Energy transformation towards climate neutrality in Poland

Transformacja energetyczna Polski w kierunku neutralności klimatycznej

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The paper presents the idea of modelling of rational energy mix in Polish Power System with multicriteria assessment methods. Desired generation stack can be predicted correctly in simplified manner under condition of choosing correct input parameters for modelling. Thus the different assumption for Polish future energy mix were discussed as well as investment assessment methods for modelling of power generation in the future in Poland under UE legislation requirements regarding decarbonisation goals up to 2050.
Keywords: EU regulations, climate neutrality, energy sector, power strategy development, assessment methods for development modelling

Dokument przedstawia pomysł modelowania racjonalnego miksu energetycznego polskiego systemu elektroenergetycznego z wykorzystaniem multikryterialnych metod oceny. Docelowy stos źródeł wytwarzania może być poprawnie zaprognozowany w uproszczony sposób pod warunkiem wyboru właściwych danych wejściowych do modelowania. W związku z tym, w artykule, omówiono różne założenia przyszłego miksu energetycznego Polski, jak również różne metody oceny do modelowania przyszłego majątku wytwórczego w Polsce, biorąc pod uwagę wymagania regulacji UE dotyczące celów dekarbonizacji do roku 2050.
Słowa kluczowe: regulacje UE, neutralność klimatyczna, sektor energetyczny, rozwój strategii energetycznej, metody oceny do modelowania rozwoju

Introduction

The European Union (EU) climate and energy policy, including its long-term vision of striving for EU climate neutrality by 2050 and regulatory mechanisms stimulating the achievement of effects in the coming decades, has a significant impact on shaping the national energy strategy. Achieving the EU's 2020 and 2030 climate and energy targets is key to a low-carbon energy transition. In line with the EU's ambition to decarbonise the European Union, in December 2020 the European Council approved a binding EU target to reduce net greenhouse gas emissions by 2030 by at least 55% compared to 1990 levels. Thus, the 40% reduction target was increased. The new EU ambition has been defined as a collective goal for the entire EU, i.e. implemented on the basis of contributions of Member States, taking into account national conditions, specific starting points, reduction potential, the principle of independence in shaping the national energy mix, the need to guarantee energy security; in the most cost-effective manner possible in order to maintain affordable energy prices for households and the competitiveness of the EU, as well as taking into account the principle of fairness and solidarity. Following the dynamically accelerating EU climate and energy trends will be a huge challenge for Poland. [1]

The base point on the path of energy transition are the 2020 targets. In 2009, a regulatory package was adopted setting out three headline targets for counteracting climate change by 2020 (the so-called 3 x 20% package), with Member States participating in accordance with their capabilities. Poland is obliged to:

- increase energy efficiency by saving primary energy consumption by 13.6 Mtoe in 2010-2020 compared to the forecasts of demand for fuels and energy from 2007;
- increase the share of energy from renewable sources in gross final energy consumption to 15% by 2020;

contribute to the EU-wide reduction of greenhouse gas emissions by 20% (compared to 1990) by 2020 (in terms of 2005 levels: – 21% in the EU ETS sectors and – 10% in non-ETS). [1]

The key importance for current policies and activities is the so-called the Paris Agreement concluded in December 2015 at the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (COP21). It results in the need to stop the increase in the average global temperature below 2°C compared to the pre-industrial levels, and try to be that it was not more than 1.5°C. During the 24th conference (COP24) in December 2018, during the Polish Presidency, was signed the so-called Katowice climate package implementing the Paris Agreement. Particular attention has been subjected to that the transformation resulting from the Paris Agreement must be carried out in a fair and solidarity manner.

In 2019, the work on the Clean Energy for All Europeans regulatory package, which was ongoing at the EU forum, was completed the package indicates how to operationalise the EU's 2030 climate and energy targets and is intended to contribute to the implementation of the Energy Union and the construction of the EU's single energy market. The Polish government

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took an active part in shaping the final wording of the provisions, as these regulations strongly affect the functioning and determination of the future of the energy market model in Poland.

In the future, it is assumed that the key EU regulations concerning the energy sector will be further revised, which will refer to the goals and tools of the European Union's energy and climate policy in a time horizon that goes beyond the 2030 framework. This applies particularly to the decisions regarding the long-term vision of reducing greenhouse gas emissions in the EU until 2050.

In 2019, the European Commission published a communication on the European Green Deal, i.e. a strategy whose ambitious goal is to achieve climate neutrality by the EU by 2050 – as a world leader in this field. Poland supported this goal, however, working out a specific national derogation, due to the difficult starting point of the Polish transformation and its socio-economic aspects. In the last dozen of years Poland has made great strides in reducing the environmental impact of the energy sector, through the modernisation of generation capacity and diversification of the energy generation structure. Our dependence on carbon fuels is still much higher than that of other EU Member States, which is why a fair transition is so important, which means considering the starting point, the social context of the transformation and counteracting the uneven distribution of costs between countries, which is more burdensome for economies with high use of carbon fuels. It should be noted that the costs relate to both the regions of coal (mining and energy production), as well as entire economies, which in a brief time incur expenditures for new capacity, often immature economically more expensive technologies, network infrastructure, which is also reflected in the price of energy.

In 2020, the world was hit by the coronavirus pandemic, affecting all global economies. This emergency situation also highlighted the important role of the energy sector, including energy security, for the functioning of the economy of Poland and other European countries. In the coming years, the energy sector will face a number of post-COVID challenges related to, inter alia, the reconstruction or substitution of supply chains in order to conduct investments, mobilise financial resources in budgets strained by the effects of the epidemic, and sometimes – verification of investment plans and accumulation of funds for key projects. It is important that investment decisions are made taking into account the aspect of green and low-carbon economic recovery. Post pandemic recovery efforts are designed to create a rapid and effective growth impulse and create new opportunities for the national economy. In addition to protective tools and activities mobilising domestic public funds, EU support will be used.

The energy transformation will require the involvement of many entities and incurring capital expenditure. In the years 2021–2040 their scale may reach approx. PLN 1,600 billion. Investments in the fuel and energy sectors will involve approximately PLN 867-890 billion. The projected outlays in the electricity generation sector will amount to PLN 320-342 billion, of which approx. 80% will be allocated to zero-emission capacities, i.e. renewable energy and nuclear energy. As a result of transformations in the fuel and energy sector, energy costs may increase. Numerous investments may obtain financial support (operational and capital), which enable changes to take place as quickly as possible and on a larger scale. It is important that the way in which the transformation is carried out ensures socially acceptable energy prices and does not intensify energy poverty. [1]

On 27th of June 2022 EU Council agreed on Fit for 55 to set higher target for RES and energy efficiency. The Fit for 55 package is a set of proposals to revise and update EU legislation and to put in place new initiatives with the aim of ensuring that EU policies are in line with the climate goals agreed by the Council and the European Parliament. Fit for 55 refers to the EU's target of reducing net greenhouse gas emissions by at least 55% by 2030. The proposed package aims to bring EU legislation in line with the 2030 goal.

The package of proposals aims at providing a coherent and balanced framework for reaching the EU's climate objectives, which:

- ensures a just and socially fair transition;
- maintains and strengthens innovation and competitiveness of EU industry while ensuring a level playing field vis-à-vis third country economic operators;
- underpins the EU's position as leading the way in the global fight against climate change [2].

Yet another recent regulation is taxonomy a green classification system that translates the EU's climate and environmental objectives into criteria for specific economic activities for investment purposes.

It recognises as green, or 'environmentally sustainable', economic activities that make a substantial contribution to at least one of the EU's climate and environmental objectives, while at the same time not significantly harming any of these objectives and meeting minimum social safeguards.

The Taxonomy Regulation establishes six environmental objectives [4]:

1. Climate change mitigation;
2. Climate change adaptation;
3. The sustainable use and protection of water and marine resources;
4. The transition to a circular economy;
5. Pollution prevention and control;
6. The protection and restoration of biodiversity and ecosystems.

A first delegated act on sustainable activities for climate change adaptation and mitigation objectives was published in the Official Journal on 9 December 2021 and is applicable since January 2022. A second delegated act for the remaining objectives was published in 2022.

Thus, the energy transformation will require the involvement of many entities and incurring capital expenditure and several scenarios to meet the EU environmental goals and Polish electricity demand in cost effective manner.

Doing research through the scenarios and methodism of forecasting energy mix for Poland there is a common approach of using the tools based on mathematic models, very deeply based on fundamentals and future environment. Those works need a lot of data and are very time consuming. The paper Is about to propose novel approach based on setting several criteria for the future energy mix based on AHP, DEA or other similar models. If the results are convergent, it will confirm the truth of assumptions.

Problems which are presented in this paper regard power generation in Poland and are based on the realistic research data.

Scenarios for Power Sector Development in Poland – general overview

Polish Energy Policy 2040 [1], [2]

Polish Energy Policy 2040 (PEP2040) is the Government Policy published in 2021 and establishes the framework towards the energy transformation in Poland. It contains strategic decisions regarding the selection of technologies for building a low-emission energy system. PEP2040 describes the state and conditions of the energy sector. Afterwards it indicates three pillars of PEP2040, on which the eight specific objectives of PEP2040 were based, along with the activities necessary for their implementation, and strategic projects. Presents territorial approach and identified sources of funding EPP2040.

The scenario is based on Polish Energy Policy to 2040 which is based on three pillars [1]:

- Pillar I – Just transition – means providing new development opportunities for the regions and communities most negatively affected by the low-emission energy transition, while creating new jobs and building new branches of industry that participate in the energy sector transition. Activities related to the transition of coal regions will be supported with funds amounting to approx. PLN 60 billion. In addition to the regional approach, the transition will involve individual energy consumers, who on the one hand will be shielded from the increase in energy prices and on the other hand will be encouraged to actively participate in the energy market. This will ensure that the energy transition is conducted justly and that everyone – even small households – can participate. The transition will use national competitive advantages, create new development opportunities and initiate broad modernisation changes, allowing to create up to 300 thousand new jobs in high-potential industries, in particular related to RES, nuclear power, electromobility, grid infrastructure, digitalisation, thermal modernisation of buildings, etc.;
- Pillar II – Zero emission energy system – it is a long-term direction in which the energy transition is heading. Decarburisation of the energy sector will be possible through the implementation of nuclear power and offshore wind energy, increasing the role of distributed and civic power generation, but also through the involvement of industrial energy, while ensuring energy security through transitional use of energy technologies based, among others, on gaseous fuels;
- Pillar III – Good Air Quality – this goal is one of the most noticeable signs of moving away from fossil fuels; thanks to investments in the district heating sector transition (system and individual), electrification of transport and promotion of passive and zero-emission houses using local energy sources, air quality will visibly improve, which has an impact on the environmental health; the key result of the transition, which will be noticed by every citizen, will be ensuring clean air in Poland.

The targets for PEP 2040 are [1]:

- No more than 56% of coal in electricity production in 2030;
- At least 23% of RES in gross final energy consumption in 2030;
- Implementation of nuclear energy in 2033;
- 30% reduction in GHG emissions by 2030 (compared to 1990 – baseline of Kyoto Protocol);
- 23% reduction in primary energy consumption by 2030 (compared to the PRIMES2007 projection).

Development Plan for Transmission System 2023-2032 [5]

Development Plan for Transmission System (DPTS) is the plan of power transmission system development. It predicts the set of investments in transmission grid based on fundamental analysis of power transmission system environment and internal constraints development scenarios. This work has been done to point out such investments that would give the input in safety of final customers supply in all possible conditions.

The investments in the plan aim to support:

- Poland's commitment to fulfil the share of RES obligation in the final energy consumption;
- Government's plan of offshore wind farms construction on the Baltic See;
- Government's plan of nuclear power plants construction;
- Connection of new power units according to the results of capacity market auction between 2023 and 2026.

Power supply improvement including minimisation of grid bottle necks. Particularly in parallel with RES development in northern Poland, both onshore and offshore.

The Plan brings first great technological revolution in the investment approach with significant share of RES in the energy mix. The novel solution in the Polish grid will be construction of HVDC line connecting to areas of Poland – south and north. The goal of this investment is to get the possibility to transmit energy produced from RES (offshore and onshore wind farms) in the north of Poland to the south of the country where most of the heavy industry (power consuming) is located in Poland.

Second approach for long-term planning of power transmission network operation is a proposal of construction of production resources made by transmission system operator. The idea behind that is to have units in the system ready for interventional needs or for improvement of network operation in case if the set of production units available for operator is not sufficient.

Polish Energy sector up to 2050 [6]

The aim of this document is to analysis four scenarios of development of Polish energy sector up to 2050, taking into account economic, social and environmental aspects of its realisation and the impact on country's economy. The proposal of that solution is four scenarios of power sector development [6]:

- Coal scenario – based mainly on coal fired units, it covers new investments in coal mining both hard and lignite. The RES share is 17%;
- Diversified scenario with nuclear power plants – it brings diversified technology mix along with nuclear power plants instead of lignite power plants. The share of RES in 2050 accounts of 38%;
- Diversified scenario without nuclear power plants – it is close in assumptions to the previous one, but in the substitution of nuclear power plants the natural gas fired power plants enters in place together with RES, which share constitutes 50% in 2050;
- RES Scenario – it assumes coal-out. The RES production increases up to 73% and gas fired cogeneration units close the production balance.

Polska NET-ZERO 2050 [7]

The study analysis possible directions of the transformation of electricity and district heat generation sectors in Poland and in the EU. The scenarios consider important from the point of view of challenges lying ahead, taking into account risks associated with fuel market turbulences in the current geopolitical situation [7]:

- The reference scenario (BASE) that assumes 60% reduction of emissions in 2050 vs. 1990, excluding Land Use, Land Use Change and Forestry (LULUCF) sector;
- The neutrality scenario (NEU) that assumes 90% reduction of emissions by 2050 vs. 1990 and net-zero emissions from all sectors, including LULUCF by the same date;
- The neutrality scenario with high fuel prices (NEU_HPRICE) that assumes the same GHG reduction targets and technological potential as the NEU scenario, but assumes higher prices of fossil fuels;
- The neutrality scenario with lower potential of offshore wind installations (NEU_LWIND) that assumes the same GHG reduction targets but lower potential of sites suitable for the construction of offshore wind installations.

Changes in the power sector will have

a significant influence on all sectors of the economy, including transport, heating and industry. Meanwhile, the decarburisation process in these sectors will impact the functioning of the power system by generating additional demand for electricity, which will require increase in production. The realisation of ambitious targets of climate policy and decarburisation of the economy leads to a deep reconstruction of Polish power sector. Modernisation of the sector will be incentivised by a fast-growing prices of emission allowances for the sector.

The report presents needed technologic changes in the power production sector that are necessary of fulfil goals in following regulations:

- European Green Deal;
- Fit for 55 together with the package of legislation acts.

The scenario also covers the present geopolitical situation resulting from Russian aggression on Ukraine that has begun in 2022.

KPRM Report up to 2060 [8]

The energy mix is defined as the energy carriers that supply the final energy for industry, households and public facilities. As the optimal model it was assumed the energy mix that provides:

- Sufficient power supply in national power grid;
- The lowest possible cost of power supply of all power carriers in the projected period.

The presented model has the character of linear optimisation and is focused on fuel technology changes that is converted to electric energy. The goal of the model is to set out the optimal model with the cheapest energy mix with the breakdown on technologies together with assurance of sufficient power reserve in the grid and realisation of binding goals for Poland that comes from European Energy Package.

The report presents the optimal energy mix structure to 2060 but is calculated up to 2090 to avoid end of the World effect. The idea is to set the technologies that have longer turnover period than 40 years and the economy of those could have negative impact on the technology choice due to depreciation and construction period. The energy sector will not stop its production in 2060. It can occur that the cheapest mix up to 2060 will not be the cheapest in the longer period and on the contrary the cheapest energy mix in the short time will not be economy optimal in longer period of time.

PEP 2040 with increased storage capacity in hydro-pump power plant

This scenario is based on PEP2040 but is extended by the big scale energy storage plants in form of hydro-pump storage power plants. Presently, in Poland there is roughly about 5% energy storage of total installed capacity. The safety and reliability level presents that sufficient level of energy storage should be at the level of around 10% for the current Polish energy mix [5]. The scenario should confirm or not the need of new investment and extension of big scale reliable power accumulators like hydro-pump storage power plants. The hydro pump storages characterises the lowest carbon footprint among other available similar storage technologies, that is presented in Fig. 1.

Moreover HPS technology has the lowest total cost of energy storage (LCOS) as shown on Fig. 2.

For the moment in Polish government plans there is potential of construction about 3 GW in hydro-pump power plants. Two in South regions and one in North region of Poland.

The planned hydro pump storages (HPS):

- HPS Tolkmicko with power capacity of 1040 MW;
- HPS Mloty with power capacity of 1050 MW;
- HPS Roznow II with power capacity of 700 MW.

EC has noticed in its documents "The future role and challenges of Energy Storage" and "Study on energy storage – Contribution to the security of the electricity supply in Europe" [11], that increasing share of intermittent sources of energy like PVs, windfarms will emphasis the role of energy storages. If the RES (Renewable Energy Sources) share will achieve 15% to 20% of total energy consumption, the electricity network operators will not manage to compensate the outages of unstable RES generation. Higher share of RES needs support of energy storages. This support is a range of services like: balancing power, frequency stabilisation, reactive power compensation, black start. The energy storage will also play significant role for stabilization of operation of new nuclear power plants in Poland. First nuclear power station will start operation in 2033 with first unit installed capacity of 1-1,5 GW [12].

The RES share above 25% (depending on energy system) would need support of energy storages in two situations:

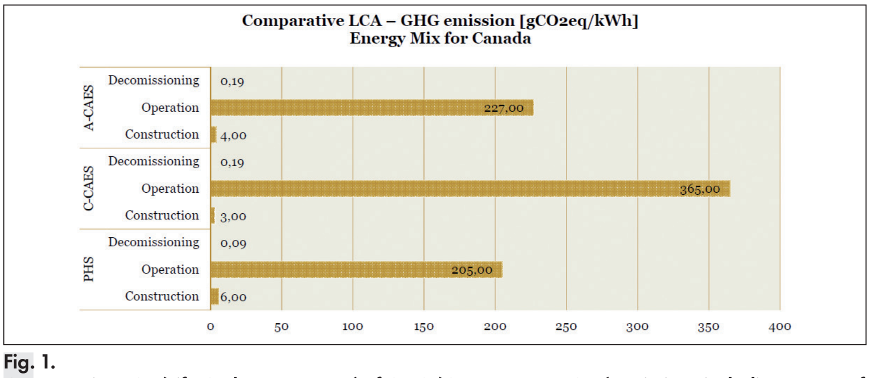

Fig. 1.
Comparative LCA (Life Cycle Assessment) of GHG (Green-House-Gas) emissions including stages of construction, operation, decommissioning on example of energy mix for Canada. PHS (Pumped Hydroelectricity Storage), a conventional C-CAES (Conventional Compressed Air Energy Storage), the adiabatic compressed air storage A-CAES (Adiabatic Compressed Air Energy Storage) [10]
Rys. 1. Analiza porównawcza LCA (Ocena Cyklu Życia) emisji GHG (Gazów Cieplarnianych) uwzględniająca etapy budowy, eksploatacji, likwidacji na przykładzie miksu energetycznego Kanady. PHS (elektrownia szczytowo-pompowa), konwencjonalna C-CAES (konwencjonalny magazyn energii sprężonego powietrza), A-CAES (adiabatyczny magazyn energii sprężonego powietrza) [10]

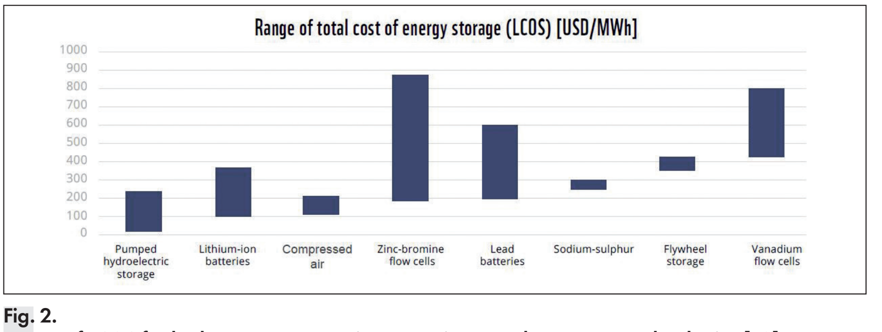

Fig. 2.
Range of LCOS for hydro pump storage in comparison to other storage technologies [10]
Rys. 2. Zakres LCOS (zdyskontowane koszty magazynowania energii) dla elektrowni szczytowo--pompowych w porównaniu z innymi technologiami magazynowania [10]

- when RES generation is high and there is surplus of generation over demand, the network disturbances may occur (frequency, voltage, reactive power) and network overload. These problems can be solved by storing of surplus of energy;
- when RES generation is low, the shortage of power my occur in relations to demand. The support from energy stored during surplus generation would be a solution in such situations.

Assessment methods [13]

The evaluation of the effectiveness of investing under market conditions would better rely on a multiparameter and multivariate analysis, taking into account diverse conditions of execution and exploitation than on classic simplified static ways without considering time factor or dynamic ways through comparison by means of discount technique. Basic differences between static and dynamic methods consist in the fact that in simple methods not the whole investment period is taken into consideration. Research focuses only on a representative year or a few years. Moreover, calculations are made on nominal data, which means that all income and expenditure to be analyzed are not discounted. In dynamic methods, however, the whole construction and exploitation period and the time factor are taken into account as well as future income and expenditure are calculated at present values [14], [15].

The following methods of investment effectiveness evaluation are called simple, because they do not consider change of value money over time:

- cost comparison CC;
- profit comparison PC;
- yield Y (accounting rate of return ARR, return on investment ROI, return on equity ROE);
- payback period comparison PBPC (payback period PBP);
- profitability account PA;
- break-even point analysis BEP.

The dynamic methods of investment effectiveness evaluation take into account change value over time, for example through discount calculus (see Fig. 3):

- net present value NPV;
- present value annuity PVA;
- internal return rate IRR;
- modified internal return rate MIRR;
- annuity AN;
- profitability index PI;
- discount payback period DPBP.

While technological reasons beyond the expected (projected) level of energy demand are objective, economic situations, however, being of dynamic nature, have a significant impact on the risk and uncertainty of investing in the power energy sector.

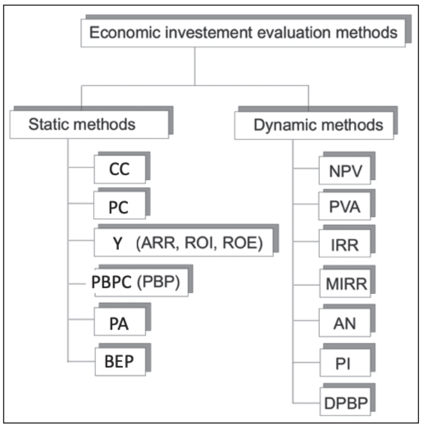

Fig. 3.
Economic investment evaluation methods [13]
Rys. 3. Ekonomiczne metody oceny inwestycji [13]

Therefore methods which are able to meet modern market demands must be sought [16].

In an investment process, the decision maker usually has to confront a situation in which there is a couple of opposite (discordant) objectives e.g., profit maximisation or minimisation of total direct costs.

The essence of a multi-dimensional decision problem lies in the fact that individual investment projects can be evaluated from different viewpoints, using both quantitative and qualitative criteria. The final choice, however, should be in terms of quantity, which means that the decision maker has to receive answers which projects are effective from the point of view of different aspects.

All methods from this procedure class are in general strongly formalised and frequently require mathematical apparatus for which special software is needed. This group comprises appealing application methods for assessing the effectiveness of an investment in power engineering, such as [13]:

- nonparametric boundary estimation;
- hierarchic problem analysis;
- artificial neural networks;
- multi-criteria ranking methods.

These methods, via the decision maker's preference modelling, allow taking into account various decision situations, including risk and investment uncertainty.

Non-parameter Estimation of Edge Values

Data Envelopment Analysis (DEA), which is a nonparametric method, was elaborated by Charnes, Cooper and Rhodes (1978) [17]. In general, the method relies on two types of data analysis. In particular, a set of investment options – Decision Making Units (DMU) – is investigated. The core issue is to obtain the effectiveness of the evaluated investment variants (options) in accordance with the so called effectiveness curve. The DEA method is a linear programming methodology to measure the efficiency of DMUs when the production process presents a structure of multiple inputs and outputs, "costs – effects". It is based on the conception of productivity measure f (productive efficiency) formulated by Farrell (1957), defined as [18]:

$$f = \frac{\sum_{r=1}^{s} \mu_r \cdot E_r}{\sum_{p=1}^{q} \nu_p \cdot J_p} \qquad (1)$$

where:
E – effects;
J – costs;
r = 1,2, ..., s:
p = 1,2, ..., q;
s – effect number;
q – cost number;
μr – effect weights;
vp – cost weights.

This method does not require the knowledge of weights because weights maximising effects and minimising costs are sought for each researched object.

In general, since the appearance of DEA, there have been other methods modifying and expanding it, which, due to their orientation, may be classified into three basic models as follows [18]:

- cost-oriented;
- effect-oriented;
- non-oriented.

Two of the above group models (due to scale effects) come in the following versions:

- with fixed scale effects;
- with variable scale effects;
- with non-increasing scale effects.

Non-oriented models come in the following versions:

- non-oriented with fixed scale effects;
- multi-plicate with variable scale effects;
- additive with variable scale effects.

The former focuses on expenditures and is known in the literature as the CCR model, its name originates from the first letters of its inventors' family names: Charnes, Cooper, Rhodes. The latter enables a classification of objects to be evaluated in term of effectiveness, which allows applying it in investment effectiveness assessment.

The extended DEA model can be used in the evaluation of investment options in power engineering in order to rate them.

This necessarily entails making additional assumptions which allow compiling a rating list that creates a ranking list of effective options. It is assumed that in the process of the optimisation of t objects, the analysed *i-th* object is not taken into account in the linear combination being created, which causes that the effectiveness of the object is not restricted by the value 1. Then, the calculated measures of effectiveness enable rating effective objects [18].

In general, the most important element in an analysis of investment effectiveness by means of the DEA method is the choice of appropriate expenditures (input values) and effects (output values), used in the evaluation process.

The DEA method has its advantages and disadvantages [18]. The former are as follows:

- the possibility of taking into account the supply (expenditure) and the demand (effects) in the research; the knowledge of the functional relation between expenditures and effects is not necessary;
- the possibility of applying in the evaluation objects using more than one expenditure to create more than one effect;
- expenditures and effects can be expressed in different units, not necessarily in monetary units;
- the possibility of discovering extreme values, which are invisible in other methods due to data averaging – in the analysed method a polyhedron based on extreme data is constructed unlike in other methods where regression curves fit mean values;
- the possibility of achieving effectiveness results in a suitable form of the relative effectiveness of the investigated investment options.

Disadvantages of the method result mainly from the lack of an easy way of providing an absolute measure of effectiveness. Only the effectiveness of the whole group of the investigated objects is measured, excluding or eliminating one object from the investigated group can have an impact on the effectiveness coefficients of particular objects. In order to calculate the effectiveness of a new object, calculations must be repeated. Moreover, for each investigated object, an individually formulated linear programming task must be solved, which can be time-consuming if a great number of investment options must be evaluated. At the same time, the DEA method shows great sensitivity to erroneous data. Since the effectiveness curve is constructed not due to the estimation of parameters but only on the basis of empirical data, one erroneous datum can significantly change the results of calculations [19].

The conclusions that should be emphasised is that the main advantage of the DEA method is the possibility of making a multicriteria evaluation of investment options. What is more, in the same decision-making model there may be variables which differ in terms of economic categories, which is very important in the process of a multicriteria evaluation of effectiveness.

Hierarchic problem analysis

The analytic hierarchy process method (AHP) is a multicriteria analysis method of decision-making, which is used to solve problems to whose analysis more than one criterion is needed [18]. The method allows presenting a decision-making problem in the form of a hierarchical structure, and assigning measures to the applied criteria (attributes) of evaluation. This results in ordering a multicriteria decision-making problem, which in turn enables rating the investigated objects – investment options.

The analytic hierarchy process method (AHP) is based on a multistage, multicriteria decision-making analysis which enables arranging investment options in the form of a tree structure (1st stage) and evaluating them (2nd stage).

Assigning weights to particular criteria/attributes plays an important role. According to [21] and [19], [23] the following assumptions must be made:

- decision-making is hierarchical process;
- particular decision-making options are characterised by many criteria;
- there can be numerical or linguistic attributes;
- weights can be assigned to particular attributes;
- at particular decision-making levels there may be different groups of experts taking part in decision-making (the so called group decision-making) or individual experts.

In general, a decision-making matrix D, in which the rows correspond to options/alternatives and the columns to attributes (criteria), is the basis for decision-making at each level.

Taking into account the number of options, multiattribute decision-making (finite number of criteria) and multitarget decision-making (infinite number of criteria) are distinguished. It is worth emphasising that in the case of multiattribute decision-making, the number of defined options is relatively small [19], [21], [23].

After rating the investment options being evaluated, an initial matrix, in which the rows correspond to options and the columns to attributes, is the basis of a decision-making process.

An initial matrix X has the following form:

$$X = \begin{array}{c} \\ ALT_1 \\ ALT_2 \\ \vdots \\ ALT_i \\ \vdots \\ ALT_t \end{array} \begin{array}{c} \begin{array}{ccccc} CR_1 & CR_2 \cdots & CR_j & \cdots & CR_k \end{array} \\ \begin{bmatrix} X_{11} & X_{12} & \cdots & X_{1j} & \cdots & X_{1k} \\ X_{21} & X_{22} & \cdots & X_{2j} & \cdots & X_{2k} \\ \vdots & \vdots & & & & \\ X_{i1} & X_{i2} & \cdots & X_{ij} & \cdots & X_{ik} \\ \vdots & \vdots & & \vdots & & \\ X_{t1} & X_{t2} & \cdots & X_{tj} & \cdots & X_{tk} \end{bmatrix} \end{array} \quad (2)$$

where:

Xij – matrix element in numerical or linguistic form.

The columns of an initial matrix X are ordering vectors of options with respect to particular attributes, they can be expressed by different measures. Weight coefficients for particular options are elements of an ordering vector. They determine a preference ordering. Ordering vector components can be expressed in numerical form (quantitative data) or linguistic form (qualitative data). It is also worth emphasising that particular orderings can have non-homogeneous orders (in the sense of an ordering relation in the set of real numbers), i.e., in one ordering a higher value and in another ordering a lower value may correspond to a better option from the decision-maker's point of view. Moreover, particular attributes may have weights which show their importance [19], [21], [23].

Weight factors are given in the form of a vector w::

$$w = [w_1 \ w_2 \cdots w_k] \quad (3)$$

In a special case, weight coefficients can be equal, which means that the problem at this level is considered to have no weight.

An element of a matrix shows what the evaluation of an option from a certain criterion/attribute viewpoint is.

The AHP method became very popular in a short period of time, and many works were written about it. Until the end of the nineteen eighties of the last century, it was applied in many fields of economy, namely:

- economics and finance management;
- transport;
- logistics;
- forecasting;
- investment programming;
- issues of choice and technology transfer.

As it frequently happens, despite its enormous popularity, the AHP method was severely criticised in later years. It was shown that the AHP method in its form had numerous disadvantages [21]. Firstly, it cannot be directly applied when there are missing data. Another thing is that the solution depends on the scale inversion. Moreover, when a new variant is added, there can appear the so called loss of importance phenomenon, which means that the ordering obtained earlier is changed in the sense of the ordering relation in the set of real numbers. One can also obtain solutions dependent on the order of aggregation operations and on determining the ordering. It means that the solution obtained as a result of aggregating a few evaluation matrices, and calculating the ordering then, will be different from the one obtained as a result of calculating the ordering for particular matrices first to be followed by aggregation [21]. A wide discussion of some disadvantages of the AHP method can be found in Barzilai's newest works – from the years 1997 – 2001.

The AHP method can be applied in research on the effectiveness of investment options in power engineering. Traditional methods used to solve the problem of effectiveness, in spite of the fact that they are popular with decision-makers, do not always allow taking into account market conditions. The AHP method, due to an integrated approach to the analysis and evaluation of options, can be a rational tool which aids strategic investment management.

In general, an evaluation procedure by means of the AHP method consists of three main stages, namely:

- creating a model for analysis and evaluation, which takes into consideration information concerning intended investment strategies;
- conducting a comparative evaluation of strategies using the model constructed earlier, which leads to a synthetic evaluation and partial evaluations of the investigated options;
- conducting a strategic analysis, which results in an evaluation of decisions and the formulation of recommendations.

Artificial Neural Networks

Artificial Neural Network (ANN) method helps to choose the most favourable investment variants/options, which allows evaluating investment effectiveness in power engineering. It results in decision-makers freeing themselves form time-consuming and mathematically advanced classical models of decision-making.

The conception of the ANN application assumes, first, determining, on the basis of earlier research, a training set which is a matrix of initial parameters and results. Next, the artificial neural network must be taught to compare its responses to the initial data with the results of the research. Then, coefficients characteristic for the network, called weight vectors, must be correlated so that the difference between the network response and the results of the research was smaller than the assumed error. Taught in this way, the neural network, which is often a multilayer structure called perceptron, allows programming a taught phenomenon. The conception assumes a phenomenological approach to the investigated phenomenon, in this case to investment processes, by means of the so called black box method, i.e., by describing values of input/output parameters without investigating the phenomenon's nature and mechanisms [24], [25], [26].

The subject of research is the evaluation of investment variants-options. Economic and technological parameters of the variant would be the initial data, the effectiveness of the variant, expressed e.g. as the ratio of the profit to the expenditures or as a simple relation of the effects to the expenditures, would be the result.

An analytical technique based on an artificial neural network would be a tool supporting an investment decision, concerning the choice of the best investment option.

On the basis of an investment and effect analysis concerning real investments in power engineering, a multidimensional base matrix B of the following form can be achieved:

$$B = \overset{\text{var. input} \qquad\qquad\qquad \text{results}}{\begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1j} & \cdots & x_{1k} & E_1 \\ x_{21} & x_{22} & \cdots & x_{2j} & \cdots & x_{2k} & E_2 \\ x_{31} & x_{32} & \cdots & x_{3j} & \cdots & x_{3k} & E_3 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ x_{ij} & x_{i2} & \cdots & x_{ij} & \cdots & x_{ik} & E_i \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ x_{t1} & x_{t2} & \cdots & x_{tj} & \cdots & x_{tk} & E_t \end{bmatrix}} \qquad (4)$$

where:
i = 1, 2, ..., t;
j = 1, 2, ..., k.

The matrix B is composed of initial data in the form of a subset of initial features (characteristic of a respective variant – e.g. realisation costs) and a subset of output data in the form of results (effectiveness coefficients – e.g. the expected profits). The data of an entry matrix will hence be a basis for two sets:

- training set;
- verifying set.

These sets will be exploited after an appropriate neural network have been created for teaching and verification purpose. Once satisfactory results have been achieved, the neural network will then be used for an investment option analysis.

Artificial neural networks are analytical techniques modelled after the neural functions of the human brain and are capable of forecasting new observations (specified variables) on the basis of other observations (made on the same or different variables), after conducting a learning process on the basis of existent data.

The subset of the basis matrix B constitutes training data for teaching a neural network which consists of e.g., two hidden layers (with 8 neurones in each layer), at error tolerance.

The learning process of a neural network can sometimes lead to solutions in a very short period of time, but at another time it may require several thousands of iterations [27]. However, it always runs automatically, not absorbing the human being who is looking for specific solutions.

The method of investment effectiveness evaluation using artificial neural networks may be applied in power engineering provided the researcher has an appropriate teaching database. The use of the method is fully justified when design offices with a long tradition apply it because they have databases that have been created for years.

The way of determining investment effectiveness presented above could provide an opportunity of a fast initial evaluation of the usefulness of a particular strategy and of choosing the appropriate way of action. However the method probably would need to be confirmed by other method of investment effectiveness calculation even if the results obtained during a simulations performed by artificial neuronal network is positive. In fact it is not known in detail how the thought process is carried out.

Multicriteria Ranking Methods (MRM)

Multicriteria ranking methods allow choosing the best variant of an investment project from the point of view of different evaluation criteria. Because the above methods stem from the Electre method (Élimination et Choix Traduisant Réalité – in French), in the literature they are often referred to as the Electre methods. The way they are used to evaluate investment effectiveness is described below [28], [29], [30].

In general, it is an interesting decision-making situation in which a finite set of projects X = {X1, X2, ..., Xt} is going to be evaluated from the point of view of K = {k1, k2, ..., kk} criteria. These criteria can be both quantitative and qualitative. However, the final evaluation should be quantitative, expressed in terms of a certain order of "goodness". In order to compare criteria, a common evaluation scale may be adopted in which particular criteria, expressed by numbers, have been assigned the following labels: bad, satisfactory, medium, good etc. Any object Xi Î {X} should be evaluated by means of the criteria. This will result in digraphs meeting particular criteria. The final general evaluation will be shown by means of a synthetic graph representing a compromise between evaluations obtained due to applying the criteria.

Basic problems, with which the decision-maker has to cope with, are as follows: non-convergence of criteria i.e., desire to bring together things which are totally unlike in their nature and formulating one-element decisions regarded as the most justifiable. It is also important so that the decision-maker will not be influenced by the magic of numbers, formalisations, where in the in the suggested procedures there were clearly determined and explained decision-maker's preferences, not obscuring the nature of the problem [29].

It is worth noticing that in multi-criteria situations, every limitation of the choice of an effective solution (optimal in the Pareto sense) means introducing additional information about the decision-maker's preferences, and as a rule they are subjective.

Methods like Electre, PROMETHEE-II and similar from that group are characterised by a high calculation complexity, which involves the necessity of using specialist software [18]. The application of this methods require use of complicated mathematical apparatus and a high level of subjectivism (e.g. the subjective choice of the type of fuzzy preference and the weights of particular criteria).

Conclusions

For the purpose of assessment methods for calculation of rational energy mix in Polish Power System the variable parameters have key importance for the value of the results. All of above presented scenarios from different sources have slightly different prognosis of electric energy demand curves that depend on power intensity of Polish economy. According to Polish Energy Law there is a necessity to keep certain margin of power reserve in the power system.

Availability of country's natural sources of energy are important as well as import capacities for modelling energy sources based on conventional power plants. Further on the carbon emission of fuels should be added like biogas, biomass, hard coal, lignite, natural gas, uranium, hydrogen. In addition the potential of renewable resources needs to be taken into account like biogas and biomass.

Generation technologies should cover investment preparation, construction period, life cycle of power generations units, capital expenditures (CAPEX), operational expenditures (OPEX), technical power potential of each technology, technology efficiency. Further, criteria are effective operational time for each technology in one period, that depends on maintenance, time to achieve optimal operational parameters, weather conditions, own consumption for the purpose of electricity generation.

Models should cover environmental issues like carbon emissions and share of renewables that depend on the SRMC (short run marginal cost). Finally assessment methods needs to be filled with imports capacities from neighbouring countries, legal constraints, social criteria's.

Having analysed potential modelling methods the preferred method for modelling the power generation mix for Poland based on various available power development scenarios in Poland is analytical hierarchy process (AHP) as the method allows presenting a decision in clear, hierarchical structure, and assigning measures to the applier criteria of evaluation that result in rating investigated options. The method has its disadvantages like lack of resistance for the lack of data, dependency on the scale inversion, new added variants may cause disturbances, to point some of them.

Nevertheless other analysed methods like DEA, ANN, MRM have also disadvantages like in DEA method sensitivity for errors that have significant impact on calculation results, generalising of data in form of presentation of the investment effectiveness for the whole group of invested objects, time consuming calculations. The ANN method results should be confirmed by other method of investment effectiveness calculation, even if the simulations performed by ANN present positive results. Finally MRM method involves use of specialist software and has high calculation complexity.

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