more ambitious. According to [5], Europe intends to achieve carbon neutrality until 2050. To achieve those targets, a model of electro – energetic and heat system for 2040 was built. This model is explained sufficiently in

Energy Policy of Poland 2040 (EPP 2040). According to EPP 2040, the aim is to achieve 28.5% of RES production in overall energy utilization in 2040[1] (39.7% in electricity production). To achieve this high RES production, a development roadmap was also proposed in EPP 2040. This roadmap proposes the installation of 16 GW of photovoltaic capacity within 20 years, with a capacity factor of around 11%. Wind offshore farms should be in operation until 2025 to reach almost 8 GW and onshore capacity will be increased for about 4 GW. No significant changes are planned for the hydro energy in Poland. This rapid RES development requires the use of Energy Storage technologies and it is expected to reserve almost 5 GW for the demand-side response (DSR). One of the major changes foreseen in the Poland energy mix will be the introduction of nuclear power energy in 2033 rising the capacity power almost 4 GW.

Concerning the heating production, 81% is assured by Combined Heat and Power (CHP), most that using coal boilers. In the future, it is expected that this CHP will be replaced by heat pumps, biomass and natural gas boilers. Also, the contribution of geothermal and solar thermal will significantly increase.

The main contributions of the present work are the detailed analysis of the Polish energy system (electricity and heating) considering the official reports published in 2017 and the forecasted scenarios for 2040. The forecasted scenarios are evaluated and compared with an optimal energy mix defined using Grey Wolf Optimisation (GWO). The optimal energy mix scenario in 2040 is defined considering the CO_2 emissions targets and energy import/export balance. Finally, a sensitivity analysis considering the reduction of the global costs associated with the wind and photovoltaic generation is presented. This analysis is important because the costs associated with these technologies are decreased significantly in recent years. The proposed methodology can be useful not only in the case of Poland but also in the analysis of the energy mix in other countries or regions.

2. Energy Transition in Poland

This section highlights recent energy mix forecasts and benchmarks them, concerning power capacity and energy produced.

[1] The target values are different according the reference documents. In the present papers, the values are transcribed from the original documents.

Energy Policy of Poland

The Ministry of Energy of Poland presented an updated 2040 forecast for the Polish energy mix in November 2019 – EPP (Energy Policy of Poland) 2040 [6]. The document includes eight scenarios with a holistic prognosis of the energy system, including electricity, heat and transport. Those scenarios include a whole supply chain (from sources capture to the end consumer). This prognosis was constructed based on five main assumptions:

- 56 – 60% of coal's share in electricity production in 2030
- 23% of RES in the final gross energy consumption in 2030
- Implementation of nuclear energy in 2033
- 30% CO_2 emission reduction till the 2030 year (in comparison to 1990)
- An increase of energy efficiency for 23% till 2030 (concerning primary energy consumption from 2007)

Polich Nuclear Energy Program

An update to the 2014 Polish Nuclear Power Programme was released at the beginning of August 2020 by the National Atomic Energy Agency [7]. This document proposes and describes four scenarios, they differ mainly by the year of the assumed nuclear power plants capacities implementation. However, two of those scenarios exclude atomic plants from the energy mix. The lowest costs are obtained with 3.3 GW of nuclear power. The main conclusion of [8] is that the presence of nuclear energy lowers the total costs of energy production. The lowest CO_2 emission in the electro – energy sector was declared with 4.4 GW of nuclear power capacity [8].

Forum Energii

Another prognosis created this time by a private consulting company Forum Energii is presented in [9]. The forecast [10] consists of four independent scenarios, which mainly differ from each other by the RES share.

Holistic conclusions from two previous forecasts prove how important is the development of nuclear energy in an economic and ecologic transition approach. The objectives of EPP 2040 are specific and straightforward, however, PPEJ and Forum Energi documents aim to more generic values and each scenario differs with those goals. For that reason, the

EPP 2040 was chosen as the reference forecast scenario.

3. Renewables Energy Potential in Poland

This chapter provides overall information about Renewable Energy Technologies (RET) in Poland. Each of them is detailed regarding its potential on the national and worldwide market and costs. Additionally, a review of the Energy Storage (ES) methods possible to apply in Polish conditions is included due to the growing need for balance caused by the non-dispatchable power generation units.

3.1 Power Generation

The history of polish hydro energy started in 1896 and 1930 reached 8000 energy plants. Nowadays there are 761 water flow power plants with a capacity of 994 MW and their potential is evaluated for 14.27 TJ [11], mainly for mini and small hydropower plants. The potential of this source is used only by 12%, whereas in Germany it's 80%, Norway – 84%, and France nearly 100%. This creates a vast area of clean technology to develop [11]. Polish technical utilisation factor (also capacity factor) was equal to 17.2% according to [12] in 2012.

Polish conditions let only use this technology for heating purposes. Its geothermal capacity is 76.2 MWth producing 817 TJ of heat in 2015. One of the largest continental European geothermal plant in Podhale produced 462 TJ of heat in 2015 [13]. Polish geothermal capacity factor in 2010 was equal to 17% [14].

The total power of PV systems with the main grid connection was equal to 178 MW in 2017. And totally with off-grid installations 268 MW [15]. Photovoltaics annual capacity factor for Poland accounts as 11% [16], which is the lower boundary of the European standard limits 10 – 21% [17].

For the polish conditions, onshore wind annual capacity factor varies depending on the data source and area 16 – 25% in southern Poland in 2014 [18], about 29% national average evaluated basing on [19] in 2017. For the offshore technology, an analysis on a Baltic sea created by Warsaw University of Technology and PKN Orlen was carried out. Between 2010 and 2018, the capacity factor varied from 39.41 to 53.69% [20]. European average annual capacity factor frames accounts between 23 – 44% in onshore technologies, and 29 – 52% within offshore in 2018 [17].

Biomass is mainly used for heating purposes or small CHP plants up to 0.5 MW. Co-combustion allows using biomass in bigger units (>100 MWe) [21].

3.2 Energy Storage

Electric energy has a feature that has to be utilized immediately after its production. It is not a serious problem in the systems based on fossil fuel power plants and nuclear reactors when the production depends on the demand. However, when the system has a significant amount of non-dispatchable generation units using natural sources, the storage becomes very important. Through the years of development, humanity invented different ways of storing energy, some of them will be briefly explained in this section. This part includes Pumped Hydro Storage (PHS), Compressed Air Energy Storage (CAES) and Electrochemical Energy Storage.

4. EnergyPLAN Model Creation and Optimization

This chapter explains the evaluation process, explaining the theory and tools used in this project as well as review the last examples coherent with this project.

A suitable environment for modelling the energy scenarios was possible with EnergyPLAN software [22]. Its main purpose is to simulate the national energy systems on an hourly basis, including heat and electricity supplies together with transport and industry sector. The accessible technology varies from thermal power plants, including nuclear and geothermal with all possible renewable technologies. The software allows the implementation of different energy storage technologies, including pump hydro, Compressed Air Energy Storage (CAES), and Vehicle-to-Grid. The outputs are energy balances and import-export balances, fuel consumption and annual costs [23]. Other similar tools can be used to perform the present analysis with similar performance. EnergyPLAN was selected because the past experience of the authors in the use of this tool and mainly in its integration with MATtrix LABoratory (MATLAB). This is particularly important to optimize the results that can be obtained by EnergyPLAN.

The software was already used to analyse the energy mix in different worldwide countries [24] including several studies from European countries such as Austria, Croatia, Czech Republic, Denmark, Finland, Germany, Hungary, Ireland, Italy, Sweden and, UK.

These cases show that the software might be used for improvement and validation of already existing projects. A similar purpose is shown in this document.

The use of EnergyPLAN allows a good evaluation of different scenarios. However, other tools are necessary to find the optimal scenario. In the present work, Grey Wolf Optimizer (GWO) [25] was used to select the best scenario among the ones tested in EnergyPLAN. In [25], GWO was compared with other meta-heuristics, showing good results in the presented benchmark. GWO is widely used in power engineering. An approach to simulate 100% RES production in Portugal in 2050 is described in [26]. In the present work, the objective of the optimization is to reduce total annual costs under restrictions of CO_2 savings and import and export balance.

The proposed methodology is divided into four main steps, as shown in Figure . First, it is necessary to calibrate the EnergyPLAN reference model using known values. A reference model helps to better understand the EnergyPLAN software and to find correction factors needed to model the RES. Based on the initial model, it is possible to use the same parameters in a forecasted model. In the present work, this model is the one proposed in EPP 2040 already described. The main goal is to determine the total annual costs, CO_2 emissions, and the import/export balance. These values will be the reference for the optimization model being used for comparison, in the case of total annual costs, and problem constraints in the case of CO_2 emissions and import/export balance. Finally, a sensitivity analysis, considering a variation in the costs (investment and O&M) of Distributed Energy Resources (DER) is performed. This sensitivity analysis also considers the same constraints regarding CO_2 emissions and import/export balance. To perform coherent results, a predefined agent will be implemented into the sensitivity analysis step simulation, containing parameters from the previous simulation.

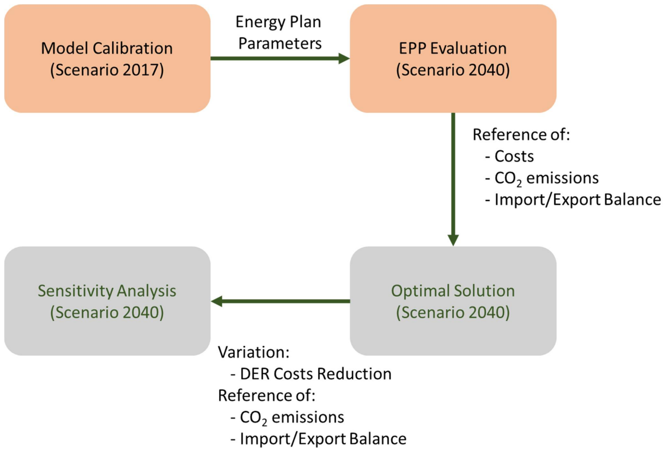

Figure 1: Sensitivity Analysis methodology

4.1 Energy Plan parameters

Concerning the most accessible and actual data, the year 2017 was chosen as a reference year to set up EnergyPLAN variables needed for further analysis. The electricity hourly demand and wind onshore hourly production were taken from the Polish TSO [27]. The remaining resources (PV, offshore wind, river hydro etc.) were implemented from EnergyPLAN data for Germany. Although, to recreate the Polish conditions, following capacity factors were assumed: for PV, the capacity factor is equal to 11% [16]; regarding offshore wind technology, which is not available yet at the polish system, data was collected from the research [20] on Baltic Sea. Based on that, the capacity factor of offshore wind was assumed as 46%. All those figures were assumed for the 2017 model as well as 2040.

The modelling intends to balance both heat and electricity demands with an assumption of a minimum 30% grid stabilization share in 2040. Grid stability is a service from TSO to keep up the grid in a stable balance. In EnergyPLAN this indicator stands for the minimum production provided by the national grid stabilising units (internal thermal power plants and nuclear). To find relevant capacities several databases were reviewed and selected [6], [11], [15], [28]–[31]. The EPP 2040 proposes 4950 MW of energy storage interconnectors or DSR, in the EnergyPLAN model, it is assumed as CAES capacity entirely. Dammed water supply is manually maintained to obtain proper energy production in this technology.

For the individual heating sources, the household energy utilization data from the year of 2017 was used [32]. For the forecast, coal boilers were replaced by the biomass and natural gas boilers proportionally to keep the same heat demand, whereas heat pumps input was taken directly from EPP 2040 [6].

Modelling different fossil fuel thermal power plants in EnergyPLAN is relatively complex and limited. To overcome this barrier, in the present work, all the conventional thermal power plants are treated as one technology with proportionally selected efficiency and manually maintained fuel distribution, the same with CHP units. The efficiency of thermal power plants increases from 36.6% in 2017 to 44.01% in 2040. This increase is due to the change from coal thermal plants to combined cycle gas turbine (CCGT).

Concerning the investment, O&M, fuel and fuel handling costs, several data are available in the literature. To make this work coherent and transparent, all data was taken from an EnergyPLAN database of costs [33].

The assumption of import/export balance at the level of 0 was decided based on EPP 2040 forecast condition, where this balance was also assumed as zero. Specific data of the European Commission on taxes and EnergyPLAN database were used as assumptions [33]–[35]. Variable costs were taken from EnergyPLAN database [33]. The assumed interest rate was 3% and CO_2 emission cost was 40.6 (EUR/t CO_2). All prices are discounted to Euro value from 2009 [33].

4.2 Optimization process definition

To run the optimization, a specific code in MATLAB add-on to the EnergyPLAN was customized. A similar approach was already used to create scenarios allowing 100% Renewable energy mix forecast in Portugal 2050 on the mainland [36].

EnergyPLAN inputs are identical as the ones used in EPP 2040 model, thus the parameters are constant through the process. The variables representing the capacities of technologies and energy storage parameters are changed in every agent evaluation. The output used in the optimisation are the total annual costs, CO_2 emissions, import/export balance and errors [37].

In this work, the objective is to minimize total annual costs (TAC - a sum of CAPEX + OPEX for each technology, considering that the total CO_2 emissions (should be lower or equal in comparison to EPP 2040 forecast scenario and the import/export balance should be close to 0 during a year. The modelled variables were capacities of wind onshore and offshore, PV, river hydro, dammed hydro, nuclear and conventional power plants. To balance electricity generation and consumption, pumped hydro and CAES technologies were used. The forecasts include electricity and heat sector, however, only the electricity sector was optimized. RES technology is becoming more accessible and its cost decrease [38], [39], therefore a sensitivity analysis was carried out.

The limits were assumed due to the potential of technologies or according to the highest found value in different forecast documents [6], [8]. All minimum capacities, except thermal power plants, are taken from the year 2017. Thermal power plants have its minimum assumed to be the CHP capacity in 2040 EPP forecast. PV has its maximum set as capacity in EPP 2040, wind onshore and river hydro, dammed hydro as International Renewable Energy Association (IRENA) potential [40]. Wind offshore and nuclear maximum capacities were taken from the existing scenario in the Atomic Agency report [8] and thermal power plants have an arbitrary maximum.

5. Results

In this section all verification values are presented for the reference model and forecast reconstruction model, then the results of the optimization and its sensitivity analysis are compared.

5.1 Reference model (2017)

Firstly, the reference model was calibrated according to the production and primary energy utilization, considering real values. The error lower than 5% was assumed as a limit for the model validation. Specific data from polish administrative entities were used to verify the model [28], [30], [32].

The software allows to include only four types of fuel, i. e. in section "biofuels" municipal waste and other alternative fuels were assigned. In this project, they are named Biofuels and alternatives.

5.2 Energy Policy of Poland 2040 Scenario (EPP 2040)

A similar procedure was applied to the forecast, validity was confirmed by the difference between the values presented in the Polish Energy Policy 2040 forecast [6] and EnergyPLAN model.

The value of total annual costs is equal to 30 943 Million EUR and CO_2 corrected emissions are 91.492 Million tonnes CO_2. Corrected emissions stand for the emission produced by the internal system including import/export balance emission produced by the external sources. This value has its divergence with the internal system emissions only in the case of modelling the reference year 2017 and EPP 2040 forecast, the GWO model has those emissions coherent. Also, the import/export balance is not exactly 0. An explanation can be given by the use of the same parameters of 2017. The parameters used in EPP 2040 report are not known. Nevertheless, the obtained import/export balance is less than 1% of total demand.

5.3 Optimization Results

In the present section, the results obtained considering the GWO methodology are presented. The boundaries of CO_2 emissions and energy import/export balance are the values obtained in the previous analysis that are 91.492 Million tonnes CO_2 and 1.83 TWh respectively. The comparison of EPP 2040 scenario and the results obtained by GWO are presented in Table 1.

Table 1. Comparison of EPP and GWO modelled scenarios for power capacity and production.

Technology	EPP, MW	EPP, TWh/year	GWO, MW	GWO, TWh/year	change in the capacity	change in the production
Thermal power plants	26 801	119.44	20 707	105.94	-22.74%	-11.30%
Nuclear	3 900	31.4	4 400	35.43	12.82%	12.83%
Dammed hydro	1 415	1.49	1 695	0.41	19.79%	-72.48%
River hydro	1 230	3.17	1 500	3.87	21.95%	22.08%
Wind onshore	9 761	57.03*	13 777	73.81*	41.14%	29.42%
Wind offshore	7 985		9 600		20.23%	
PV	16 062	15.46	7 533	7.25	-53.10%	-53.10%

* values for wind onshore and offshore are summed up.

Comparing the two scenarios (see Table 1), it is possible to observe that the wind technologies experienced the highest capacity growth. Offshore wind achieved its maximum capacity limit. Also, the production in river hydro increased significantly (22.08%). This is very important to compensate the unbalances created by the technologies based in renewables. In contrary, PV technology is the least supported technology and its variation to the EPP scenario is the biggest one. This can be explained by the investment costs associated with this technology as well as the low capacitor factor. It is important to mention that the increase in PV use will result in a higher demand for storage capacity.

Table 2. Comparison of key indicators

Key indicators	EPP forecast	GWO method	change
CO_2 emission, [Million tonnes of CO_2]	91.492	83.431	-8.81%
Total Annual Costs, [Million EUR]	30 943	29 663	-4.14%
RES share of Primary Energy Sources, [%]	28.5	30.3	6.32%
RES share of electricity production, [%]	39.5	42.8	8.35%
RES electricity production, [TWh/year]	87.48	94.96	8.55%

The optimization produced over 4% costs savings with CO_2 emission reduction for almost 9% (see Table 2). Share of RES in electricity production fulfils the EPP conditions. Operation costs stay at the same level, whereas variable and investment costs decrease.

5.4 Sensitivity Analysis

A sensitivity analysis considering RES costs reduction was carried out. Investment, operation and maintenance costs were decreased by 5-20% with a step of 5%. As expected, the global investment decreases and the savings are around 1.046 billion euros a year which represents 3.53% when compared with the initial scenario. Considering the obtained values, it is possible to conclude that decreasing costs of RES did not bring any significant changes in the energy mix and CO_2 emissions (about 0.1% variation), while the total annual costs decreased slightly. Considering electricity sector, total annual costs of RES in this sector decreased by about 21.56% and total annual costs of the electricity sector by about 6.59%

The only change that occurred during the analysis is almost 1 GW declined in the PV fulfilled by the Onshore growth - 841 MW, and a very little decrease in nuclear energy. This can be explained by the lower capacity factor of PV in Poland (around 11%).

6. Conclusions and discussion

This paper presents an alternative scenario for the energy mix in Poland in 2040. The proposed scenario was obtained using an optimization process based on Grey Wolf Optimizer (GWO). Comparing with the official energy mix scenario proposed in EPP 2040 [6], it is possible to conclude that the proposed solution allows a total annual cost reduction of 1.3 billion euros (over 4%) respecting, with some minor differences, the total CO_2 emissions and the import/export balance. From the results, it is possible to verify that the CO_2 emissions are lower in the proposed method (less than 9%) and the import/export balance are the same.

The savings have been obtained mainly through the use of more offshore wind power capacity, and by the use of more river hydro generation. Other important difference, comparing the obtained scenario with the EPP 2040 one is the reduction of PV capacity from 16 GW to 7.53 GW. This can be explained by the costs associated with this technology and to the lower capacity factor in Poland. The nuclear power capacity is similar in both reports.

A sensitivity analysis, considering the reduction of investment cost in renewable base technologies are also presented showing a reduction of the total annual costs. The overall conclusion stands that no significant changes in the energy mix willing to appear if declining those costs.

As future work, it is expected to compare the performance of GWO with other heuristics to this specific problem and the improvement of the existing methodology using an optimized initial solution. Another aspect that should be addressed in future work, are the costs associated with the transmission grid development. In the propose solution, huge capacities of wind power and nuclear will drastically increase power flows in the north-west part of the country.

The proposed methodology can be used to evaluate the energy mix scenarios in other countries, contributing to the decision support in the selection of best technologies to achieve the environmental targets minimizing the costs. The final result will be different in each country depending on the availability of natural resources and in the existing technologies. Another important aspect that can significantly change the results of this analysis, it is the available or planned interconnections with neighbours. The interconnections can be seen as a flexible load/generator that can compensate the imbalances in the system in the analysis.

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