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1. Introduction

The Polish energy sector is at the crossroads. On the one hand, it is still anchored in the traditional coal-based structure; on the other, global and domestic ecological challenges necessitate the need to change this structure. International commitments and EU policy make us consider the role and place of nuclear energy as one of the potentially viable and feasible directions of sector development. However, even the construction of a single nuclear plant is a great investment project that has a significant impact on the entire economy of the country. This work attempts to develop appropriate methodology in order to capture the effects of such a venture both in economic and environmental terms, as well as to discuss possible scenarios for energy sector development. Established methodological framework is also applied to forecast expected results of specific announced energy policies. Therefore, the work combines theoretical and practical aspects and allows us to gain deeper insights into Polish energy sector specifics as well as its role in the entire economy, also in an environmental context. The authors believe that the publication may be of interest to readers who have already been introduced to the subject, but also those who want to familiarise themselves with it. The first group will find specific, quantitative models and forecasts here, the second, we hope, will be able to understand the complexity of the sector's issues and critical relationships occurring in it.

1.1. Power sector and GHG emissions

Greenhouse gases as gaseous components of the atmosphere make it difficult for infrared radiation to escape the atmosphere and are the cause of the greenhouse effect. These include carbon dioxide, ozone, chlorofluorocarbons, methane, nitrous oxide, halons and water vapour. Water vapour and carbon dioxide (CO2) have the strongest on the greenhouse effect. They strongly absorb radiation and are overwhelmingly responsible for the increase of the Earth's temperature. The process of fuel combustion for heating, but above all, for the production of electricity is responsible to a high degree for the increase of CO2 concentration in the atmosphere. In turn, the consumption of energy, and especially electricity, is synonymous with civilisation's progress and in itself one of the determinants of societal well-being. Electricity is mainly produced from fossil fuels: coal, oil, and natural gases, which all – but mainly carbon – emit CO2 during combustion. Therefore, the reduction of greenhouse gas emissions can be achieved by eliminating or limiting the combustion of fossil fuels, as well as ex-post, through the use of capture technology of the CO2 emitted from coal-fired power plants. Given the expected increase in the production and consumption of electricity and the need to reduce the combustion of fuels containing coal, there is a need for the development of alternative sources of energy. The development can be achieved by increasing the share of renewable energy, but also by the construction of new nuclear power plants and relying on them to a greater extent to supply energy to the national power systems. At present, nuclear power plants supply around a noticeable part of the world's electricity, while in the European Union more than 150 reactors produce even more than 30% of the required electricity. Resistance to the construction of new nuclear power plants in many countries, including Poland, is however very high, which is a derivative of historical conditions and political stereotypes but also changes in consumer preferences.

Another parallel scenario which would result in a significant reduction of CO2 emissions is to base the power systems on renewable energy sources. Either way, the share of renewable energy sources in the primary energy balance has been increasing significantly, reaching in some countries more than 20% of the total energy sources available. However, at the current level of technological development, these energy carriers cannot guarantee stability and reliability of the power systems' operation. There are also some unlikely scenarios to be considered, the effects of which could be significant, had they occurred. These include forecasts which assume complete abandonment of conventional coal-based energy or the exact opposite – the construction of new coal units only. At the level of individual countries, one can also consider a complete loss of the independence of the system and relying on the import of electricity or basing the system on one dominant energy carrier. Resistance in their implementation includes not only economic or technological elements but also political and social ones.

The Polish National Energy System ("KSE") is traditionally based on natural resources of national origin in the form of coal and lignite (significantly more than 80% share in electricity production and over 70% in installed capacity), which means a very high dependency on Polish energy production on fossil fuels. The share of these fuels is exceptionally high compared to other developed economies. These resources will presumably keep playing an essential role in the KSE. However, this is at the expense of significant environmental degradation in the form of greenhouse gas emissions, mainly CO2, and the need to store large amounts of ash and slag. Besides, the fossil fuel resources are exhaustible and in some areas insufficient to make economically viable new investments, although here, also, the increase in energy prices may paradoxically result in the launch of many investments that at the current stage are not justifiable in the appropriate rate of return.

In the light of the agreements reached at the United Nations Conference on the issue of climate change, as well as the legal regulations and the introduction of additional costs for greenhouse gas emission allowances as well as the expected subsequent legal provisions of the European Union, the change of the energy sector's structure in Poland and the decrease of the share of coal energy will be unavoidable. The share of coal-fired power plants in the Polish Power System is already decreasing significantly, in favour of the rapidly growing share of energy based on renewable energy sources ("RES"), and in the future probably also in favour of nuclear energy (see Ministerstwo energii, 2018; MIT, 2018), although this will require some one-off investment decisions with a longer implementation horizon. However, the decarbonisation process of the power sector should be continued due to two critical factors: the exhaustion of the natural resources and the impact of environmental conditions on the industry, including a dramatic increase in the cost of traditional ways of electricity production. This increase results from several overlapping factors: depletion of lignite resources, growing costs of investment in new coal blocks, which must be equipped with additional CO2 capture systems (which negatively affect the efficiency of the technology) and also parallel systems of improvement of their efficiency, increasing costs of emissions permits with each new EU ETS perspective, despite long-term trends such as the decline in coal prices (ARA prices).

The above factors will have a significant impact on the final energy mix of the country and, consequently, on the functioning of the entire Polish economy. The greenhouse gas emissions are a derivative of the activity – both in the energy sector itself and in other sectors of the economy.

1.2. Polish nuclear power plant program

The ambition to expand the Polish energy sector with the inclusion of nuclear energy spans decades. The plans to construct a nuclear power plant (NPP) were initiated even before the collapse of the communist regime. An intensive planning stage took place in the late 60s and early 70s, and in December 1972 it was determined that the site of the first Polish NPP should be in the area by the Żarnowieckie Lake, in the north of Poland. The initial construction of the NPP commenced in the 1980s. However, with the downfall of the communist order across Europe and the start of the transition period, the project was abandoned in December of 1990.

Upon abandoning the initial initiative to construct an NPP, the program received a new impetus in the 2000s, and in 2009 the government started to implement activities aimed at the construction of an NPP. In the subsequent period, the government sought to address the issues such as institutional and legislative framework; education and training of human resources; research facilities; siting analyses for an NPP and others. Implementation of nuclear power has been envisaged in a series of government's documents. Furthermore, Poland has submitted itself to two Integrated Nuclear Infrastructure Review missions executed by IAEA, including a preparatory mission carried out in April 2010 and the core mission in March 2013. Besides, the site selection process was revisited with the review of the standard set of conditions including access to cooling water; access to the power grid; the area's seismic stability and structure; access to transport routes; appropriate meteorological conditions and others. New site proposals were presented and, finally, in February 2013, a list of twenty-eight potential sites was narrowed down to three sites of 'Choczewo', 'Lubiatowo-Kopalino' and 'Żarnowiec'. However, in December 2014 PGE (Polska Grupa Energetyczna) terminated the characterisation, licensing and permitting contract, citing slow progress. Although the new siting studies at Choczewo, Krokowa and Gniewino were expected to be completed by 2020 (WNA, 2018b), currently the Ministry of Energy considers only the 'Bełchatów', 'Lubiatowo-Kopalino' and 'Żarnowiec' sites (Ministerstwo Energii, 2018: 39–40).

Although the implementation of the Polish NPP program is still mostly at a preparatory stage and is characterised by numerous delays, Poland has a fairly extensive experience with the nuclear industry. Poland already has a radiation waste handling system in place, as well as two research reactors and a related pool of experts. Namely, Poland has built research reactors 'MARIA' and 'EWA' (decommissioned), as well as two spent fuel storage installations located at Otwock-Świerk. Nevertheless, up until now, there has been no isotopic enrichment facility, nuclear fuel manufacturing facility, nuclear fuel processing facility, or NPP in Poland.

The justification for the introduction of nuclear power in the energy mix is multifaceted. The primary goal of Polish energy policy is to satisfy the energy-related needs of citizens and industry at competitive prices and in compliance with the participation of Poland in the implementation of the European Union's climate and energy policies. Furthermore, the program seeks to prevent the increases in energy prices and keep the prices stable (Ministerstwo Gospodarki, 2014: 1). In the near future the household consumption of electrical energy in Poland is expected to be rising while, on the other hand, the expansion of Polish economy is sure to result in the demand for energy increase. As of the second decade of the XXI century, the consumption of energy in Poland is significantly below the average of the leading European Union economies, and it has been decreasing since the 1990s (Eurostat, 2018).

A forecast citied in Polish Nuclear Power Program estimates that the capacity of energy generation sources should be increased by at least a third in order to satisfy the future electricity consumption needs (Ministerstwo Gospodarki, 2014: 2). Namely, the domestic demand is expected to increase from 119.1 TWh as of 2010 to 161.5 TWh by 2030. However, Poland has a limited capacity of domestic energy generation and needs to devise alternative forms of electricity generation. In this respect, traditional forms of electricity generation are getting increasingly tricky; hard coal exploration is increasing in costs, and new deposits of lignite are harder to acquire. Additionally, Poland is almost entirely dependent on external supplies of natural gas. Consequently, there is a need for diversification of fuel base for electricity generation, and a requirement to ensure stable and reliable supplies of electricity.

Besides, the electricity production structure in Poland is expected to sustain a reduction in the share of power plants fired with coal-derived fuels. Predominantly, these changes in the energy mix are due to the planned decommissioning of electricity generation capacities. The principal causes of these changes are the ageing and deterioration of current capacities, as well as their failure to comply with the EU requirements concerning environmental regulation. It is estimated that at least 12,000 MW of generating capacity will have to be decommissioned by the year 2030 (Ministerstwo Gospodarki, 2014: 43).

Concerning the points mentioned above, the development of the future structure of electricity generation in Poland will also be dependent on the adopted climate policy, particularly concerning the EU's environmental regulation. At the moment, Poland's power industry is responsible for emitting approximately 150 million tons of carbon dioxide annually. The cost of these emissions is primarily environmental, but it is also financial. On the level of the EU, there is a system in place regulating carbon emission allowance trading system and the emission restrictions based on the EU Directives: IPPC (as from 2016) and IED (as from 2020) – see EU 2008 and EU 2010. In this respect, the costs of emission allowance prices are expected to exceed €25 per ton after 2025.

Poland has some of the largest reserves of coal in Europe and is one of the largest coal producers in Europe. In 2016, 48% of the country's primary energy consumption was based on coal (WNA, 2018b). Consequently, as long as carbon emissions are affordable, coal will remain economically attractive as a source of energy and, by and large, in the foreseeable future electric energy generation will be primarily based on coal. However, although coal will remain the most important source of electric energy and heat production, in accordance to the EU regulation, electricity generation mix in Poland will have to be gradually adjusted from high-carbon-emission sources to zero-emission and low-emission sources. In this regard, renewable sources of energy are expected to increase. There is a low probability that carbon capture and storage systems (CSS systems) will be applied commercially at any time in the future, due to their high cost and technical difficulties. Thus, a goal of development of nuclear power is to contribute to the growing diversification in the fuel mix and enable a decrease in the CO2 emissions and of pollutants such as SO2, NOX and dusts.

Nuclear sector is commonly perceived as a driver of scientific progress and innovation as well as economic development. It is expected that at least two additional jobs within the region will be generated for each single job existing in the operating NPP. Additional jobs are expected to be created at the construction stage in the form of positions related to the construction site, while indirect jobs are expected to be created in relation to each nuclear facility and fuel cycle establishment (Ministerstwo Gospodarki, 2014: 20). Furthermore, Poland is likely to benefit from nuclear energy due to immediate access to the East-Central European EU Member States and to Germany (the most significant EU market). Also, the existence of an NPP has some public benefits. These benefits include consistent operation, system stabilisation and system fuel diversity as well as fuel price hedging. Furthermore, increased diversification of supplies of fuels and energy sources has a geostrategic significance.

Thus, taking into account Polish carbon emission reduction obligations and its limited potential concerning renewable sources of energy, the energy needs of society and industry, and social, economic and political benefits of the project, the construction of an NPP appears to be a suitable option for Poland. However, the development of a nuclear power program is likely to be one of the most significant endeavours in the Polish economy in general, and almost certainly the most extensive developmental program in the Polish energy sector. Obviously, the estimation of costs and the economic viability of such a construction project are fundamental. However, similarly to other large scale infrastructure projects, the NPP construction costs tend to be under-estimated. Furthermore, the costs of NPPs are susceptible to a variety of variable and context-dependent expenditures, which results in unreliable estimates. Consequently, it is essential to identify the main factors which determine the lifetime costs of an NPP.

1.3. Motivation

In October 2016 Paris Agreement of 2015 (PA) has been ratified by Poland. In his comment, the former Minister of Environment emphasised that the PA guarantees further use of Polish extensive hard coal and lignite resources[1]. This statement

1 See the news archive on the website of the Ministry of the Environment – Ministerstwo Środowiska, https://archiwum.mos.gov.pl/aktualnosci/szczegoly/news/porozumienie-paryskie-ratyfikowane-przez-polske/ (accessed: 5.11.2019).

identifies the key barrier in non-carbon energy processing development in Poland – the availability and low price of coal against the high price of investment in low-carbon technologies, including nuclear power, is a real barrier.

In the further part of the statement, the Minister stated that Poland would reduce the emission of CO2 using the cutting edge technologies in construction of the new power blocks and by sequestration of CO2 by the forests. In this statement, neither the renewable energy sources nor nuclear power were mentioned, but they should certainly be considered in the intense discussions on climate change mitigation strategy in Poland because they are mentioned in official documents. There are several government documents important for creating national climate change mitigation strategy in Poland. The documents include 'Polish Nuclear Power Programme' adopted by Council of Ministers in 2014 (PNPP) and 'Energy Policy of Poland until 2030' adopted in 2009 (EPP2030). The last one will be replaced by 'Energy Policy of Poland until 2040' (EPP2040), which is still under preparation, as of the end of 2019. There is one more document under preparation referring directly to the decarbonising problem, i.e. 'National Programme for the Development of Low-Emission Economy' (NPDLEE).

The documents mentioned above define possible paths of changes in Polish energy system, based on economic and technological development scenarios. Since the documents have arisen before the ratification of the PA or they are still in the discussion phase, there is a need to analyse these scenarios as well as their results from the perspective of the PA. The analyses will allow to verify the underlying assumptions as well as supporting policy mechanisms and apply them while defining the national climate change mitigation strategy required in the frame of the PA. The general question is, what will be the impact of these programs on the pursuit of reducing emissions. It is essential to relate the assumptions on the NPP construction to other measures in the energy sector, to see the NPP's role in energy policy context as well as low emission economy context. Can the NPP be a significant step forward in pursuit of the reduction of GHG emissions in Poland? This reduction is the central research theme of the project.

To answer this and other questions concerning decarbonising of Polish economy, an analytical tool is needed enabling quantitative comparisons of results of different scenarios of economic and technological development – a national economy model paying particular attention to demand and supply of energy and GHG emissions. The model should enable comparisons of results of different energy mixes, and thus different low carbon energy supply options, including nuclear power, which has not been used in Poland so far. All of this leads to the conclusion that the evaluation should be made with a model integrating economic, energy and environmental issues of national economy (model of 3E type). In such a case, a multisectoral model using input-output data (I-O) is a proper choice, because such models are a standard in 3E modelling. To meet the 3E modelling conditions, the multisectoral model should be extended to cover the national energy system in a more detailed way than in standard form as well as to include emissions resulting from economic activities.

Multisectoral models vary however in terms of structure, which determines model complexity: from elementary, static I-O models to very complex, dynamic, fully integrated I-O-econometric or CGE models (West, 1995; Kratena, Streicher, 2009). The last ones require specialised computer software for their implementation and can hardly be used by non-specialist in modelling. So, the final structure of the model must be a trade-off between simplicity and complexity of the model depending on the required quality of results as well as qualifications of the final user.

The purpose of this monograph is to describe the assumptions, methodologies and data used for model building, which will help to assess the impact of changes within the energy sector in Poland – in particular in the context of nuclear power plant construction – on the reduction of greenhouse gas emissions. In order for a reliable ex-ante evaluation of the envisaged initiatives to be possible, it is necessary to identify the probable sequence of such initiatives, as well as an accurate description of the existing reality. The forecasting of the impact of the energy sector on other areas of the economy is challenging in that the sector in itself constitutes a significant part of the economy and develops with the economic cycle, other sectors of the national economy as well as the global economy. At the same time, changes in this sector are conditioned by some endogenous factors, but also factors which are extremely difficult to forecast, such as innovations, weather disasters, and even individual human errors.

* * *

This monograph is a synthesis of previous analyses referring to the anticipated changes in the energy mix as well as the construction of a model aimed at estimating the impact of the changes mentioned above on the emissivity of the economy. It is a result of a project carried out within the Coordinated Research Project (CRP) of International Atomic Energy Agency, (IAEA Research Contract No: 22416) co-financed from the funds for science in the years 2016–2019 by the Polish Ministry of Science and Higher Education (Contract No 3783/IAEA/2017/0). Other countries participating in CRP include Armenia, Australia, Chile, Croatia, Ghana. Lithuania, Pakistan, Republic of South Africa, Turkey, Vietnam and Ukraine.

The next (second) chapter analyses the existing documents and scenarios that use various methods to forecast key figures and relate to the future of the energy sector in Poland. In the light of these documents, scenarios for analysis are also proposed, which are an attempt of a synthetic and expert approach to the development challenges of the Polish economy. One particular scenario, the implications of which are analysed in the third chapter, is the launch of electricity production based on one or more nuclear power plants. This chapter discusses the CNEST model, used for the estimation of the costs of energy production in nuclear units, together with the results for Poland and the comparative analysis. The next, fourth chapter of this work contains a description of the methodological approach and the necessary relations included in the applied model, in particular, referring to key assumptions and data. The fifth chapter describes the Empower.cc.pl model, the process of its adaptation to the conditions of the Polish economy and the available data, and indicates how analysis of the model scenario proceeds. All of the data collected in the previous chapters is the starting point for the preparation of the scenarios and the analyses using the final version of the Empower.cc.pl model, which are presented in the sixth chapter, while chapter seven concludes.

2. Energy policy and GHG emissions

This chapter presents the existing forecasts for the long-term energy mix in Poland, which results from the necessity of adopting a target energy mix for modelling purposes. The target energy mix directly implies the structure of greenhouse gas emissions in the assumed time horizon, but also indirectly influences it through expenditures necessary for the achievement of the planned mix, in particular, related to possible investments in nuclear energy. The basic concepts necessary for the building of the model will be discussed and then key analytical documents, both laic and expert, will be presented, indicating possible scenarios for the development of the energy provision situation in Poland, based on various analytical workshops. Of course, there are many more scenarios and forecasts regarding the future energy mix and its implications for various areas of the economy and the natural environment. Nevertheless, all of them, in the case of Poland, reside in a specific spectrum, conditioned by geophysical and political factors, in particular, those resulting from Poland's membership in international organizations and in particular in the European Union. The analysis of the existing scenarios is, in turn, a starting point to formulate one's own expert scenarios, which will be included in the model and thus serve their intended purpose.

2.1. Energy mix issues

The concept of energy mix refers to a combination of a variety of primary energy sources serving the energy needs of a specific region. It contains fossil resources (e.g. coal, gas, oil), nuclear energy, non-renewable waste, as well as a variety of renewable resources (wood, biofuels, hydro, solar, geothermal, biogas, renewable waste, heat from heat pumps, etc.) (Bukowski, Śniegocki, 2011: 6).

The structure of the primary energy mix/mixes calculated for individual countries diverge significantly depending on the applied counting methodology or region, although traditionally the energy coming from fossil resources dominates. In turn, the primary energy as to its structure and absolute values do not correspond to the values characteristic for the secondary energy consumption, mainly but not exclusively due to losses in the conversion and transport processes. In addition, the primary energy mix should not be confused with the power generation energy mix, which represents the percentage share of various energy sources (fossil, nuclear, hydro and renewable) used to produce electricity only. The energy mix refers, therefore, to the structure of energy production and consumption according to the criterion of energy carriers or production methods. In fact, this means that we are dealing with several types of energy mixes, which may cause inconsistencies in comparing their specific types.

In order to analyze the energy structures relating to the conversion process of the primary energy contained in carriers and fuels into its secondary forms consumed by final recipients (see Figure 2.1), a calculation is performed of the energy demand included in the primary energy balance and of the energy mix connected with the secondary energy consumption including the conversion models of values between various types of mixes. Such models also take into account the structure of production and the available power of the energy-generating sources. It is aimed at finding the optimal balance between the guaranteed amount of power in the national power system and the simultaneous maintenance of the economic profitability threshold of the power supply.

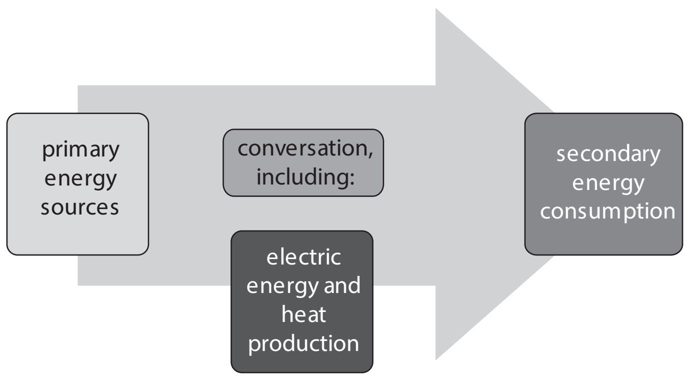

Figure 2.1. Transformation of primary energy into secondary energy

Source: own diagram.

Thus, the following types of energy mixes can be distinguished:
- demand for primary energy, divided into carriers;
- demand for secondary energy, divided into carriers;
- electricity production divided into fuels or types of power plants;
- mix of production capacity of the power plants divided into their types or used fuels.

All types of mixes will be similar to one another, in spite of differences in scope, that is, they will cover the same categories, although their results are not comparable. All types of energy mixes, therefore, refer to the same subject of research, but they present results from different perspectives.

It should be noted that the structure of production capacity is not the same as the production structure. The degree of utilization of a given power plant varies. The performance of some of the sources depends on random factors (e.g. wind), and the need to continually provide back-up power to counteract power outages in daily or seasonal fluctuations in demand or supply results in overcapacity ready for commissioning.

Each type of energy mix presents a relative share or absolute values of individual components in the secondary energy consumption or total production capacity. In their description, different units of measurement are used – for example, joules ("J") or tonnes of equivalent oil ("toe"), electricity generation in watt-hours ("Wh"), and production capacities in watts ("W"). In turn, primary energy consumption is a measure of total domestic energy demand and covers energy consumption by the energy sector itself, losses in energy conversion, losses in energy distribution and secondary energy consumption. However, it does not contain primary energy consumption for purposes not related to energy production, i.e., for example, fossil fuel consumption in the chemical, pharmaceutical and construction sectors used for the production of a number of products, for example, polyethene, polypropylene, asphalt, medicines, ethylene, mortars etc. Primary energy consumption is shown in Figure 2.2. Primary energy production contains every kind of energy extraction in a useful form, from natural sources, however, conversion of energy from one form to another, for example, electricity and heat in power plants or coke production is not considered to be primary production. Differences between production and consumption of primary energy result from the impact of export and import, the storage of energy carriers (gasoline and heating oil storage, stocks of raw materials processed in energy production, etc.), inter-sectoral transfers, own needs consumption, and finally, statistical differences. In a simplified form, the energy conversion formula is expressed as follows:

$$\text{Primary energy} = \text{secondary energy} \cdot \text{conversion factor}$$

(PEF – Primary Energy Factor/Electricity Conversion Factor).

The primary energy ratio is a link between secondary energy consumption and primary energy, and facilitates easy estimation of the latter based on actual secondary energy consumption, as explained in Figure 2.2.

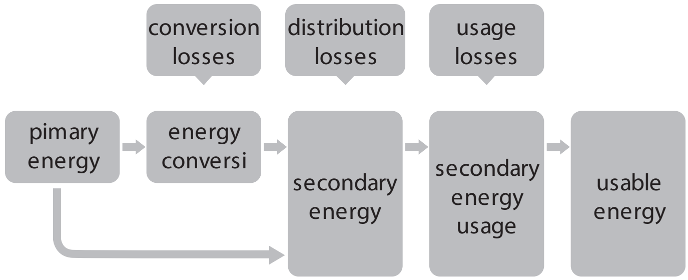

Figure 2.2. Primary energy consumption

Source: own elaboration.

Eurostat data (Eurostat, 2018) on the energy sector in Europe indicate that primary energy consumption in 1990–2016 decreased by 1.7%, while fossil fuel consumption fell by 47%, and oil consumption (including petrochemical products) by 12%. However, natural gas consumption increased by 31%, nuclear fuel consumption by 6%, and renewable resources consumption by a total of over 200%. Initially, during this period, primary energy consumption grew, reaching its peak in 2006, when it started to decline and fell by 10% by 2016. This indicates both a significant transformation of the energy mix, but also a decrease in the energy intensity of the European economy, which, despite several episodes of stagnation, developed significantly during this period of time. As a result, the energy mix has also been changing. The share of coal in primary energy consumption in the EU fell from 29% in 1990 to 15% in 2016. However, there are some significant differences between particular countries. On the one hand, we have Poland, Estonia, Bulgaria and the Czech Republic and on the other, there are Sweden, Finland, Latvia, as well as Iceland and Norway (countries of the European Economic Area). The first group of economies are based in the overwhelming majority on fossil fuels, mainly coal and lignite, and the second on the renewable energy sources (mainly hydro, geothermal and wind power plants). This has a significant impact on the level of the PEF conversion rate, since the conversion rate for non-renewable sources is at the level above 2.0, and for renewable sources within the range of 0.28–0.36. This means that energy mix scenarios containing a high share of renewable energy sources will require a significantly lower level of primary energy consumption.

In the Polish economy, after its decline in the nineties, in the first decade of the 21st century, primary energy consumption increased by 6.5 Mtoe – from 91 to almost 98 Mtoe (0.7% per year), with temporary decreases in consumption observed in 2009. According to GUS's (GUS, 2018) data, at the same time, there was an increase in secondary energy consumption from 54 Mtoe to over 62 Mtoe. This illustrates the operation of a few basic processes: the reduction of energy intensity in industry resulting in significant reduction of energy consumption per unit of product, stable decline in consumption in the household sector related to technological progress of insulation systems and heating and lighting systems, and on the other hand a significant increase in energy consumption in the transport and services sectors (Skoczkowski, Bielecki, 2016).

Taking into account the abovementioned premises, it can be noticed that the concept of energy mix aims to harmonize several variables such as demand for energy, availability of resources, in particular fuels, available technical potential and changes in the intensity of the energy consumption, that is energy efficiency. From the point of view of the overall functioning of the power system (the interest of the producers and consumers of electricity), the optimal energy mix should guarantee sufficient supply of power in the Polish National Energy System and the lowest possible average cost of power supply for all energy sources. Therefore, the basis for creating the structure of the mix is the forecast of values such as secondary energy demand, secondary energy supply or production capacity. These, in turn, should take into account a number of detailed data, starting from the dynamics of economic growth, growth dynamics in specific sectors and the resulting demand for secondary energy, price dynamics, changes in energy export and import, pace of changes in energy efficiency and energy intensity of production, as well as the costs of producing alternative options, including environmental costs, fuel prices, and finally with demographic changes and consumer habits. It will be possible to satisfy the demand for energy with the use of various solutions, including coal, gas, renewable or nuclear installations. Each of them brings with it inevitable economic, technical or ecological consequences. Long-term and medium-term forecasts should be based on the analysis of short-term index databases. For proper determination of future possible energy mix scenarios, methods from two categories are used:

- top-down descending analyses,
- bottom-up ascending analyses.

The first and most commonly used method entails considering data on a macro scale such as future energy demand, production volume and structure, imports/exports balance and as a result, determining the fuel mix structure. This method is much easier to use due to numerous simplifications.

The second approach is based on a series of data, mainly technical data of individual power subsectors, regarding power, output, network losses, so that an energy mix can be calculated from them. Their structures have a significant impact on the profitability of the entire sector and its individual parts because they affect the costs of capital investments (CAPEX) and operating costs (OPEX). The operating costs are primarily influenced by the current prices of energy carriers; however, the cost of capital investment can be estimated. Statements of average capital costs (investment expenditures) and operating costs calculated for Poland are summarized in Table 2.1.

Table 2.1. Average capital and operational costs in Poland

CAPEX Investment Expenditure	Capital cost of the installation Uninstallation cost in PLN million/MW	
Power plant – coal	6,2	
Power plant – coal (new technology)	6,2	
Power plant – lignite	7,0	
Power plant – lignite (new technology)	7,0	
Power plant – natural gas (CCGT)	4,1	
Gas turbines	3,1	
Nuclear power plant	16,3	
Nuclear power plant (partly prepared)	16,3	
Biomass	9,8	
Biomass and coal combined combustion	7,1	
Agricultural biogas plants	15,6	
Photovoltaic cells	7,2	
Small hydro plants	18,7	
Wind power plant on land	6,1	
Wind power plant on sea	13,0	
Urban cogeneration – gas	4,5	
Industrial cogeneration – gas	4,5	
Urban cogeneration – coal	8,9	
Urban cogeneration – coal (new technology)	8,9	
Industrial cogeneration – coal	8,9	
Industrial cogeneration – coal (new technology)	8,9	
OPEX operational costs	Fixed costs in PLN thousands/MW	Variable costs in PLN thousands/MW
Power plant – coal	120,0	10,5
Power plant – coal (new technology)	120,0	10,5
Power plant – lignite	132,0	12,5
Power plant – lignite (new technology)	132,0	12,5
Power plant – natural gas (CCGT)	93,0	4,2
Gas turbines	93,0	4,2
Nuclear power plant	420,0	0,0
Nuclear power plant (partly prepared)	420,0	0,0
Biomass	310,0	8,4
Biomass and coal combined combustion	124,0	11,1

Agricultural biogas plants	600,0	8,8
Photovoltaic cells	78,0	0,0
Small hydro plants	500,0	12,0
Wind power plant on land	110,0	0,0
Wind power plant on sea	520,0	0,0
Urban congregation – gas	160,0	5,2
Industrial congregation – gas	160,0	5,2
Urban congregation – coal	165,5	12,6
Urban congregation – coal (new technology)	165,5	12,6
Industrial congregation – coal	165,5	12,6
Industrial congregation – coal (new technology)	165,5	12,6

Source: based on KPRM (2015).

An alternative to the top-down/bottom-up way of dividing the methods of analysis and forecasting of the energy mix is the reference to the purposes of such analysis:

- analyses starting from the assumptions of the input data (forecasting),
- analyses starting from the output data (backcasting), i.e. indicating which of the input data will be optimal for achieving the desired effect.

To ensure the versatility of an analysis, comparison of many scenarios takes place. One of the scenarios is referred to as the reference scenario and corresponds to current trends (Business As Usual – BAU); however, the time perspective for the estimation of the energy mix plays an important role, due to the need to account for the depletion of natural resources. This is particularly important in the case of Poland, as non-renewable energy carriers in Poland are limited. Their identified inventory, along with the time perspective of exhaustion, are presented in Table 2.2. Of course, these quantities may change as far as discoveries of further deposits are concerned; however, it is challenging to expect that these changes will significantly change the current inventory of these resources.

Table 2.2. Inventory of non-renewable natural resources in Poland

Resource	Geological (billion tons)	Industrial (billion tons)	Extraction (billion tons per year)	Exhaustion timescale (years)
Coal	60	4.0	78.0	50
Lignite	18	1.3	59.0	22
Natural gas	143	73.0	5.0	15
Crude oil	24	15.0	0.7	21

Source: own calculation, based on the Polish Geological Institute (2017).

The above data shows that lignite will still be an essential fossil fuel component of the energy mix until about 2030, but it will probably not constitute a significant alternative by 2050 and in the following years. Domestic natural gas and oil resources are minimal, and even with intensified exploration, they are not a suitable fuel base for the power sector, which uses imported resources in technologies based on these raw materials. The potential future share of shale in the energy mix is still unknown and, therefore, there are no reasons to include this resource in the forecasts as a real element of calculation. Therefore, it is necessary to include in the forecasts a significantly decreasing or at least not a growing share of coal, a slightly growing or stable on the short term share of lignite, stabilized share of crude oil and natural gas and a growing share of other resources, mainly renewable energy sources (mainly wind). These tendencies, however, cannot be extrapolated to infinity due to the rapidly changing environment. Taking into account all the most important geological, technological, economic and political factors, the following megatrends can be distinguished:

- the abandonment of highly carbon-emitting technologies, mainly of the outdated type,
- limited possibilities for the use of carbon technologies with CO2 capture due to technological limitations (drastic decrease in efficiency of the energy blocks),
- irrevocable effect of coal substitution by other types of energy sources, such as nuclear fuel or renewable sources,
- increase of electricity liquidity through cross-border connections and growing share of energy import and export (moving away from the energy autarky).

2.2. Analytical review of official strategic documents

The crucial role of energetics in the structure of the Polish economy, combined with the awareness of the restrictions related to the current energy mix (depletion of deposits, high emissivity) made it the subject of interest for both state bodies and research institutions. Over the last decade, a number of institutions, both domestic and foreign, have developed and described, using macro and microeconomic as well as technical data, available optimal or highly probable energy mixes. The following section presents the most important ones, describing both the methodology for their preparation and the results of the forecasts. One should note that all of them exist within the spectrum of natural conditions described above, and take into account their dependence to a lesser or higher degree on geopolitical premises, international obligations as well as forecasts in the field of technology development.

2.2.1. Analysis of The Chancellery of the Prime Minister

The forecast for the secondary electricity demand in Poland by 2060 was the starting point for this study (KPRM, 2015). At the same time, the convergence of the energy intensity of the Polish economy to the level set by the least energy-intensive Western economies was assumed. The United Kingdom, Germany and France were selected as the reference points, where the energy intensity of the economy fluctuates around 0.23 kWh/USD of GDP and is relatively stable over time. To determine the forecast of electricity consumption, it was assumed that:

$$\boldsymbol{D_t} = \boldsymbol{Y_t E_t}\,, \tag{1.1}$$

$$\boldsymbol{E_{t+1}} = \lambda E_t + (1-\lambda)E\,, \tag{1.2}$$

where:
Dt – demand for electricity in year *t* (consumption in kWh),
Yt – Gross Domestic product in year *t*,
Et – energy intensity of the economy in year *t*.

E corresponds to the minimum energy intensity, set at 0.23 kWh/USD of GDP (average energy intensity of Germany, France and Great Britain). The λ parameter was set at 0.966.

The optimal mix calculation was made for different levels of power demand based on gross domestic electricity consumption (155 TWh) and the resulting average power demand in the power system at about 17.7 GW and at the peak, at about 25.5 GW. Thus, the assumption was made that the surplus of the maximum demand for power during the year is approx. 44% of the annual average value. The assumed safety margin relative to the production implied by the maximum demand should amount to approx. 18%. Ultimately, therefore, the ratio of available capacity along with the reserve in the months of the highest demand to the average annual demand amounted to approximately 165% and the power losses due to maintenance shutdowns amounted to approximately 9.5% of the installed capacity. The transmission losses of the National Power System were calculated on the basis of data concerning the balance of electricity in professional power grids and on this basis it was found that the average loss ratio for all lines is 7.2%. Therefore, the approach in terms of methodology is complete but contains data referring to the current technical condition of the energy system. The analysed scenarios included:

- agreements for new mine-building investments or total abandonment of new lignite deposits,
- construction of a nuclear power plant or complete exclusion of this technology.

In addition, the following cases were considered:

- maintaining a minimum share of renewable energy sources in electricity production at the level of 19.1% from 2020 to the end of the horizon or its increase in the years 2020–2050 to 50%,
- reduction of CO2 emissions by 80% in the years 1990–2050,
- the possibility of extending cross-border connections to 4.4 GW in 2030,
- reduction of the required power reserve from 18% to 13%,
- high vs low emission costs – two critical emission permit price scenarios. As a result, a series of energy mixes scenarios were obtained (for better readability presented only in relation to electricity production), which are presented in the next sections of the chapter.

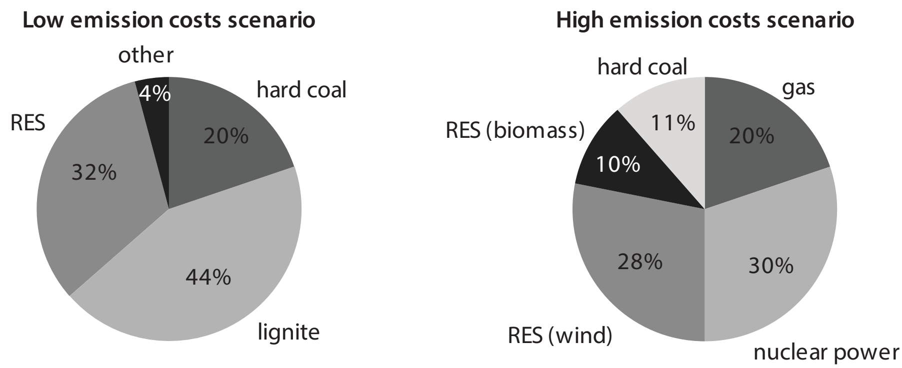

Figure 2.3. Economic option (BAU – basic)

Source: based on KPRM (2015).

A strong dependence of the structure of the forecasted mixes on the scenario of the evolution of the costs of CO2 emission permits must be noted (Figure 2.3). In the low permit costs scenario, the economically optimal mix is based mainly on hard coal and lignite power plants. In the case of high permit costs, atomic technology dominates (limited in the model to 10 GW of installed capacity), followed by wind farms and gas power plants. Both scenarios assumed the use of some of the gas-fired power plants as reserve or peak power, which results from the relatively low construction and maintenance costs of this type of power plant and high prices of natural gas. Due to the shortages of the power reserve and the necessity to fulfil the 20% share of RES, a share of biomass/biogas plants was assumed.

In the scenario assuming high emission permit prices, the share of coal and lignite power plants in the mix completely disappears. The installation of new, already prepared investments in hard coal power plants (approximately 4 GW) is only recommended in the first years of the scenario. The coal power plants are replaced by natural gas-fired power plants and nuclear power plants. At the moment of natural shutdown of lignite-fired power plants and the expiration of most of the installed capacity in hard coal-fired power plants, the share of wind farms on land as well as nuclear and gas plants almost doubles. It should be noted that such a scenario implies a significant displacement of expenditures, and in relation to wind energy, it disregards the ability of effective acquisition and installation of such resources. In this context, this scenario is, therefore, questionable in terms of technical feasibility.

The nuclear power scenarios (Figure 2.4) envisage construction and commissioning of nuclear power plants (at least two) in 2024–2035 time period, with a total installed capacity of 6 GW.

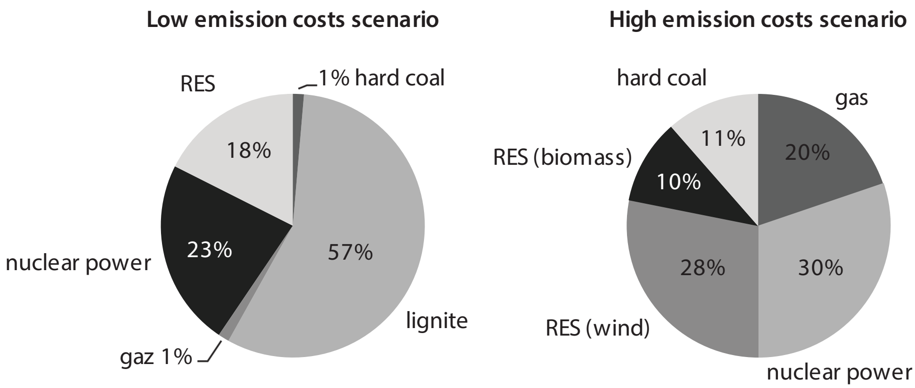

Figure 2.4. Nuclear power construction scenarios

Source: based on KPRM (2015).

The inclusion in the forecast of the construction of a nuclear power plant changes the mix structure only for the low emission costs scenario, in which this technology did not occur so far. The second scenario is almost identical to that obtained in the base variant because its structure included installations of the nuclear power plant. As a result of the decision to build a nuclear power plant, the dynamics of the installation of new hard coal power plants did not change significantly. Despite the construction of 6 GW nuclear power plants, investments in new lignite-fired power plants, based on new deposits of this resource, remain beneficial for economic reasons.

The construction of nuclear power plants results in the mix's cost increase by approximately PLN 2.2 bn annually. On the other hand, a much smaller increase in emissions is estimated – only about 26% (while in the economic variant, this increase is estimated at 57%). In addition, a 10% increase in import intensity of the energy sector is expected, which is related to the import of nuclear fuel.

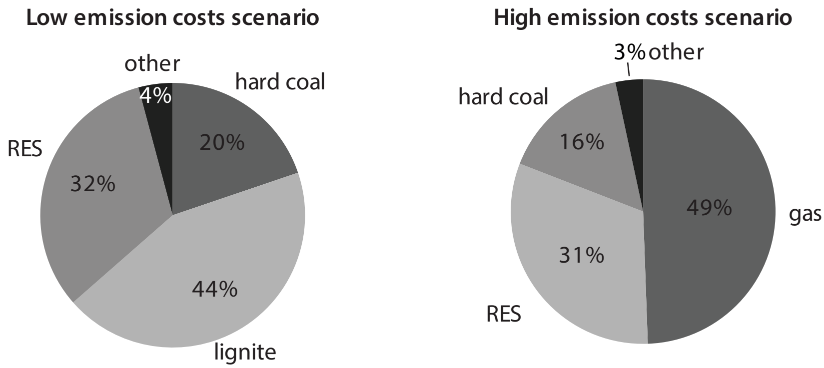

Figure 2.5. Resignation from the construction of a nuclear power plant

Source: based on KPRM (2015).

The structure of the mix in the absence of the construction of a nuclear power plant (Figure 2.5) in case of low emission costs does not differ fundamentally from the structure of the base option. In the high-cost scenario, energy from nuclear power plants has been replaced by new capacities in natural gas and wind farms. The cost of the mix is similar (cheaper by about 1% than the economic option in the scenario of high emission costs, which corresponds to approximately PLN 0.7 billion per year). Significant differences are visible in the forecasted emissivity. The use of nuclear energy would result in a reduction of about 45% in emissions, whereas in the option of abandoning the construction of nuclear power plants, the decrease would be around 30% (for the high emission costs scenario). Of course, this scenario does not take into account changes in the emissivity of other parts of the economy, which may also be influenced by changes.

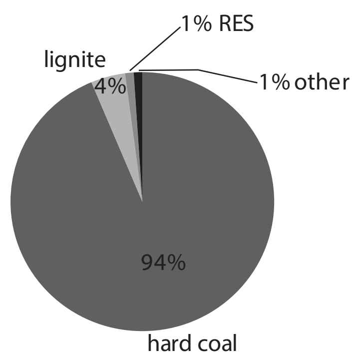

Figure 2.6. Lack of new lignite deposits

Source: based on KPRM (2015).

The lack of new lignite mines (scenario presented in Figure 2.6) significantly reduces the presence of coal technology in the mix, assuming the low CO2 emission cost scenario. The launch of new power plants based on currently operated lignite deposits is limited in this variant only to the activation of additional power in a small capacity (around 2 GW), while in the economic variant, new power plants of this type are regularly commissioned for a total power almost 10 times bigger. Lower energy production from lignite-fired power plants has been replaced with a surplus produced by coal-fired power plants. The cost of the mix has not changed. However, import intensity increased significantly (71.5% compared to 53.5% in the economic variant). Emissivity has slightly improved, although it is still high – the increase in emissions would be around 46%, or 10 percentage points fewer than in the base variant, due to the lower emissivity of hard coal. The limitation of lignite extraction would not influence the optimal structure of the energy mix in the scenario of high CO2 emission costs.

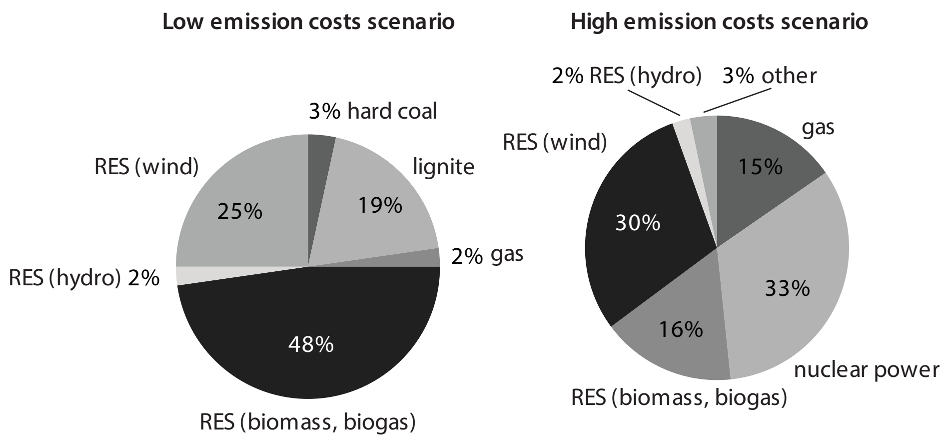

Figure 2.7. A gradual increase in the required minimum share of RES from 19.1% in 2020 to 50% in 2050

Source: based on KPRM (2015).

In both scenarios presented in Figure 2.7, the required RES share influenced by international commitments is guaranteed, in an optimal mix, primarily by wind farms, biogas-powered power plants, small hydroelectric plants and biomass-burning installations, although the model does not address the technical limitations of the implementation of this type of solution (e.g. areas with a sufficient wind intensity). In both scenarios, reserve power is created by natural gas-fired power plants. In the low emission costs scenario, the remaining part of the mix are coal-fired power plants. The increase of the RES share in this scenario forced an increase in the cost of the optimal mix compared to the BAU baseline scenario, estimated at about 13%, or about PLN 6.3 billion annually. The emissivity of the mix decreased significantly and was estimated at around 57% in comparison to the baseline scenario. Assuming high prices of CO2 emission rights, the change in mix structure was significantly lower (there was an increase in energy production from wind farms and biogas plants). The projected impact on the cost of the optimal mix is insignificant (increase by about 1%), while the improvement in emissivity by about 80% is essential. The material also analyses a number of sub-scenarios by introducing additional decision variables such as: the possibility of launching additional lignite deposits, reduction in the level of emissions by 80%, extending cross-border connections to 4 GW in 2030 together with ensuring delivery guarantees at specified times and lowering the required power reserves from 18% to 13%. Regardless of these variables, the critical issue affecting the forecast remains the emission costs, directing the forecast towards solutions based on further use of coal or alternative solutions.

2.2.2. Scenarios of the Warsaw Institute for Economic Studies

Five alternative scenarios were developed and analysed in the study (Bukowski, 2013), which discussed their advantages and disadvantages, as well as their costs and benefits in comparison with the reference scenario ("BAU" – as in Figure 2.8), in which the coal orientation of the Polish energy sector is maintained. It was assumed that the reduction of emissions from the energy sector (by 70–80% compared to 1990) is necessary and entirely achievable at costs comparable to the reference scenario and in the absence of emission fees. In a situation where the reduction target would be higher (90%), it was considered necessary to use relatively expensive CCS technology – carbon sequestration, the economic feasibility of which would depend on the future level of emission costs. In the case of progressive increase of permit costs up to EUR 45/tCO2 assumed in the report, the cost of the coal scenario in 2050 would be much higher than the cost of almost zero-emission energy equipped with CCS systems. The lower cost of modernization scenarios also means lower expected energy prices for end consumers. In 2050, they would pay more or less the same price for electricity as German consumers pay today, while the level of emissions – both individual and aggregate – would be significantly smaller. According to the authors, this illustrates the potential that, thanks to technical progress in the field of renewable energy and the skilful application of zero- or low-emission conventional technologies, is associated with the proposed ways of the energy sector's modernization. In order to determine the energy mix scenarios, it was assumed that:

- the modernization of energetics should aim at a diversified, stable and environmentally friendly energy mix;
- significant (70–80%) reduction in emissions in the energy sector is possible at a cost fully comparable to the cost of the carbon scenario, but the condition is to abstain from CCS;
- using CCS would mean a 90% reduction in emissions; however, the total cost would also increase; the costs of transformation of the energy sector would still be a small fraction of the whole economy;
- the key to success of the low-emission modernization is a skilful use of a variety of energy technologies with particular emphasis reserved for distributed generation based on renewable sources.

As a result, the following scenarios of energy mixes were obtained:

- Basic BAU scenario (coal dominance, emission reduction),
- MOD – Full diversification (includes nuclear energy),
- MOD – French model (significant share of nuclear energy),
- MOD – European coal (high share of coal plus CCS sequestration),
- MOD – Distributed self-sufficiency (significant share of gas),
- MOD – Distributed integration (increase in imports).

The following conclusions were made in the material:

- Hard coal remains the most important source of energy in the electricity generating sector; however, its share will be reduced significantly over time.
- Lignite will be less and less competitive due to the increase in the emission permits' costs.
- Nuclear energy will develop gradually; its share in 2050 will be limited by the time frame and stagnation of demand in 2040–2050.
- Renewable energy sources will develop on two levels – systemic (wind farms) and dispersed (mainly photovoltaics, but also biogas plants). These sources will already have achieved competitiveness before 2030, but their participation will be limited by technical factors (limited availability of sources, limited potential of biogas plants).
- Gas power will act as a reserve and will supplement the limited capacity power within the electricity market, and will also fill the niche in the heating sector.

It should be noted, however, that the study mentioned above, while creating the energy mix scenarios, used comparative methods against global and European trends, combined with abstraction from endogenous factors of the Polish economy. This gives more extensive differences in the presented structures of energy mixes with a lower level of confidence and lower probability of their implementation.

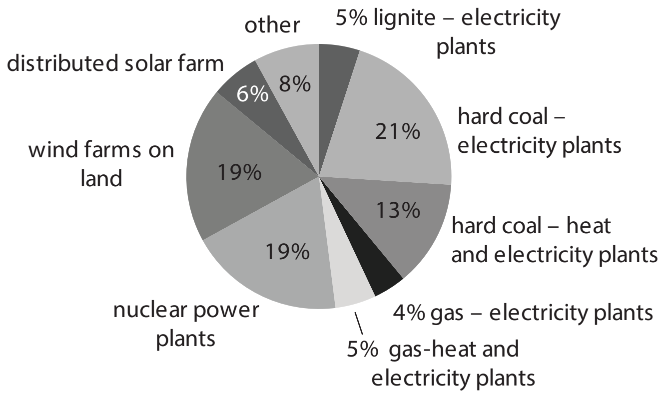

Figure 2.8. Forecasted energy mix in Polish electric power industry in 2050

Source: based on Bukowski (2013).

2.2.3. The assumptions of the Ministry of Energy

The Ministry of Energy presented assumptions for the energy mix of Poland until 2030 (Ministerstwo Energii, 2009), which assume that the percentage share of hard coal and lignite will be reduced. However, as a result of the growing demand for energy, the generation of electricity from coal is to remain at the same level as today. The energy mix in this approach is to be based on hard coal and lignite in 60%. However, it has not been precisely specified what exact share of these two raw materials will be present in the mix. This uncertainty results from the ongoing analyses of new concessions and lignite deposits. Analyses regarding the amount of available resources are still being carried out.

The National Energy System (KSE), based mainly on coal-fired power plants, is one of the largest in Europe; its installed capacity has already exceeded 40 GW. Total installed capacity in coal-fired power plants is 28.638 MW, which is over 70% of installed capacity, while electricity production in these sources is over 83%. The age structure of boilers and turbine sets operating in Polish power plants indicates that over 60% of them have been working for over 30 years. Hence the conclusion that in the next 20–30 years they will be gradually withdrawn from the power system. As early as 2018 blocks in the following power plants should be decommissioned: Adamów (5 × 120 MW), Bełchatów (2 × 370 MW), Łagisza (120 MW), Łaziska (2 × 125 MW), Siersza (120 MW) and Stalowa Wola (120 MW).

In 2016, the Polish power industry was based on hard coal and lignite in nearly 85% (Figure 2.9). Thus, it reduced its dependence on this raw material by less than 15% in the last 25 years. Over the next 13 years, the dependence of the Polish power industry on coal is, according to assumptions, to fall by nearly 25%. The production of electricity from coal is expected to remain in the next few years at a similar level as currently, counting in absolute terms. The Ministry of Energy has also taken into account the significant increase in electricity demand in the Polish economy and in Polish households (Figure 2.10). This increase is to be covered by the remaining elements of the Polish energy mix: gas, renewable sources (especially offshore wind farms) and a nuclear power plant.

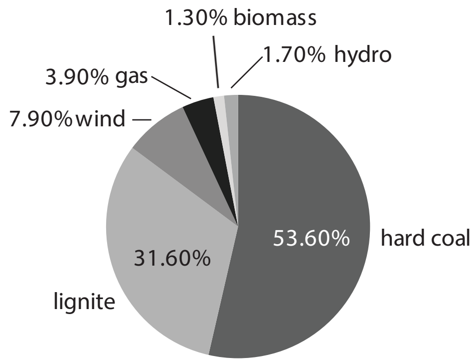

Figure 2.9. Baseline scenario BAU

Source: based on Ministerstwo Energii (2009).

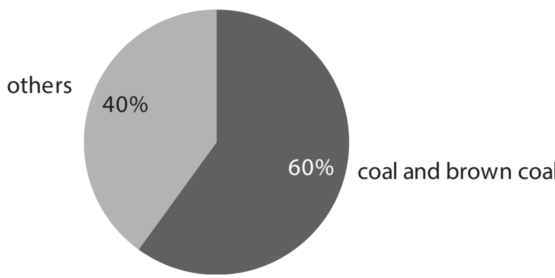

Figure 2.10. Mix 2030

Source: based on Ministerstwo Energii (2009).

The assumptions illustrate the maintenance of “coal first” policy, i.e. the policy of the primacy of coal with the admission of admixture of new sources, whose structure will depend on Poland’s possibilities, which are yet to be determined.

2.2.4. Forecasts of the Energy Market Agency

The main objective of the Energy Market Agency’s forecast accompanying the Polish Energy Policy until 2030 was to check whether and to what extent the activities envisaged by it will meet the adopted policy objectives, i.e. improvement of energy efficiency, development of competitive energy markets, diversification and increase of energy supply security, development of RES and meeting the greenhouse gas reduction commitments. Two primary documents have been prepared:

- Fuels and energy demand forecast until 2030, Agencja Rynku Energii S.A. (ARE, 2009).
- Fuels and energy demand forecast until 2030 – update, Agencja Rynku Energii S.A. (ARE, 2011).

Additionally, National Energy Conservation Agency S.A. (KAPE) prepared "Fuels and energy demand forecast until 2050", using the methodology and results of the Energy Market Agency" (KAPE, 2013). The purpose of the documents was the ex-ante evaluation of the effects of the implementation of the set of solutions presented in "The Politics of Polish Energetics until 2030". The update of the ARE forecast has been prepared as part of the works on the Nuclear Power Development Program in Poland. In turn, the fuel and energy demand forecast until 2050 prepared by KAPE S.A. was created with the assumption of realizing the directions recorded in the Energy Policy of Poland until 2050 (Figure 2.11). The main assumptions adopted for the calculations were as follows:

- international pressure to reduce greenhouse gas emissions will be maintained, the European climate policy will be continued as a result of the EU ETS system's operation, and a gradual increase in the prices of CO2 emissions permits will take place. For the purpose of the forecast, the adoption of the most ambitious targets for CO2 emissions' reduction by 2050 (by 80% relative to base year – 2005) was not assumed;
- RES will be present in the country's energy balance, and RES targets for 2020 will be maintained until 2050, but without their further development;
- a policy aimed at improving energy efficiency of the economy will be continued and will result in energy intensity decrease to the level of EU average in the base year;
- development of European energy markets (including the power market) and transmission infrastructure will take place, which will ensure diversification and stability of energy supplies including the improvement of import possibilities;
- the Polish nuclear energy program will be implemented with the possibility of further development of nuclear power after 2035 in the case of feasibility of further nuclear power plants construction;
- current environmental regulations will be implemented, in particular, those concerning emissions of SO2, NOx and dust in the power industry;
- due to the high degree of uncertainty regarding the prospects for using natural gas and unconventional oil (shale) in Poland, their production will be maintained at a low level similar to the one for the entire forecast period;

- no restrictions of availability were assumed for hard coal, oil, natural gas and nuclear fuel in global markets; hence the ability to meet the demand for these fuels within the economy through import was assumed;
- the forecast of import prices in Poland was developed on the basis of the New Policies scenario of the International Energy Agency.

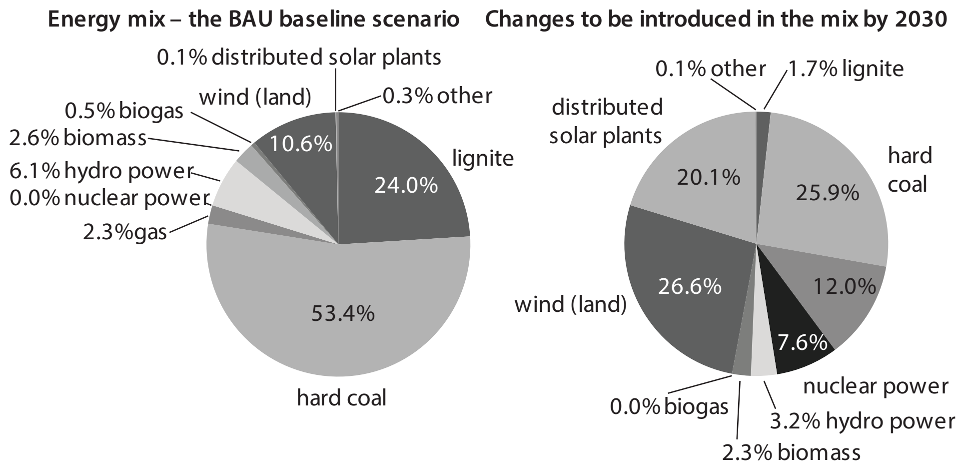

Figure 2.11. ARE Scenarios

Source: based on ARE (2011).

According to the forecast, by 2020 CO2 emissions will be reduced by approximately 15% compared to 1990, and in 2030 they will remain at 8.5% below the 1990 level. By 2030 energy efficiency will reach the level of EU-15 countries from 2005. In 2020 18.4% of electricity will be produced by RES and in 2030 – 18.2%. The main conclusions from the study are to do with the cost competitiveness of nuclear power plants. Higher capital expenditures (EUR 67.8 billion in the base variant with nuclear power plants (Figure 3.9) and EUR 60.6 billion in the variant without them – the main difference in the years 2020–2025) will be reimbursed due to lower fuel and emission costs. The analysis shows that nuclear power plants not only significantly reduce greenhouse gas emissions (reduction of the electricity sector emission by a dozen or so per cent by 2030), but they also reduce the impact of fluctuations in CO2 emission costs on energy prices in Poland and do not cause their increase.

2.2.5. Deloitte report for the Ministry of Economy

The critical issue addressed in the study titled "Polish power industry ahead of the changes" (abbreviated in Baranowska-Skimina, 2011) is the fact that the Polish energy sector will need significant capital investments. This is a natural consequence of the ageing of the existing power plants and transmission installations. Similarly to the previously discussed reports, data on infrastructure deterioration are presented – nearly 40% of power units in Poland are over 40 years old, and over 15% are older than 50 and eligible for immediate shutdown. Modernization expenditures are also forced by EU requirements, in particular concerning the reduction of dust, nitrogen oxides and carbon dioxide emissions. The need to comply with emission requirements may be the reason for compulsory shut-down of the power units which use high-emission coal. In this context, the total funds necessary to modernize the Polish energy sector (investments in energy blocks and the transmission grid) have been estimated at PLN 150–200 billion over the next 15 years. Investment processes will have a significant, if not decisive, impact on the change in the structure of energy generation and of the energy mix. Not all factors are yet sufficiently recognized as far as the necessary investments are concerned, but essential trends in the Polish energy sector should be noted. The report describes the following tendencies:

- reduction of emissions and the counteracting of climate change,
- development of technologies for renewable energy sources (RES) and technical possibilities of energy generation,
- increased decision-making role and public awareness,
- reduction in the importance of fossil fuels, mainly coal,
- improvement of energy efficiency,
- new business models and the role of traditional energy companies.

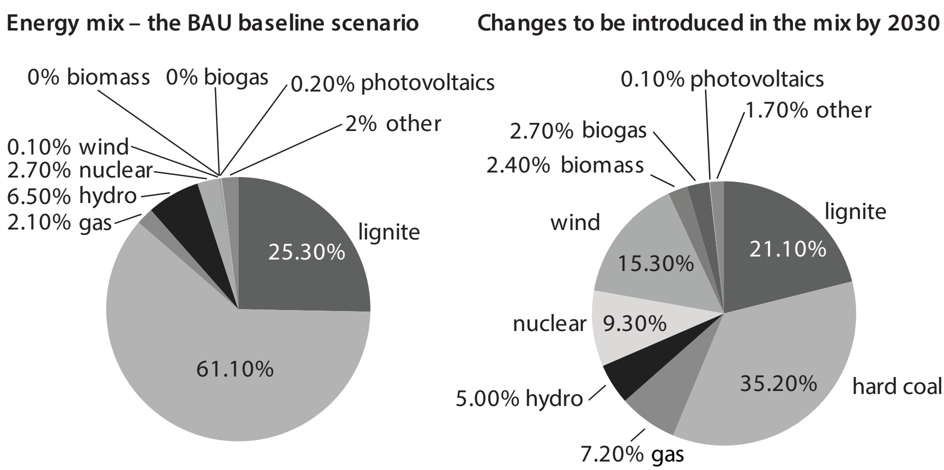

Figure 2.12. Deloitte report energy mixes

Source: based on Baranowska-Skimina (2011).

All of the above are not temporary tendencies, and their impact will be comprehensive, that is, they will interact with each other but to various degrees. The energy mix will thus reflect their future importance and impact. The report does not present the influence of one individual factor at any given time, rather their collective influence on the Polish power industry. As a result of the recognition of these factors, two critical scenarios are presented, which are depicted in Figure 2.12.

2.2.6. Scenario analysis "Coal in the Polish energy sector by 2050"

The report (Gawlik, 2013) focuses on the mining industry in Poland but also presents fuel scenarios for the power industry. The analyses of fuel and energy systems were made based on three models:

- TIMES-PL – optimization model of fuel and energy system development,
- PolPower – a model of the electricity generation sector,
- POLYPHEMUS – power industry's pollution distribution model.

The first model reflects the system in a general way, and it is simplified, mainly in terms of temporal resolution. It allows for the performance of long-term analyses and optimizing fuel structure. The PolPower model is a supplement enabling analysis of the functioning of individual generating units (power units), hourly resolution and modification of the mix. The last of the 3 models makes it possible to analyse the spatial distribution of pollutants. Based on these models, 16 scenarios were prepared:

Scenario 1: Reference scenario (REF)

Base variant, referential. Domestic demand is met with surplus until 2040. After this time, the energy sector will have consumed almost all available fuel supply (Figure 2.13).

Scenario 2: Reference scenario with increased demand (REF-HIGH)

This scenario differs from the reference scenario (REF) in its higher demand for electricity (other parameters remain at the reference level). This results, in the last decade of the forecast, in the increase of demand for coal exceeding the level of domestic supply and the import levels so far. In comparison with the REF scenario, the energy sector's demand for coal would be higher by around 7%. It is a scenario with the highest (calculated in model calculations) demand for coal (Figure 2.13).

Scenario 3: Reference scenario with reduced demand (REF-LOW)

In this variant, the demand for electricity is assumed to decrease in comparison with the reference variant (other parameters remain at the reference level). This results in a considerable surplus of supply throughout the forecasted period, exceeding significantly the demand for coal in the energy sector (a drop in demand by approximately 8.8%).

Scenario 4: Reference scenario with high emission costs (REF-CO2 HIGH)
This scenario differs from the reference scenario (REF) as far as the costs of CO2 emission permits are concerned (other parameters remain at the reference level). Nevertheless, in the last decade of the forecast, the demand for hard coal in the power industry will have grown (as compared to the REF scenario), because high costs of emission permits limit lignite consumption.

Scenario 5: Reference scenario with high fuel prices (REF-PLUS)
The scenario assumes high fuel prices (other parameters remain at the reference level). This change has minimal impact on the demand for coal, which is practically no different from the reference scenario (REF).

Scenario 6: High (HIGH)
The scenario assumes high levels of the following parameters: demand for electricity with high fuel prices and high costs of CO2 emission (other parameters remain at the reference level). In this scenario, the competitiveness of coal within the power industry will have fallen sharply.

Scenario 7: Stabilization (STATUSQUO)
This scenario differs from the reference one (REF) only in the supply of domestic coal, which is low in this case, and the raw material's deficit would be covered by imports.

Scenario 8: Degression (COLLAPSE)
In this scenario – in addition to low domestic coal supply – low demand for electricity was assumed while at the same time high fuel prices and high costs of CO2 emission permits were assumed (low demand and supply of coal).

Scenario 9: Gas (GAS)
This scenario is characterized by a higher than the reference scenario's supply of gas from domestic sources and lower gas prices (other parameters remain at the reference level). Compared to the REF scenario, the demand for coal in the energy sector is lower by several million tons in 2030–2040, as gas becomes a more competitive fuel (Figure 2.14).

Scenario 10: Gas with high emission costs (GAS-CO2 HIGH)

This scenario is a modification of the gas scenario with high costs of CO2 emission permits. However, the change in this parameter means that the demand for coal in the power industry falls and the surplus of it grows. This is a scenario in which model calculations give the lowest level of demand for hard coal within the power industry (Figure 2.14).

Scenario 11: Nuclear (NUCLEAR-MIX)

In this scenario, it is assumed that after 2025, three nuclear units will appear successively in the energy system (1.5 GW each). As a consequence, coal within power industry will be in lower demand (in the range of 11–13 million tons per year in comparison to the REF scenario) – by 2050 this decrease would reach almost 30% (Figure 2.15).

Scenario 12: Nuclear with a high power increase (NUCLEAR-MAX)

This scenario assumes maximum power gains from the nuclear power industry (increases by 1.5 GW every 5 years, starting in 2025), and high costs of CO2 emission permits. The demand for hard coal in the power industry falls clearly in the years 2030–2035, then it grows and drops again. Due to the high costs of emission permits, nuclear power is more likely to replace lignite. Oversupply of coal is noticeable until 2035 (Figure 2.15).

Scenario 13: Implementation of CO2 sequestration technology (CCS)

In this scenario, it is assumed that CCS technologies will reach commercial maturity by 2025 (2030 was typically considered the reference year), and the costs of CO2 emission permits will be high. The demand for hard coal in the energy sector, determined in model calculations, will be the same until 2030 as in the reference scenario, and then it will increase (Figure 2.16).

Scenario 14: No implementation of CO2 sequestration technology (WITHOUT-CCS)

In this scenario, it is assumed that CCS technologies will not be implemented commercially within the forecast horizon, while the costs of CO2 emission permits will be high. As a result, demand for hard coal in the power industry after 2035 will clearly fall, increasing the supply surplus above the level of average demand from other recipients. The WITHOUT-CCS scenario results in the second-lowest coal consumption within the energy sector – after scenario 10 (GAS-CO2) (Figure 2.16).

Scenario 15: Increase in the share of renewable energy sources (RES)
In the RES scenario, the share of renewable energy sources in the national energy mix is higher than in the reference scenario (REF), while at the same time high costs of CO2 emission permits are present. Compared with the reference scenario, the demand for hard coal in the energy sector will be lower (Figure 2.17).

Scenario 16: Stabilization of the share of renewable energy sources (WITHOUT-RES)
In this scenario, it is assumed that after 2020 the share of renewable energy sources will not increase, but at the same time, the costs of CO2 emission permits will be high. By 2025, the demand for hard coal in the energy sector will be the same as in the reference scenario. It will fall in the next five years and in the last decade will be higher than in the reference scenario.

It should be emphasized that the scenarios refer primarily to the demand for hard coal and only on this basis, the scenarios for energy mixes are created. Some of them only slightly differ in demand for coal, and as a result, differences in energy mixes are also insignificant. They were separated only due to the impact they have on the demand for fossil fuel, such as hard coal, and the overall level of production. Some of the energy mix scenarios, which imply significant changes in the power industry are presented below in the form of figures (Figure 2.13 to Figure 2.17); however, scenarios which are modifications of one parameter in comparison to the reference scenario and do not affect the mix structure were excluded. The high and low reference scenarios give similar levels of structure and differ in the overall amount of primary energy demand.

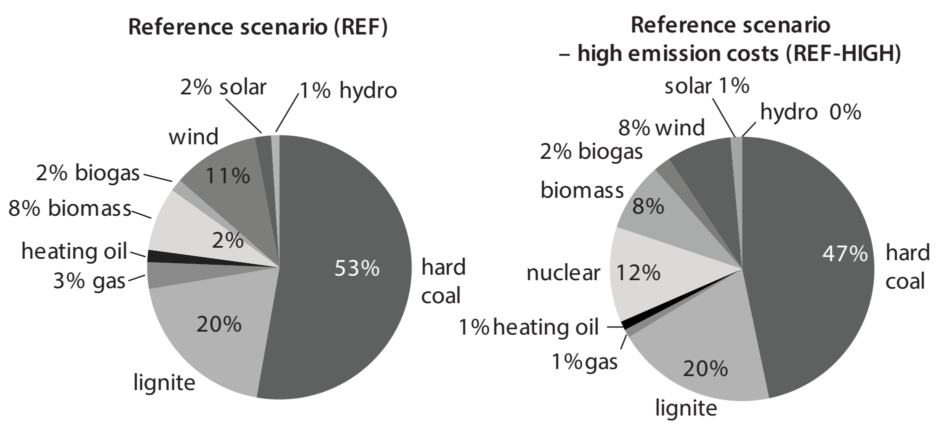

Figure 2.13. Reference scenarios

Source: based on Gawlik (2013).

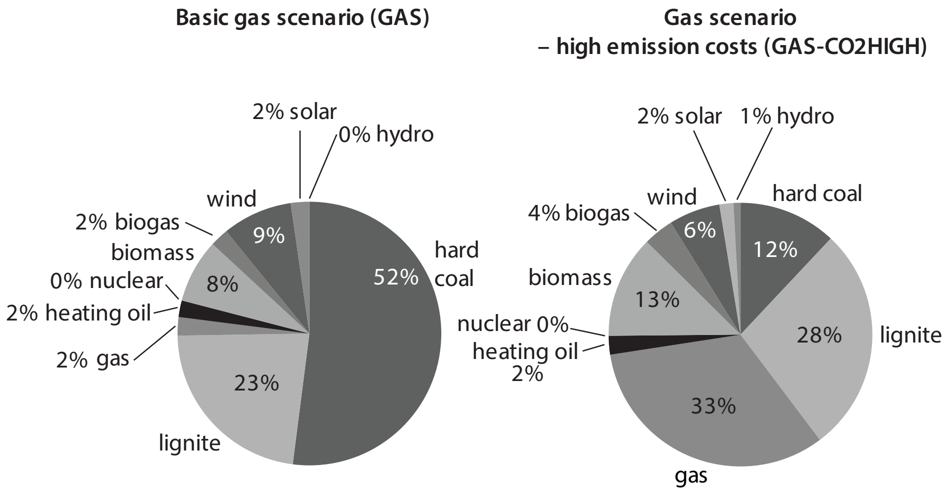

Figure 2.14. Gas scenarios

Source: based on Gawlik (2013).

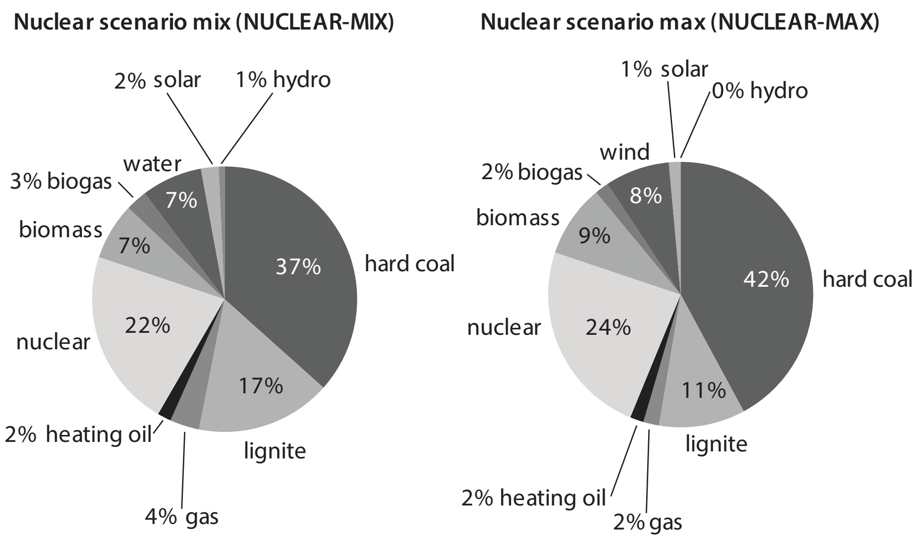

Figure 2.15. Nuclear scenarios

Source: based on Gawlik (2013).

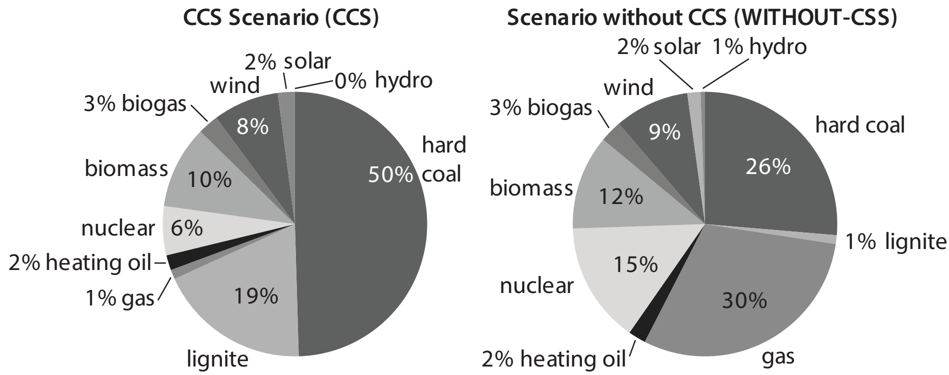

Figure 2.16. CCS scenarios

Source: based on Gawlik (2013).

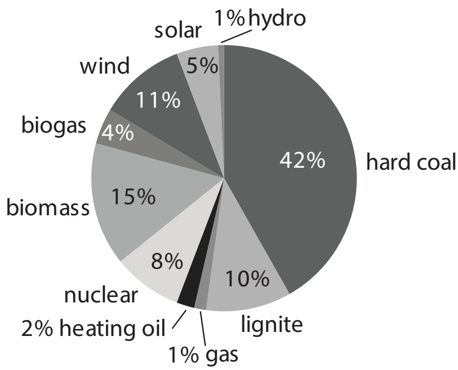

Figure 2.17. RES scenario (RES)

Source: based on Gawlik (2013).

2.3. Differences and similarities in the results of studies and their sources

The forecasts proposed by a number of aforementioned institutions agree that the energy demand in Poland will grow over the next 20 years, with additional demand being met by renewable energy, nuclear energy and gas, which will lead to the diversification of the energy mix and a decrease in it of the relative role of coal. On the other hand, the consumption of coal in absolute terms will decrease only slightly or remain unchanged, which is why it will remain a vital source of primary energy for the Polish economy. The data collected by PSE S.A. (Polskie Sieci Elektroenergetyczne) show that the current (from the turn of 2017/2018) Polish energy mix is as follows: wind farms generate 8.2% of energy, hard coal power plants – almost 47%, lignite – 33%, industrial power plants – about 7%, gas power plants – 4%, and hydroelectric plants – almost 3%.

Forecasts of energy demand correlated with GDP growth based on historical data are the critical elements in the estimation of the future energy mix. The level of energy demand growth results from the forecasts of the economic growth's pace, through the so-called energy-consumption coefficients of GDP or energy productivity (the inverse of energy consumption). However, planning of the non-linearity of economic growth and, as a result, the related energy consumption constitutes a problem. The method applied in this case was the extrapolation of the short- or medium-term trends onto a long-term trend, reaching even the end of the century. However, changes of a demographic, political and technological nature are often breakthrough, which leads to the collapse of trends, slowing or accelerating them, as well as their reversal.

According to the PSE S.A. (Polish Power Grid operator) data, consumption and production of electricity developed as in Table 2.3 below.

Table 2.3. Consumption and production of electricity in Poland 2010–2017

In TWh	2010	2011	2012	2013	2014	2015	2016	2017
National electricity consumption	155,0	157,9	157,0	158,0	158,7	161,4	164,6	168,1
Electricity production	156,3	163,2	159,8	162,5	156,6	161,8	162,6	165,8

Source: PSE (2017).

Thus, the increase in energy consumption in recent years has reached 2% per year. Extrapolation of this trend up to year 2020 has been presented on the chart below (Figure 2.18) and is well above the path assumed by the official Energy Policy (Ministerstwo Energii, 2009).

A significantly higher fluctuation in electricity production, which results from changes in the structure of energy imports and exports is noteworthy here. In recent years, Poland has ceased to be a net exporter and has become a net importer, and the levels of gross exports and imports depend on the price structure between neighbouring countries. For example, dry years cause reduced energy production in hydropower plants, and wet years – an increase in such production, which results directly in export or import by countries such as Sweden. The analogous situation applies to wind farms. Other elements influencing electricity production are the inevitable changes in energy efficiency, which is currently treated as one of the essential resources determining the rationality of energy use, and thus the consumption of natural resources. In other words, an increase in efficiency means stabilization or even a decrease in primary energy consumption, even with an increase in final energy consumption. In January 2018, the fourth "National Action Plan on Energy Efficiency" was adopted by the Council of Ministers, however, despite further announcements, Poland has no more significant achievements in the area of energy efficiency. Nevertheless, it is expected that within the next decade, Poland will reach or approach the average level of the European Union. The primary savings are to take place in the areas of construction – thermo-modernization and lighting (LEDs, integrated energy management systems). Access to European funds may be an essential factor in this area. In general, however, the most significant differences in the presented forecasts, occur in the structure of electricity carriers. They mainly result from different assumptions regarding the pace of construction of nuclear power plants, updates of raw material prices' forecasts and consideration of the effects of planned energy efficiency measures. This, in turn, translates into different predicted energy consumption as well as lower demand for new capacity of coal-based power plants. On the other hand, a number of similarities (resulting from specific endogenous factors in the power sector) between the situation in Poland and European trends are worth emphasizing:

- Polish electricity industry is dependent on fossil fuels such as lignite and hard coal in an above-average dimension. A quick reduction in the share of coal in the energy mix structure will not be possible, and the process of reducing the share of coal will require time and high investment expenditures.
- The energy and climate package and the introduced EU-ETS system increased the costs of greenhouse gas emissions (mainly CO2) for producers of electricity from hard coal and lignite. This will affect the sector in a twofold way in the foreseeable future – further increase in the emissions' costs will take place, and profitability of electricity production from coal will deteriorate. A derivative of this will also be an attitude change and an increased reluctance to invest in new coal blocks unless they are equipped with an effective CO2 sequestration system.
- The increase in the cost of emissions will result in the withdrawal of technologies that have so far guaranteed electricity production at the lowest costs, and thus an intense price pressure on electricity as a good, and hence an increase in the attractiveness of investing in non-carbon sources of production.
- About 2/3 of power units were built long ago in the era when the foundations of the modern power sector were being established – from the second half of the sixties up to the first half of the eighties. This means almost 1/5 of these units is older than 40 years, and about 2/5 are older than 30 years. Therefore, more than half of the blocks will have to be replaced or very seriously modernized over the next decade.

- echnical progress in the area of renewable energy sources is and will be intense, and the efficiency achieved primarily in the field of wind energy and photovoltaics, as well as a decrease in investment costs, will result in an increase in production from these sources.
- As a derivative of the above, the popularity of natural gas will increase as a result of gaseous power plants taking over the role of peak sources indispensable in the case of the anticipated development of non-sizable wind and solar sources.

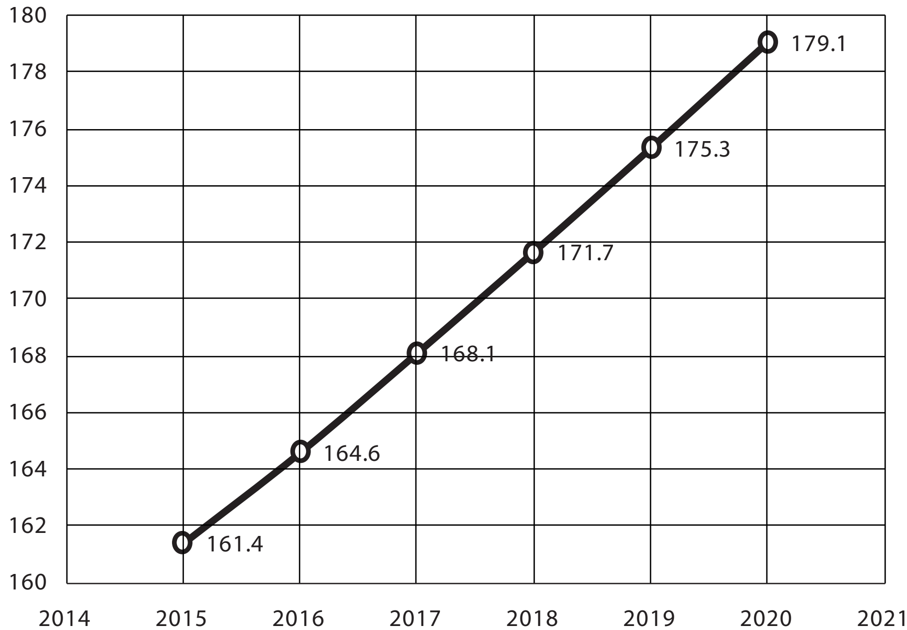

Figure 2.18. Extrapolation of electricity consumption trend in Poland

Source: own calculation.

Additionally, it should be noted that the outlooks used in the forecasts concern 2030, 2050 and even 2090. They are therefore burdened with high risk and depend on political and economic decisions that will have to be taken in the future, as well as on a number of factors such as future demand, supply, growth or stabilization of energy import opportunities (development of cross-border connections), prices of individual raw materials, technological progress, etc. In addition, the adoption of unrealistic assumptions may cause high fluctuations in the share of individual fuels in the energy mix as a result of methodologically correct calculations. On the other hand, the adoption of interval values in place of points increases the confidence level/probability of the scenario implementation. This means that the point values are markedly more erroneous than the interval values in the form of +/–15%. Such scenarios fulfil the purpose of predicting the value of a variable with a given probability. Point forecasts defined as the middle of the range were considered the best assessment of the value of the variable explained in the forecast period.

2.4. Recommended approach and recent developments

This section contains its own, proprietary, expert forecast, built for the needs of the Empower.pl model, and is an attempt to take into account the conditions resulting from the previously presented studies as well as a free assessment of the situation.

The available forecasts use the time horizon of 2020, 2030, 2050 and 2090. For the purposes of this study, the 2030 time horizon was used, for the following reasons: it is used in many studies and official documents, and it enables the use of benchmarking for data contained therein, it seems to be long enough (in relation to 2020) in order to fully implement the adaptation and modernization processes in the power sector and it gives a stronger basis for inference about the structure of electricity supply and energy mix in comparison to the 2050 or 2090 time horizons. It was also assumed that the problem of technologically and economically effective CO2 sequestration (capture and storage, or processing of carbon dioxide) would be successfully solved in the next decade, which is a sine qua non condition for maintaining the share of coal within the energy mix. The forecast also follows official government documents (PEP 2030) in which domestic demand for primary energy by 2030 does not change significantly and will remain at the current level of about 102–103 Mtoe annually. Therefore, the shares of individual energy carriers in the mix remain to be determined. The efficiencies in generating electricity adopted for this purpose are presented in Table 2.4.

Table 2.4. Expected electricity generation efficiencies

Generation type	Efficiency in %
Coal power plant	35–45
Gas power plant	47
Gas-steam power plants (IGCC)	45–55
Biomass power plants	25
Nuclear power plant (in combination)	37–41 (up to 60)

Source: own estimations.

It was assumed that the possible increase in final energy consumption, according to the trends observed by 2017, will not have a direct impact on primary energy consumption due to a significant increase in energy efficiency. This means an application of a simplified assumption that the increase in consumption will correspond to the value of efficiency of energy consumption improvement, eliminating the impact of the consumption increase. Figure 2.19 below presents the comparison of data from PEP 2030 with the extrapolation of the trend of the current dynamic increase in energy consumption.

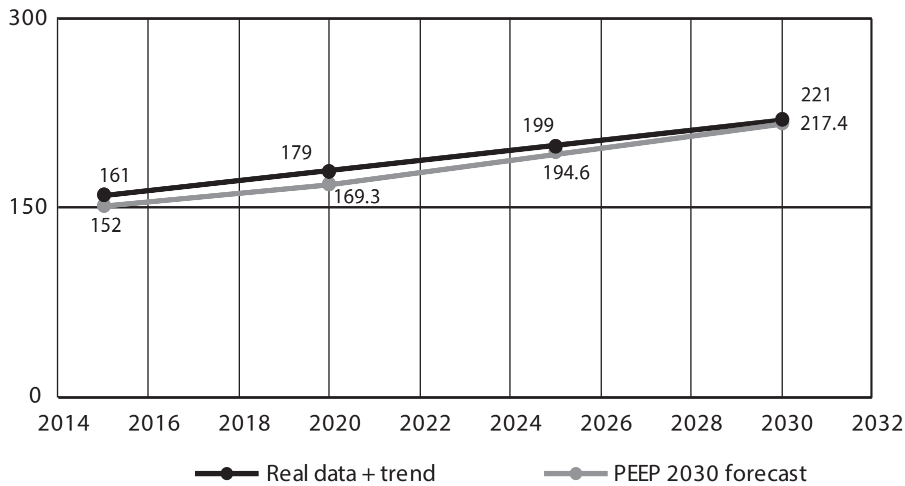

Figure 2.19. Extrapolation of the electricity consumption trend (in TWh)

Source: own estimation.

For the purposes of this document, it is assumed that 1 TWh = 85,984.52 Mtoe. The range presented in the chart for 2030, therefore, corresponds to the interval 18,693,034.65–19,002,578.92 Mtoe. On this basis, an increase in energy demand of 1.7% per year was assumed. In 2030, net energy production will amount to approximately 220 TWh. This will be the result of many growth factors, such as increased prosperity, including the development of electric transport and electrification of heating, and factors limiting demand such as the increase of energy efficiency, passive housing development and demographic changes in Poland. The growing demand for energy will be correlated with the increase in demand for peak power (from about 25 GWe to about 40 GWe in 2030). Currently, the total installed capacity in coal-fired power plants is 28,638 MW, which represents over 70% of installed capacity, while electricity production in these sources is over 83%. Due to the age of carbon blocks, the degree of their decapitalization and deteriorating efficiency, they will have to be withdrawn from production, the process, scale and speed of which are not known. Therefore, it was assumed that the following blocks would be withdrawn: Adamów (5 × 120 MW), Bełchatów

(2 × 370 MW), Łagisza (120 MW), Łaziska (2 × 125 MW), Siersza (120 MW) and Stalowa Wola (120 MW – out of three one working in the so-called "cold reserve"). On the other hand, assuming an unfavourable increase in CO2 emission costs, practically all blocks could potentially be excluded from operation, except for the most modern ones – 858 MW in Bełchatów, 464 MW in Pątnów and 460 MW in Łagisza. The withdrawal of coal blocks will require replacing them with other sources of energy generation – gas and steam blocks, nuclear reactors or renewable sources. The sum of their installed capacities should correspond to the sum of the power of the withdrawn blocks. The following are alternative development paths:

- implementation of the nuclear program in the 1.6 GW limited variant, one 3 GW plant, two – 7 GW, three with a total capacity of 9 GW or more, up to 14 GW;
- implementation of the renewable sources of energy development program, including big wind farms in the Baltic Sea with 3.2 GW capacity (in optimistic variants up to 9 GW);
- replacements of obsolete coal blocks with modern ones using the effect of coal gasification.

All of the above are possible in the 2030 time horizon (they can be implemented under certain conditions); however, the cycle of designing and building a nuclear power plant lasts about 10 years and the shortest period of construction of a nuclear power plant is 5 years.

In the materials referred to in the previous chapters, the share of hard coal in the mix varies from 2% to 72%, depending on the assumptions made for the calculations. It should be noted that both of these extreme values are highly unlikely. The real level of hard coal share in the mix is likely to be 32–54%, provided that the investment in the modernisation of the power plants is completed. The presumption of continuous lignite share in the mix is a greater difficulty due to the fact that this fuel is highly emissive, hence the high costs associated with it, and the fact that the previously exploited deposits of this raw material are now depleted. When Poland withdraws from the investment in lignite-based blocks in the future, the share of this raw material in the mix will have to drop. Therefore, the range for it was set at 14–24%. This share is possible, however, assuming an economically effective solution to the problem of carbon sequestration. Similarly unknown is the future share of nuclear energy in the face of difficulties and delays in the implementation of the Polish nuclear program. The lack of implementation of the program will result in a zero share of nuclear fuel, full implementation – in a maximum 30% share in the mix.

Renewable energy sources should not fall below the current share (13.5% according to GUS data for 2016), but the upper limit is also challenging to identify. For the purposes of the analysis below, it was assumed that this share would not exceed 38%. Within the RES group, the use of gravitational energy of water, wind energy (including construction of large offshore wind farms), solar energy, geothermal energy and supplementary energy from biomass and biofuels were assumed. Similarly, the share of natural gas depends on the relations that will be shaped in the future, that is first of all on the relation of raw material prices to electricity prices (profitability of gas blocks), energy policy of the country and acceptable level of dependence on this raw material and on the speed and development level of energy based on the renewable energy sources. It was assumed that the share of natural gas would fluctuate between 0% and 10%. The increase in the share of this resource will be impacted by the limitations related to renewable energy sources in the form of small and medium-sized wind farms (restrictions on windiness within the country), as well as limitations in solar exposure. The construction of an off-shore wind farm will not have such an impact. It is also possible to compensate for the production of renewable energy from onshore wind farms, mainly at night, with energy from other sources – not only gas but also renewable. The term "other sources" covers mainly energy imports related to transitional power deficits of the national power system. As such, they are characterized by zero emissivity, because the sources of generation are unknown, and above all, they are not located within the country.

In light of the above data and findings, the following scenarios were constructed for the 2030 time horizon:

- Maintaining the status quo assuming a reflection of the current structure of the fuel mix, extending the work of the existing power units and a full and direct transfer of emission costs or failure to meet international obligations costs to the end customer (an increase in electricity prices fully covering the increase of the power plant operating costs).
- Implementation of the nuclear program in Poland in two variants: limited to 11 GW and full – 14 GW.
- Development of energy industry based on renewable energy sources in three variants: maintenance of the status quo – 9 GW, limited development – 15 GW and full – 18 GW.

For the analysis, the set installed capacity levels were adopted, which were then recalculated using primary energy indicators. Table 2.5 presents the proposed scenarios for energy (fuel) mixes.

To sum up the above considerations, the coal mix must be based on the following scenarios for the development of the national power industry: "Carbon scenario"

– based mainly on modern coal units; “Nuclear scenario” – based on a construction of one or several nuclear power plants and “Renewable energy development scenario” including a construction of giant wind farms on the Baltic Sea and the use of dispersed renewable sources. There is also potential to create a “gas” scenario – a development of energy industry based on natural gas; however, this option does not implement the priority of energy security of the country and has not been included in the analyses.

Table 2.5. Proposed scenario for energy mixes

	Scenario I Status quo	Scenario II nuclear full	Scenario III nuclear limited	Scenario IV RES full	Scenario V RES limited
Hard coal	54%	32%	37%	32%	41%
Lignite	24%	14%	16%	14%	18%
Nuclear fuel	0%	30%	23%	0%	0%
RES	14%	20%	20%	38%	32%
Natural gas	3%	4%	4%	9%	7%
Other	5%	0%	0%	7%	2%

Source: own calculation.

The most recently (Nov 2018), issued for public consultation, document EPP2040 includes as a priority no.5 development of up to five nuclear power plants within the forecasted period and sets a date for completion of a first one in the year 2033. Taking this into account, envisaged energy mix in year 2030 supposed to be based in 60% on coal and 21% on renewable sources. Simultaneously, the efficiency of power generation is expected to be increased by 23%, together with a reduction of 30% of greenhouse gases emission. Final mix is mainly based on the use of its own energy resources, while gas and liquid fuels would supplement it in a case of shortages. Publication of EPP2040 draft has raised much controversy about its feasibility, but as mentioned above, it is still at the public consultation stage.

3. Estimates of costs of nuclear energy

3.1. Determinants of lifetime projection cost

Although NPPs share many of the characteristics of other large capital intensive infrastructure projects, they have unique and idiosyncratic features which impact their costs. The main components of nuclear power economics are capital costs and operational costs. In addition to these primary sources of expenses, there is a plethora of costs that can be considered in an estimation of the NPP construction cost.

The capital cost comprises the most significant portion of the NPP construction cost; World Nuclear Association estimates that capital costs comprise at least 60% of the Levelized Cost of electricity (LCOE) (WNA, 2018a). These costs include the cost of site preparation, construction, and financing of an NPP. Furthermore, capital costs can be calculated either with or without inclusion of financing costs. If financing costs are included, then the capital costs will depend on the construction time of the plant, the interest rate and the financing model. The second-largest sources of costs are operational costs. The operational costs include the costs of fuel, operation and maintenance, and the costs of decommissioning the plant, including waste management. Finally, other costs include the costs related to environmental concerns, system costs, nuclear-specific taxes and other possible expenditures. In the following paragraphs, I will address these costs in detail.

3.1.1. Capital costs

The main components of capital costs are overnight costs and financing costs. Overnight costs include primary the costs of engineering, procurement and construction; therefore, these are mainly project management, land acquisition, building (infrastructure and buildings) and associated contingencies costs. Building of a nuclear reactor is a massive endeavour which requires development and engagement of large and specialized workforce, large amounts of construction material (concrete, steel, etc.), production and/or purchase of particular components, and involvement of all facets of society. World Nuclear Association estimates that 80% of overnight costs concerns engineering, procurement and construction where a majority of the funds are spent on equipment, labour and materials (WNA, 2018a). The construction costs of an NPP are significantly higher than the construction costs of gas or coal-based electricity generating facilities (see Chapter 3 of this monograph). Specificity of an NPP construction assumes the use of unique materials, sophisticated technology, extensive safety and back-up control features. The NPP systems are complex and assume arrangements for providing electricity, cooling and ventilation, development of informatics systems and introduction of other technologies. Thus, the majority of construction costs will be dedicated to nuclear and conventional (turbine) islands, site development and associated works and labour.

A single, new, large capacity nuclear power unit could be expected to have a capital cost of more than several billion dollars to meet engineering, procurement and construction costs (IAEA, 2009: 6). However, the nuclear industry has recently been under pressure to reduce capital costs. The large number of operating NPPs and the experience developed through the years of operating them allowed for the development of cost-effective manufacturing and construction methodologies. These often include modular factory construction of key systems to minimize site work and time. Consequently, modern NPP designs come with higher confidence in controlled costs, and universally recognized and licensable safety features (IAEA, 2009: 6). Furthermore, construction of a series of units (of an identical type) implies reduced unit costs for each subsequent unit. However, in contrast to this development, the current official forecasts of NPPs costs have risen significantly. Namely, the projects which are currently being delivered are often first-of-a-kind, and, consequently, they are characterized by unforeseeable contingencies (Harris et al., 2012). The subsequent implementations of these new technologies should be more cost-effective; however, presently, they result in increased costs. Therefore, the choice of technology is likely to have a significant impact on the costs of an NPP construction.

On the other hand, financing costs are expected to be determined primarily by the length of construction and current interest rates on debt. The construction time includes the period from the first onsite works to the connection of the NPP to the grid. As noted above, similarly to other large infrastructure projects, NPP projects tend to be delayed and over budget. However, these are particularly critical points with respect to NPPs as historical evidence demonstrates that extended construction periods significantly increase the costs. IAEA estimates the required preparatory period with the construction of the first power station to be approximately ten to fifteen years. This expectation is dependent on the country's developmental level, including previous experience with NPP construction. On the other hand, considering the construction period itself, excluding the initial period needed for the development of the required infrastructure, the typical time for a nuclear power construction is at least five years. "The Economic Future of Nuclear Power" report notes that a shift from a five-year to a seven-year construction period is likely to increase the share of interest payments in the overall expenditure from 30% to 40% (Tolley, Jones, 2014). As noted above, the experience in developing NPPs resulted in decreased construction periods in the last decade. However, the shift to new technologies, in particular to Generation III reactors, has added further uncertainty in length and, consequently, the costs of NPPs construction projects.

On the other hand, the 2015 edition of "Projected Costs of Generating Electricity" demonstrates that economic competitiveness of nuclear power is also highly dependent on interest rates (IEA, NEA, 2015). According to these estimates, in case of a 3% discount rate, nuclear power is cheaper in comparison to the alternative electricity generating sources across states. On the other hand, at a 7% discount rate, its costs in terms of LCOE are similar to the costs of coal. Furthermore, the report estimates that the increase in discount rate from 3% to 10% results in doubling of LCOE (see Table 3.1).

Table 3.1. Projected nuclear LCOE for plants built 2015–2020, $/MWh

Country	Discount rate		
	3%	7%	10%
Belgium	51.5	84.2	116.8
Finland	46.1	77.6	109.1
France	50.0	82.6	115.2
Hungary	53.9	89.9	125.0
Japan	62.6	87.6	112.5
South Korea	28.6	40.4	51.4
Slovakia	53.9	84.0	116.5
UK	64.4	100.8	135.7

Source: IAE/NEA (2015) – Table 3.11, assuming 85% capacity factor.

There is a large variety of options for the financing of NPPs construction. In principle, nuclear power cannot be introduced in a country without some government support, and an indeed privately financed NPP has never been built. However, the crucial role of the government in the implementation of an NPP construction project is to ensure economic and regulatory stability, and credibility of the decisions with respect to the power sector. With respect to financing, some governments choose to build NPPs with their own funds or through national utility companies.

For instance, Mochovce-3 and Mochovce-4 nuclear units in Slovakia are principally financed on the basis of the investor's – Slovenske Elektrarne – operating flows. This is the model adopted by Poland, where the principal investor is PGE (Polska Grupa Energetyczna S.A.). Additional government involvement in a nuclear power project may take forms such as asset ownership, equity participation, risk sharing, or provision of various incentives, including loan guarantees (IAEA, 2008: 4).

In general, low carbon projects have proven to be financially unfeasible as pure merchant operations, fully exposed to a deregulated electricity market. Consequently, the adopted financing models are predominantly conditioned by the extent of market liberalization. In particular, long-term electricity price needs to be assured in order to justify the high costs of investment across the expected life of the plant. However, at the turn of the 20th century, there was a significant drive to privatize utilities and deregulate electricity prices (IAEA, 2009: 3). Deregulated electricity markets are susceptible to price volatility, thus exposing a potential investor to risk. If a return on investment is to be made through electricity sales generated by the new plant, then at least 10–20 years of operation would be required to pay back capital and interest (IAEA, 2009: 3). Therefore, financing of NPPs typically requires some guarantees concerning the price of electricity in the long term. These are likely more difficult to negotiate in a deregulated market than in a regulated one. Consequently, the financing models are typically a mix of governmental incentives, private investments and long-term power purchase arrangements.

A power purchase agreement (take-or-pay contract) is an agreement to sell electricity at a pre-established price for a contracted, typically long term, period. The agreement supports the loan arrangements for a project and defines the source of repayment to the investors. On the one hand, this arrangement provides a guarantee of future revenue to the owner; on the other hand, it provides a guaranteed supply at an established price for the electricity purchaser. For instance, in Turkey, in order to secure an investment in the 4 × 1200 MWe Akkuyu NPP, a formula for long-term power prices was devised, which involves the Turkish Electricity Trade & Contract Corporation (TETAS) buying a fixed proportion of the power at a fixed price of US$ 123.50/MWh, for 15 years (IAEA, 2014: 100). In the UK, the financing scheme implements a 'contract for differences' model. Contract for differences implies that if the market price is lower than the agreed 'strike price', the government or the transmission system operator pays the difference per kWh, while if the market is above the strike price, the generator pays the transmission system operator or government (WNA, 2018a). Other forms of financing, such as the Finnish Mankala model for cooperative equity, are implemented, where the shareholders receive guaranteed volumes of energy, in accordance with their equity interest and where participating companies are obliged to purchase energy at the cost of generation, irrespective of whether this cost is below or above current market price. Recently, technology suppliers have also been taking part in the financing of facilities under construction; such was the case of the Visaginas NPP project in Lithuania, in 2012.

Considering other aspects of financing, in comparison to the other industrial branches, there are more opportunities for nuclear power. Additional funds may be acquired from the European Bank for Reconstruction and Development (EBRD), the European Investment Bank (EIB) or EURATOM (via means of the Euratom Loan Facility).

3.1.2. Operating costs

While NPPs are expensive to build, they are relatively cheap to run. Once the construction is completed, similarly to hydropower plants, operations and maintenance of the existing NPPs are results in relatively low cost. As indicated above, operating costs include the cost of operation and maintenance and cost of fuel. Operation and maintenance account for approximately 66% of operating costs (WNA, 2017: 7). Operation and maintenance costs include wages, as well as costs of consumables, materials, operating equipment and purchased services. Thus, they comprise costs such as repairs and equipment replacements; staff wages; materials and supplies; utilities; annual licence charges; overheads (property taxes, insurance, etc.); administrative expenses and others. Naturally, some maintenance costs will be incurred whether or not the plant is operational and generating electricity. Operation and maintenance costs are particularly influenced by regulatory requirements. Following the Fukushima 2011 accident, additional costs result from safety reassessments such as in-service inspections, additional fire protection features, enhanced operator training or reinforced security measures.

Fuel costs account for 34% of operation costs. The main elements of the fuel cycle include:

- mining of the uranium ore,
- production of uranium concentrates,
- conversion from U_3O_8 into UF_6,
- enrichment of the uranium with the U-235 isotope,
- production of fuel materials,
- manufacture of fuel elements/assemblies,
- burning the fuel in the reactor,
- storage of the spent nuclear fuel,
- reprocessing of the spent nuclear fuel,
- processing of the radioactive waste generated,

- storage/disposal of radioactive waste (Ministerstwo Gospodarki, 2014: 123).

Naturally, each stage has its underlying cost. However, the distinctive economic advantage of nuclear energy in comparison to coal and gas-based energy generation is the low fuel costs, which contribute a relatively small portion to the overall costs. It is estimated that fuel costs for NPPs amount to about 15% of LCOE. In contrast, the fuel costs of a gas or coal power plant is about 80% or more of LCOE (IAEA, 2009: 4). On the other hand, uranium-235 isotope is expected to produce two to three million times the energy equivalent of coal. Thus, even a significant increase in fuel prices will have a relatively small effect on the overall cost of nuclear power energy. While the uranium market was stable for much of the 20th century since the 2000s, there were significant price fluctuations accompanied by a sizable price increase. Uranium ore mining in Poland may be an option to address this issue; however, the ore is unevenly deposited, and the volume of the deposits is low. Nevertheless, the raw uranium price is still a modest part of the overall production costs and, therefore, uranium mining is economically unviable.

While in itself uranium is comparatively low-priced, it has to be processed. In this regard, it has to be converted, enriched and fabricated into fuel, which may account for about 50% of the total fuel cost. World Nuclear Association estimates that fuel price is comprised of the following: 41% – Uranium; 31% – enrichment; 4% – conversion; 8% – fabrication and 16% – waste fund (WNA, 2017: 8). Only a small number of companies in the world perform the conversion and enrichment of uranium, and they are subject to political and governmental controls. However, for most of the reactors, more than one vendor is available, and the fuel supply can be diversified. Nevertheless, the issue of the integrity and reliability of the fuel supply is always present. Therefore, the issue of creating multiyear reserves of nuclear fuel is particularly important. According to Polish Nuclear Power Programme, a 12-month or a 24-month reserve corresponds to about 20 tons of fuel (Ministerstwo Gospodarki, 2014: 121).

On the other hand, as noted above, fuel cost figures include used fuel management and final waste disposal. The handling and disposal of radioactive waste is an essential issue in the application of nuclear power. Due to its particular nature, radioactive waste must be appropriately processed, solidified, packaged and, finally, stored. Radioactive waste needs to be managed in such a way as to avoid imposing an unnecessary burden on future generations (IAEA, 2007: 58). In contrast to the waste management capabilities developed for medical, industrial and research applications, additional volume and the radioactive isotopes associated with nuclear power require enhanced waste management capabilities. Most countries store low and medium level radioactive waste. However, highly active waste (e.g. nuclear fuel) requires to be stored in deep geological storage (e.g. the Waste Isolation Pilot Plant in Carlsbad, New Mexico, USA).

In Poland, the problem of nuclear waste storage appeared in the late 1950s when the first nuclear research reactor was activated. Since 1961, the state-owned Radioactive Waste Disposal Enterprise (ZUOP) in Różan addresses the issue of storage and transportation of medium-level radioactive waste. Currently, a significant portion of radioactive waste comes from the 'MARIA' reactor, while the rest comes from other institutions making use of isotopic techniques (e.g. hospitals, clinics). As it is estimated that the capacity of this storage facility will be reached as early as around 2024–2025, the most urgent task, is to build a new storage facility (Ministerstwo Gospodarki, 2014: 127). However, the issue of highly active waste presents a more demanding challenge. In 1998 ZUOP decided to establish an underground research laboratory to prepare for the long-term placement of used fuel. Five sites were considered: Lanieta, Klodawa, Damaslawek, Jarocin and Pogorzel (WNA, 2018b). Occasionally, management of spent fuel and radioactive waste might be fostered through an agreement among countries. However, it is assumed that in the initial period of the NPP operation the spent fuel will be stored within the NPP itself, while the spent nuclear fuel storage facility will have to be constructed approximately thirty to forty years after the first NPP is commissioned (Ministerstwo Gospodarki, 2014: 130).

Decommissioning costs are usually fully included in the operating costs. Decommissioning of redundant nuclear facilities involves decontamination, dismantling and demolition of facilities (IAEA, 2006: 4). Annual charges levied on electricity consumers may cover decommissioning costs. However, a range of possibilities exists. For example, in France, nuclear operators are required to establish funds covering decommissioning and waste management from the beginning of a plant's operation (Ministerstwo Gospodarki, 2014: 32).

3.1.3. Other costs

An additional type of costs that should be considered are the costs related to society; in particular the costs with respect to health and the environment. These costs are not typically included in the calculation of the costs of fossil fuel-based electricity generation facilities. If this were the case, the costs would include emissions of pollutants such as particulates or greenhouse and other gases, and they would significantly increase the price of coal or gas-generated electricity. However, as mentioned above, in the EU, there is a trading regime which penalizes carbon emissions. On the other hand, operators of NPPs are required to create provisions for nuclear waste disposal, and therefore, this cost is internalized.

In addition, there is a possibility to include the costs of dealing with a severe accident. Accidents typically have a very resonant effect on the nuclear industry. The accidents at Three Mile Island in 1979 and Chernobyl in 1986 resulted in very few NPPs being ordered subsequently (IAEA, 2009: 3). In 2011, in Japan, the Fukushima I (Fukushima Dai-ichi) power plant was also affected by a nuclear accident, which also had a ripple effect throughout the world. According to the Polish Nuclear Power Programme, the Fukushima accident bears no direct consequence with respect to Poland, as the reactor in question at Fukushima I was a forty-year-old, second-generation reactor, while regulations in force in Poland only allow for modern reactors of generation III and III+, whose designs prevent the possibility of the occurrence of similar accidents (Ministerstwo Gospodarki, 2014: 88). However, the accident in Fukushima raised awareness of nuclear security issues. Such expenses – connected to a potentially severe accident are typically not covered by the electricity consumer, but by the community in general. The costs related to society have a particularly important resonance in Poland. Polish Nuclear Power Programme cites unsatisfactory social acceptance for the development of nuclear power. In this respect, the support for the construction of an NPP spent fuel storage facility, and radio-active cemetery are very low, with a tendency of adverse impact on social acceptance in the event of nuclear breakdown anywhere in the world (Ministerstwo Gospodarki, 2014: 15). However, stable public support and broad political consensus, necessary for the implementation of a nuclear power program, requires consistent educational campaigns.

In relation to the public directed educational campaigns, it must be emphasized that regulatory, organizational, and research infrastructure assumes additional expenses. Poland has a shortage of nuclear experts, and the specialists who worked on the construction of 'Żarnowiec' power plant during 1980 are retired. The costs related to educational campaigns are expected to be covered by both the investors and the public institutions.

Furthermore, provisions must be made for backup generation at times when the generating plant is not operating. The costs incurred in providing backup and transmission/distribution facilities are known as system costs. Regardless of electricity generation technology, system costs relate mainly to the need for reserve capacity to cover periodic outages, whether planned or unplanned. These costs are paid by the electricity consumer, usually as part of the transmission and distribution costs. Furthermore, in power grids where renewable sources contribute to a large share of electricity generation, intermittency forces other generating sources to increase or power down their supply at short notice. This unpredictability can have a significant impact on an NPP profitability and its financial viability in markets where intermittent renewable energy capacity is significant.

The risk related to the development of an NPP project is often also political. Additional source of costs is the nuclear-specific taxes. These types of taxes are levied in several EU countries. For instance, in 2014, in Belgium, the tax raised some €479 million, while in Sweden, in 2015, it was the tax raised about €435 million (WNA, 2018a). Higher nuclear taxation is one of the more substantial risks. Additionally, subsidies for renewable and low-cost electricity generation also present economic risk.

3.2. Cost estimation model and assumptions

To calculate the economic viability of an NPP over its whole lifetime, it is common to estimate the LCOE (levelized cost of energy) at present value. LCOE represents the price that the electricity must fetch if the project is to break even (after taking account of all lifetime costs, inflation and the cost of capital as expressed through a discount rate). It is a standard metric used for the comparison of the economic feasibility of a variety of electricity generation technologies.

However, although the determinants of nuclear power costs seem well recognized, the actual costs of an NPP built are incredibly variable. These variations can be attributed to a range of factors, including greenfield vs established site investment; differential labour costs; more experience in reactor construction; economies of scale for building multiple units; streamlined licensing and project management, and others (WNA, 2018a). Additionally, as mentioned above, similar to other big infrastructure projects, the estimates of NPP construction costs are highly variable and appear quite unreliable.

This is inherently the case with Poland. PGE estimated LCOE from NPPs to be between €6.5 and €6.8 cents per kWh (WNA, 2018b). A single power plant is expected to cost between 50 and 60 billion zloty (€12–14 billion) (WNA, 2018b). In order to address the validity of these estimates, it is necessary to address the abovementioned set of factors and the effects of their variation. However, the number of factors and complexity of their interactions necessitates the use of specialized tools which will facilitate the estimation of costs, given the assumptions of a set of likely scenarios.

The Cost of Nuclear Energy Spreadsheet Tool (CNEST) model is one such tool. CNEST financial model was developed in September 2017 by the IAEA via a subcontract to Dean Capital Strategies GmbH, Vienna, Austria (DCS) (Dean, 2017). The model is based on Microsoft® Excel™ spreadsheet. The purpose of this financial model is to provide a robust analytical tool which can be used to evaluate the cost of nuclear power, that is, the cost of electricity and levelized unit cost of electricity (Dean, 2017). Model's scenario calculations depend on the entry of several categories of inputs. The CNEST model allows the flexibility to analyse: size and performance characteristics of a potential NPP project; capital costs; life-cycle costs; financing assumptions; initial offtake contractual tariff structure: power purchase agreements, contract for difference or merchant contracts; costs of ratepayer subsidies; macroeconomic and tax assumptions and other. The CNEST model allows the user to analyse a potential project using 9 major input categories. Thus, the model allows for significant flexibility and the opportunity to analyse in depth a multitude of likely scenarios with a relatively simple user interface. Furthermore, the model incorporates a set of control features which minimise the likelihood of erroneous or conflicting entries.

The model consists of six sheets. The Introduction worksheet provides necessary information about the model. The Inputs worksheet lists all potential entries that can be manipulated. The Summary worksheet is where a summary of the cost of electricity and built-up levelized unit electricity cost outputs of the model are located, and where the comparison of models can be performed. This sheet also provides the opportunity for users to assess the relative contributions of each tariff revenue component. The Annual Projected Cash Flows & Returns worksheet provides a summary of the modelled project's annual economics. Therefore, this worksheet provides the user with a concise annual summary of the project's cash flows, including tariff, operating expenses, and other details. The Charts worksheet provides a visual representation of all critical areas. Finally, the Cash Flow worksheet accounts for the entire cash flow.

In order to assess the effect of the abovementioned factors on the electricity cost, it is necessary to identify the most plausible set of scenarios considering the potential development of an NPP program in Poland. According to the Polish Nuclear Power Programme of 2014, the initial intention was to install capacity of 1000 MWe by 2024, increase it up to 3000 MWe by 2030, and finally get it to 6000 MWe (Ministerstwo Gospodarki, 2014: 19). According to the most recent energy draft policy of the Ministry of Energy, from November 2018, the goal is to build two NPPs, each with a capacity of 3000 MWe, totalling up to six large (1–1.5 GWe) nuclear units to be built by 2043 (Ministerstwo Energii, 2018). This is in line with current international trends as most countries are investing in large nuclear power reactors, typically of 1000–1500 MWe unit size (IAEA, 2009: 7). Consequently, as the CNEST evaluates the outcomes of a single module, we will review two scenarios: 1500 MWe and 3000 MWe.

Naturally, overnight (capital) cost is expected to have a direct impact on the LCOE. The NEA's calculation of the overnight cost for an NPP construction rose from about \$1900/kWe at the end of the 1990s to \$3850/kWe in 2009 (WNA, 2018a). On the other hand, according to the 2015 'Projected Costs of Generating Electricity', the overnight costs ranged from \$2021/kWe in South Korea to \$6215/

kWe in Hungary (IEA, NEA, 2015: 41). According to the estimates of ARE (Agencja Rynku Energii) from 2013, estimated overnight cost for Poland, for years 2025 and 2035, for generation III reactors are €3850/kWe and €4000/kWe, respectively (Ministerstwo Gospodarki, 2014). Keeping in mind the range of these values, in order to assess the levelized cost of generating electricity across the most plausible set of scenarios, three values of overnight costs are considered: €3500/kWe, €4500/kWe and €5500/kWe.

The choice of a financing model for the Polish NPP is still largely undetermined. Initially, the State Treasury was expected to take a significant part in the financing of the project, but this option was rejected in later stages. In 2015 PGE indicated to the Ministry of Economy that a contract for difference is the best way to minimize market risk for the investment. However, in 2016, the Government rejected the use of contract for difference as being too costly (WNA, 2018b). As CNEST allows for the assessment of the impact of contract for difference, power purchase agreement and merchant contract (demand and price are set in a deregulated electricity market) financial models, these options will be explored in the analysis.

It is expected that the interest rate (all-in interest rate during the construction period, including margins and fees) will have a significant influence on the profitability of an NPP. On the other hand, in CNEST, the discount rate applied to the net present value calculations in the LCOE methodology represents the overall cost of capital applicable to the project (Dean, 2017: 5). The default LCOE discount rate is the project internal rate of return, and it is dependent on the all-in interest rate. To assess the effect of interest rates on the LCOE, three possible scenarios of all-in interest rates are considered: 6%, 8% and 10%.

As noted above, it is expected that a shift from the expected five-year construction period to a seven-year construction period is likely to significantly increase the impact of the interest payments in the overall costs. On the basis of this rationale, these two options are considered in the analysis. The expenditure profiles across the 5 year construction period are set to 20%, 15%, 25%, 25% and 15%. On the other hand, the expenditure profiles across the 7 year construction period are set to 15%, 10%, 15%, 25%, 15%, 10% and 10%. The Table 3.2 presents the whole list of the variable parameters.

Finally, it is necessary to include a set of fixed (non-variable) inputs in the model. However, as many of the elements of the Polish nuclear program are still uncertain, and many of them are hard to foresee, these parameters need to be set somewhat arbitrarily. The CNEST model comes with a set of inputs that are representative of the experience in global project finance markets and refer to recent, representative new NPP construction projects. These values are taken as a reference for the setting of the remaining inputs.

Table 3.2. Variable inputs of estimated scenarios

Net Installed Capacity (MW)	1500, 3000
Total Overnight Cost (€/kWe)	3500, 4500, 5500
Contractual structure (financing model)	Contract for differences, power purchase agreement, merchant
All-in interest rate	6%, 8%, 10%
Construction period duration	5 years, 7 years
Expenditure profile – 5 years construction period	20%, 15%, 25%, 25%, 15%.
Expenditure profile – 7 years construction period	15%, 10%, 15%, 25%, 15%, 10%, 10%

Source: own elaboration.

Firstly, the regulations in force for Poland only allow the construction of modern, generation III and III+ reactors. These conditions are relevant for the determination of the operational life of an NPP. Generation II reactors are assumed to have a lifetime of forty years. However, all the generation III reactors are designed to operate for 60 years. This value is kept constant across scenarios. These facts are also relevant for the load factor of an NPP. Third-generation reactors have the load factor of no less than 90% (with availability in excess of 92%) (Ministerstwo Gospodarki, 2014: 41).

Consequently, the load factor is set to 90%. Average annual degradation rate is assumed to be 10%. Furthermore, as mentioned above, it is expected that the uranium price, as well as the fuel price, will have only a minor impact on the LCOE. Fuel costs have been relatively stable over time. Even the rise of uranium price between 2003 and 2007 did not affect conversion, enrichment and fuel fabrication costs. Consequently, it seems reasonable to set a constant price of fuel at CNEST default of 6.1€/MWh. The CNEST model allows the user to define the capital structure. Maximal nominal committed senior credit amount is set to €9 billion; maximal nominal subordinate credit amount is set to €1 billion; while the maximal government grant amount is set to €650 million. Permanent senior debt repayment tenure is set to 30 years while subordinate debt tenure is set to 40 years. Total project contingency amount is set at 10% of total overnight cost. Required minimum after-tax equity internal rate of return is set to 17%. Annual fixed operation and maintenance expenses are set to €65 million, while non-fuel variable operation and maintenance expenses are set to 4 €/MWh. Average annual maintenance capital cost expenditures as share of total overnight cost are set to 3.5%. General and administrative expenses are set to €20 million, and similarly, minimum restricted cash balance is set to €20 million. Decommissioning cost is set at 10% of the total overnight cost. The tenure of offtake agreement for power purchase agreement and contract for difference is set to 40 years. Annual variable non-tariff ancillary revenue is set to 1.3 €/MWh. Average market tariffs across each five year operation period are set to 7 €¢/kWh, 8 €¢/kWh, 9 €¢/kWh, 10 €¢/kWh, 11 €¢/kWh. Average year over year inflation factor is set to 2.5%. Applicable corporate income tax rate is set to 19%, while the aggregate weighted average useful life of assets is set to 27 years. The figure below presents an example of the CNEST Input sheet, which lists all variable and constant inputs for this particular scenario.

Project Size and Operating Characteristics	Units	Input Value
Net Installed Capacity (MW neti e/)	MW	1 500 MW
Net Capacity Factor, Ops Yr 1	%	90,0%
Annual Electricity Production, Ops. Yr. 1	MWh	11 834 100
Average Annual Plant Degradation Rate	%	0.10%
Project Useful Life	years	60 Years
Capital Costs	Units	Input Value
Total Overnight Costs {TOC } *, CYF	EUR €/kW	3 500
Financing Costs, YOE	EUR €	864 025 099
IDC, Project Contingency & Escalation, YOE	EUR €	2 279 306 695
Total As-Spent Costs { TASC }	EUR €	8 393 331 795
Total As-Spent { TASC } Unit Cost	EUR €/kW	5 596
CAPex Expenditure Time Frame	Units	Input Value
Construction Period Duration	years	7 Years
CAPex Expenditure Profiles	Units	{TOC}*
Construction year 1	%	15.0%
Construction year 2	%	10.0%
Construction year 3	%	15.0%
Construction year 4	%	25.0%
Construction year 5	%	15.0%
Construction year 6	%	10.0%
Construction year 7	%	10.0%
Total	%	100%
Contingencies & Escalation During Constructior	Units	Input Value
Total Project Contingency Amount	% { TOC } *	10,00%
Project Cost Escalation During Construction: { TOC }	%p.a.	2,50%
Construction Financing and Debt Funding Ratio:	Units	Input Value
Nominał Committed Senior Credit Amount (maximun	EUR €	9 000 000 000
Nominał Government Grant Amount (maximum)	EUR €	650 000 000
Nominał Subordinated Credit Amount (maximum)	EUR €	1 000 000 000
Targeted Senior Debt Funding Ratio (cumulative)	% ofuses	70.00%
Targeted Government Grant Funding Ratio (cum.)	% ofuses	5.00%
Targeted Subordinated Debt Funding Ratio (cum.)	% ofuses	7.50%
Senior: All-in Interest Rate on Drawn Bal. (base+mar	% p.a.	6.00%
Senior: Commitment Fees on Undrawn Committed A	% p.a.	1.50%
Senior: Up-front Premia, Fees and Expenses	%	2.00%
Subordinate Credit Facilities: All-in Interest Rate	% p.a.	4.50%

Permanent Financing and Equity Assumptions	Units	Input Value
Permanent Senior Debt Repayment Tenor (after COI	years	30 Years
Subordinate Debt Tenor (after COD)	years	40 Years
All-in Interest Rate on Perm. Senior Debt (base+mar	%	6.00%
Required Minimum Annual Senior DSCR	X	1.35x
Actual Min. Annual Senior DSCR occurs in Ops. Yr. 1	X	2.02x
Minimum Annual Senior Coverage Test Satisfied?	Pass/Fail	Pass
Required Minimum Average Senior DSCR	X	1.45x
Actual Average Senior DSCR	X	2.59x
Minimum Average Senior Coverage Test Satisfied?	Pass/Fail	Pass
Actual Cumulative Senior Debt Ratio at COD	%	70.00%
Actual Cumulative Subordinate Debt Ratio at COD	%	7.50%
Actual Cum. Government Grant Funding Ratio at CO	%	5.00%
Actual Cumulative Equity Funding Ratio at COD	%	17.50%
Senior Debt IRR	% p.a.	7.10%
Required Minimum After-tax Equity IRR	% p.a.	17.00%
Actual After-tax Equity IRR	% p.a.	18.00%
Project IRR (After-Tax), Nominał	% p.a.	9.29%
Weighted Average Cost of Capital (WACC)	% p.a.	9.09%
Nuclear Fuel and Fabrication (F&F) Expenses	Units	Input Value
Nuclear Fuel and Fabrication Unit Costs, CYF	EUR €/MWh	6.10
Operations & Maintenance (O&M) Expenses	Units	Input Value
Annual Fixed O&M Expenses, CYF	EUR €	65 000 000
Non-Fuel Yariable O&M Expense, CYF	EUR €/MWh	4.000
Maintenance CAPex	Units	Input Value
Average Annual Maintenance CAPex as % {TOC } *	%	3.50%
Average Annual Maintenance CAPex Budget, CYF	EUR €	183 750 000
Project Co. General & Admin. (G&A) Expenses	Units	Input Value
Average Annual Fixed G&A Expenses, CYF	EUR €	20 000 000
Decommissioning Works Expenses	Units	Input Value
Net Decommissioning Works Costs as a % of {TOC }	%	10.00%
Net Decommissioning Works Cost Budget, CYF	EUR €	525 000 000
Reserves and Minimum Restricted Cash Balances	Units	Input Value
Senior Debt Service Reserve Requirement (at COD)	EUR €	326 920 102
Operating Reserve Requirement (at COD)	EUR €	121 486 588
Major Maintenance Reserve Requirement (at COD)	EUR €	218 421 007
Decommissioning Reserve Requirement (Ops, Yr. 1)	EUR €	38 498 160
Minimum Cash (Restricted) Cash Balance (at COD)	EUR €	20 000 000
Debt Service Reserve Account (DSRA):		
Months' of Debt Sen/ice Included in DSRR	Months	6 Months
Operating Resen/e Account (ORA):		
Months' Forward Operating Budget Basis for ORR	Months	6 Months
Interest Rate Applied on Resen/es and Cash Balances	% p.a.	2.5%

Project Contractual Structure	Units	Input Value
Type of Offtake Agreement (Initial Period)		CfD
Tenor of Offtake Agreement	years	40 Years
Include C/D „Clawback" or „Collar" Prices in Tariff?		No
Currency Denomination of Project (all cash flows)		EUR €
Non-Tariff Ancillary Project Revenues	**Units**	**Input Value**
Annual Variable Non-Tariff Ancillary Revenue	EUR €/MWh	1.300
Average Market Tariffs (Generator Tariff, net)	**Units**	**Input Value**
Ops. Yrs. 1 - 5, CYF	EUR € 0/kWh	7.000
Ops. Yrs. 6-10, CYF	EUR € 0/kWh	8.000
Ops. Yrs. 11-15, CYF	EUR € 0/kWh	9.000
Ops. Yrs. 16-20, CYF	EUR € 0/kWh	10.000
Ops. Yrs. > 20, CYF	EUR € 0/kWh	11.000
Long-Term Average, CYF	EUR € 0/kWh	10.167
Macroeconomic & Tax Assumptions		
Average YoY Escalation (Inflation) Factor	% p.a.	2.50%
Applicable Corporate Income Tax Rate	%	19.00%
Applicable Dividend Tax Rate	%	5.00%
Aggregate Weighted Average Useful Life of Assets	years	27 Years
LUEC Analysis Discount Rate Override		No

Figure 3.1. CNEST Input sheet – variable and constant inputs for an example scenario

Source: own elaboration based on CNEST sheet.

3.3. Results

In total, all possible combinations of variable inputs result in 108 scenarios. As indicated above, the varied parameters are capital (overnight) costs, net installed capacity, discount rate, length of construction and financing model. Considering the LCOE, the maximal and minimal values are 10.51 €¢/kWh and 30.6 €¢/kWh, with mean and median 16.69 €¢/kWh and 15.21 €¢/kWh, respectively. Immediately, it should be noted that initial estimations of the LCOE ranging between 6.5 €¢/kWh and 6.8 €¢/kWh seem way too optimistic (see above). However, the analysed scenarios only address a single NPP, thus increasing capacity to 6000MWe (two NPPs) is likely to further decrease the LCOE. On the other hand, the total as-spent cost ranges between approximately €7.6 billons and €24.6 billion, with a mean and median of €14.71 billion and €13.88 billion, respectively. These estimates are in line with the estimates stated above.

Naturally, it is expected that overnight cost (in €/kWe) will have an immediate effect on total as-spent cost and the LCOE. In this respect, the cost of capital of €3500/kWe will result in the average LCOE of 13.08 €¢/kWh and average total as-spent cost of €11.81 billion. The cost of capital of €4500/kW will result in the average LCOE of 16.64 €¢/kWh and average total as-spent cost of €14.72 billion. Finally, the cost of capital of €5500/kWe will result in the average LCOE of 20.34 €¢/kWh and the average total as-spent cost of €17.59 billion. Figure 3.2 presents a kernel density of the LCOE across overnight costs.

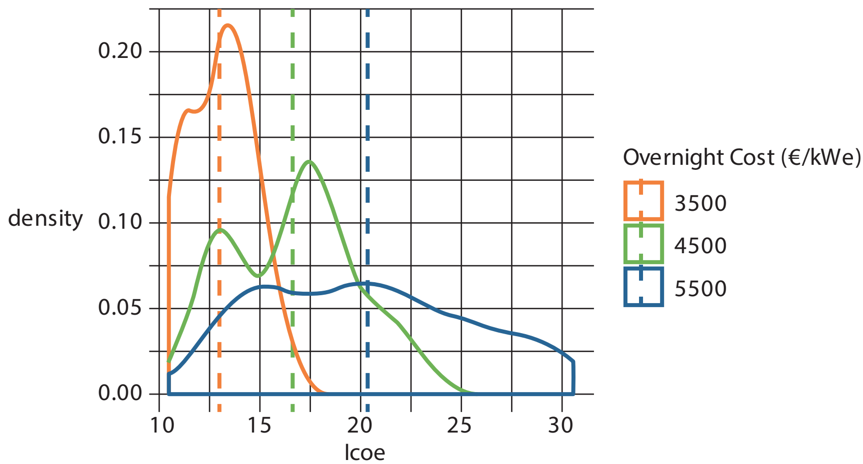

Figure 3.2. Kernel density and average values of LCOEs across overnight costs

Source: own elaboration.

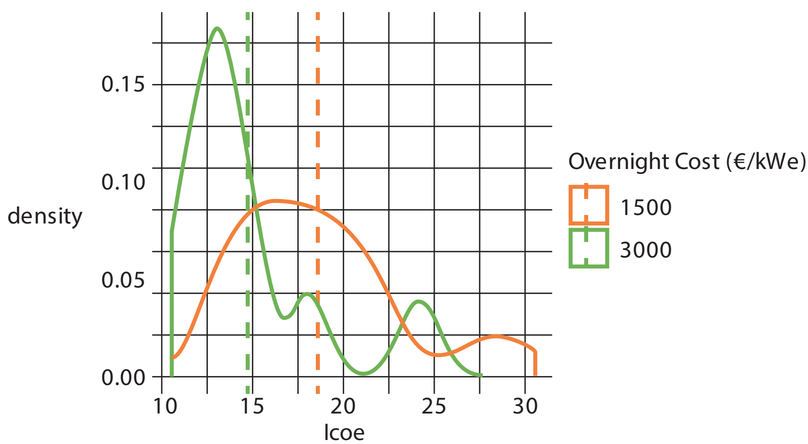

Figure 3.3. Kernel density and average values of LCOEs across net installed capacities

Source: own elaboration.

Considering installed capacity, in the long term, the larger capacity is a more economically viable option. At capacity of 1500 MWe, average LCOE is at 18.6 €¢/kWh, while at the capacity of 3000 MWe the same average cost is at 14.78 €¢/kWh. Considering the total as-spent cost, the cost of capacities of 1500 MWe and 3000

MWe are on average €10.325 billion and €19.098 billion, respectively. Thus, by doubling the installed capacity, the total as-spent cost is increased by approximately 85%. Figure 3.3 presents the kernel density of LCOE across net installed capacity.

Financing does not influence total as-spent cost. However, there are significant differences in terms of the LCOE. The contract for difference is the most affordable form of financing at an average of 14.75 €¢/kWh, but it is closely followed by power purchase agreements at 16.69 €¢/kWh. Pure merchant arrangement is clearly the least desirable option of financing with an average value of 20.48 €¢/kWh. However, the difference between contract for difference and power purchase agreements significantly decreases if the focus is only on 3000 MWe net installed capacity. In this case, the average LCOE for contract for difference is at 12.83 €¢/kWh while the average LCOE of power purchase agreements is at 13.13 €¢/kWh. Figure 3.4 presents the kernel density of the LCOE across types of financing (contractual structure).

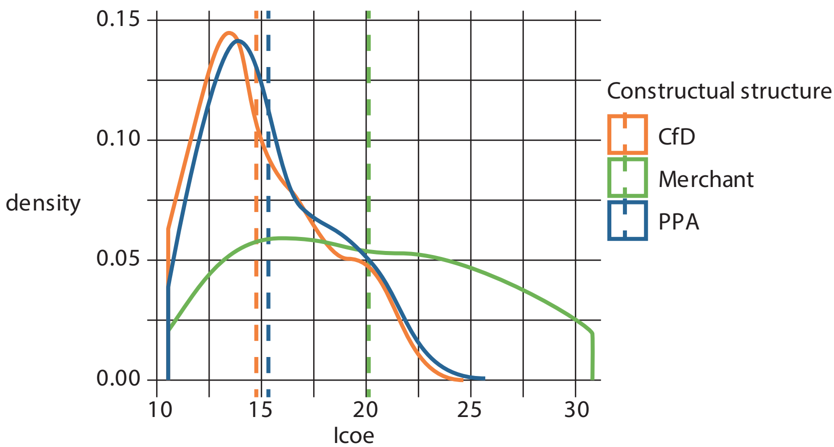

Figure 3.4. Kernel density and average values of LCOEs across contractual structures

Source: own elaboration.

Considering the length of construction, the prolongation of two years leads to a somewhat decreased LCOE. Thus, while for the 5-year long length of construction LCOE is, on average, 16.80 €¢/kWh, the 7 year-long length of construction will result in, on average, LCOE of 16.57 €¢/kWh. However, in contrast to LCOE, the increase in the length of construction leads to an increase in total as-spent cost. Thus, while for the 5-year long length of construction the total as-spent cost is on average €14.01 billion, the 7-year length of construction will result in, on average, total as-spent cost of €15.41 billion. Figure 3.5 presents the kernel density of LCOE across types of financing (contractual structure).

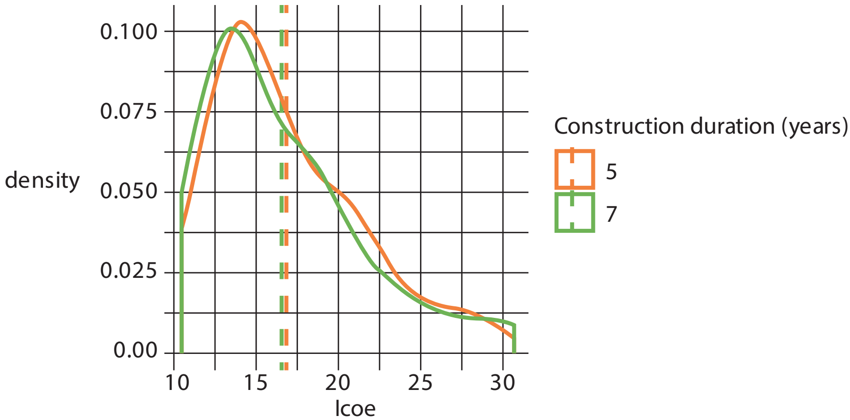

Figure 3.5. Kernel density and average values of LCOEs across construction duration periods

Source: own elaboration.

Finally, with respect to the all-in interest rate, there is evidence that an increase in interest rate will progressively increase both the LCOE and total as-spent cost. However, the effect of the increase is relatively small in comparison to the effect of the financial model. Thus, interest rates of 6%, 8% and 10% will result, on average, in the LCOE of 16.64 €¢/kWh, 16.69 €¢/kWh and 16.73 €¢/kWh, respectively. In the same vein, these interest rates will result in total as-spent cost of €11.81 billion, €14.72 billion and €17.59 billion, respectively. Figure 3.6 presents the kernel density of the LCOE across all-in interest rates.

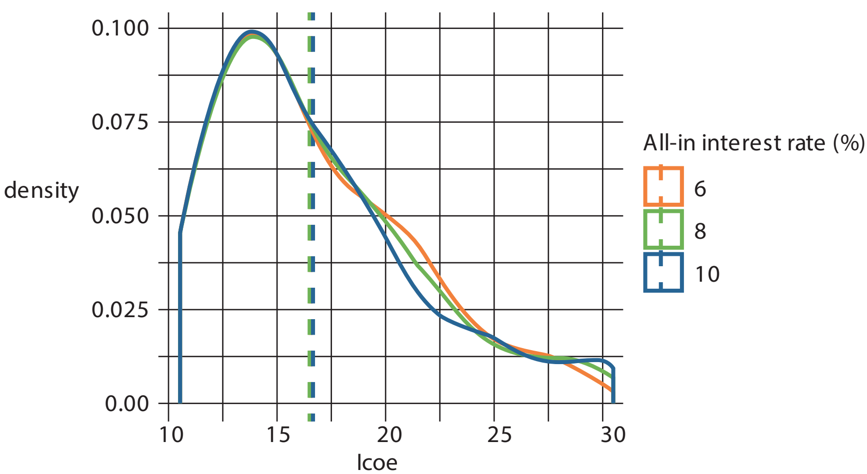

Figure 3.6. Kernel density and average values of LCOEs across all-in interest rates

Source: own elaboration.

3.4. Conclusion

On the basis of these findings, the set of inputs can be identified, which will result in the best-case scenario for the Polish NPP construction project. In this respect, the best-case scenario implies a set of inputs which is likely to result in the smallest values of the LCOE and the total as-spent cost. Firstly, the most substantial impact on the LCOE was observed with respect to capital cost, financial model and net installed capacity. Obviously, the capital cost should be as low as possible in order to minimize the cost of the LCOE and the total as-spent cost. Furthermore, while the construction of several reactors simultaneously will have a significant effect on the increase of the total as-spent cost, it also has an effect of decreasing the LCOE. Therefore, keeping in mind the goals of the Polish nuclear power program (Ministerstwo Gospodarki, 2014; Ministerstwo Energii, 2018), net installed capacity should be maximised. Finally, financing through the means of contract for difference provides overall the lowest LCOE and total as-spent cost; however, financing via power purchase agreements is only a slightly less desirable option. Therefore, with 3000 MWe net installed capacity, the overnight cost of €3500/kWe and financing model based on contract for difference it can be expected that the LCOE will vary between 10.51 €¢/kWh and 10.84 €¢/kWh while total as-spent cost may range between €15.01 and €16.81 billion. Under these conditions, the above-listed estimates will be fairly robust with respect to the range of analysed interest rates and lengths of construction. Alternatively, the introduction of power purchase agreement may be implemented as a financial model. This change will not significantly affect the estimated range of total as-spent cost, but it will increase the LCOE to 12.04 €¢/kWh. These estimates require further improvement with respect to the details of financial models and the actual development of the Polish nuclear program. Furthermore, they may be subject to volatility due to peculiar circumstances and the instability of energy markets. However, although imperfect and provisional in nature, this collection of estimates may be considered as indicative of the set of scenarios which are likely to result in the lowest costs in further development of Polish nuclear program at the present time.

4. Input-output methods for power system analyses

4.1. Data for modelling

Input-output tables are a part of the national accounts system (see for example Eurostat, 2013 or Plich, 2002). They are one of the ways of presenting the flow of product in the economy from a producer to a user. In this context, the products are all goods and services, which are the subject of payments in transactions made in the economy, including the services of primary factors of production. I-O tables constitute a valuable source of information for conducting analyses at the mesoeconomic level because the flows presented in them concern sectors of the economy. This is important in the case of analyses of the energy sector due to its role in the economy, and especially in the electricity production sector, without which, practically speaking, the economy could not function.

Input-output tables are presented in various forms, which depend, among other things, on the data processing stage, the method of flow valuation and the way imports are treated. Here a typical scheme of I-O table is analysed to facilitate the understanding of relationships presented in this chapter, and particularly that between the power industry and the rest of the economy. In Figure 4.1, a diagram of a typical I-O table is shown. Flows of products are classified in this table according to two criteria:

- origin (rows of the table),
- destination (columns of the table).

Products by origin are divided into:

- primary production factors, which include imported goods, labour, indirect taxes and profits (representing capital expenditures),
- secondary production factors, i.e. economic goods and services that are products of the production sectors.

In turn, products by destination are classified as:

- products for intermediate use (secondary production factors for sectors),
- products for final use, among which private consumption, government spending, exports, investments, and changes in inventories are distinguished.

In applications, the classifications' primary factors, as well as the final demand, are presented with greater detail than in this example. The classifications used here, however, are sufficiently detailed at the stage of discussing the fundamental issues in the field of I-O analysis.

			Destination (use)									
			Buying sector				Final use (categories)				Output (total use)
			1	2	…	n	Personal consumption	Government consumption	Gross domestic investments	Exports	
Origin (inputs)	Selling sector	1	X_{11}	X_{12}	…	X_{1n}	C_1	G_1	I_1	E_1	X_1
		2	X_{21}	X_{22}	…	X_{2n}	C_2	G_2	I_2	E_2	X_2
		…	…	…	…	…	…	…	…	…	…
		n	X_{n1}	X_{n2}	…	X_{nn}	C_n	G_n	I_n	E_n	X_n
	Imports		M_1	M_2	…	M_n	M_C	M_G	M_I	M_E	
	Value added	Indirect business taxes	T_1	T_2	…	T_n					
		Employee compensation	W1	W_2	…	W_n					
		Profits and capital consumption	Z_1	Z_2	…	Z_n					
Output (total supply)			X_1	X_2	…	X_n					

Figure 4.1. Schematic view of an I-O table

Source: own elaboration.

In the table, several basic identities can be indicated, such as:

- elements of the final demand of the i-th sector add up to the final demand for these products of this sector:

$$Y_i = C_i + G_i + I_i + E_i \,, \tag{4.1}$$

- elements of value added of j-th sector add up to the value added created in this sector:

$$D_j = T_j + W_j + Z_j \,, \tag{4.2}$$

- system of production balance equations (relationships between output, intermediate use and final use of products):

$$X_i = \sum\nolimits_{j=1}^{n} X_{ij} + Y_i, \quad for\ i = 1,\ldots,n\ , \tag{4.3}$$

- system of cost equations (value of the sector's output as the sum of intermediate inputs and value added:

$$X_j = \sum\nolimits_{i=1}^{n} X_{ij} + D_i, \quad for\ j = 1,\ldots,n\ . \tag{4.4}$$

The term *sector* may denote here a product or an industry. In the classic I-O analysis, it is assumed that each industry produces one and only one product (assumption about the uniformity of industry production). In this case, the three terms – *sector*, *industry* and *product* – can be used interchangeably. In practice, however, apart from products resulting from the central business profile, enterprises conduct side activities that increase the value of their output. From the point of view of data aggregation on flows in the economy, the consequences of this are twofold.

Firstly, the output can be classified with the use of two different criteria:

- criterion of economic activity of enterprises is the basis of classification of industries, according to which the by-products are classified to the type of activity defined by the primary production profile of the enterprise producing the by-product;
- criterion of product, being the basis of product classification, in which products are classified in accordance with their properties, regardless of whether they are the primary products or by-products of the enterprise.

Secondly, the flow of goods and services within the economy can be described in two dimensions: in the industry cross-section and in the product cross-section layout. Before the construction of IOTs that meet the uniformity assumption, so-called "supply and use tables" (SUTs) must be compiled. Due to the two criteria, they are assembled in the form of two complementary tables:

- *a supply table* showing which industries supply a specific product and which products are supplied by a specific industry; the totals in the last column present the total supply of output by product and the totals in the last row, supply of output by industry;
- *a use table*, the idea of which is close to IOT, i.e. its rows represent the specific product used by subsequent industries (intermediate use) as well as categories of final use, and columns represent the use of different types of products as an input for the production process of a specific industry.

IOTs are derived on the base of the use tables, by transforming either industries to products or products to industries, with different assumptions. The resulting matrix shows only products or only industries, both in rows and columns. They are called "product by product" or "industry by industry" matrices.

At the end of this short presentation of I-O tables, it should be mentioned that the rules of construction of I-O tables can differ with regard to imports (flows with or without imports), pricing (basic prices, producer prices, market prices), measurement of flows (in physical flows or in money terms including current and constant prices). The manner in which the IOT is prepared affects the construction of models based on them.

At the end of this short presentation of I-O tables, it should be mentioned that in practice their construction can be more complicated due to the treatment of imports (transactions represented with or without imports), pricing (transactions valued in basic prices, producer prices or market prices), transaction measurement (in natural units or in money terms including current and constant prices). The manner in which the IOT is prepared affects models constructed on the base of them. Here we present only basic models and their modifications related to energy and emissions modelling.

4.2. Classical models of input-output analysis

4.2.1. Basic models

A prerequisite for the harmonious course of production processes is the maintenance of such relations between the production of various sectors so that the markets of the products of these sectors remain in balance. This applies in particular to the electricity sector due to the need to balance production with demand for technological reasons in diurnal terms. The shortage of production forces the limitation of demand by switching off the electricity supply for groups of consumers and excessive production can lead to system failure. In the case of excess supply, exports or energy stores can be used as buffering mechanisms while surplus of demand can be reduced by the use of demand management tools, which can be included in contracts with recipients, entitling the electricity suppliers to reduce demand for power in exchange for a lower energy price[2].

The production relationships depend on the technologies used in the sectors. Production technology is understood here as the inputs of production factors necessary to produce one unit of a particular sector product. For example, to generate 1 MWh of electricity, it is necessary to use specific quantities of products from other sectors, primarily from sectors that extract or process fuels used for electricity production, such as coal, gas, oil, uranium, etc. – depending on type of power plant,

2 They are referred to as Demand Side Responses (DSRs).

as well as manpower and capital resources. The proportions of the volume of inputs of production factors to the expected amount of product produced with their use are called technical coefficients. Technical coefficients can be estimated based on:

- technical norms,
- engineering data (non-normative) based on knowledge of technological processes,
- expert methods,
- statistical methods.

In microeconomic analyses, specific technologies can be considered, and then technical coefficients are determined directly for each technology based on technical norms, engineering data or expert methods. In the case of mesoeconomic analyses, where technologies are considered at the level of production sectors, technical coefficients are averaged coefficients of all individual technologies involved in the production within the given sector. Because it is usually impossible to determine them directly, i.e. as the weighted average of all technologies used in the sector, they are usually estimated using statistical methods, mainly based on input-output tables. Because the input-output table reflects production flows between sectors, it can be used to capture production relations between sectors, defined as technical coefficients. They are usually presented in the form of a matrix, whose columns represent the production technology of a given sector.

The classical approach assumes that technical coefficients are constant. Their estimation is the starting point for the construction of the production model and the price model, which are the two most well-known models of input-output analysis. They result directly from the system of production balance equations and system of cost equations. In order to fully understand the meaning of both models and dependencies that occur between them, it is first necessary to transform the flows presented in Figure 4.1 and the resulting system of production balance equations 4.3 from money terms to quantitative terms. To do this, let's enter the following notation:

p_i – the price of one unit of a product of the i-th sector;
Q_i – the quantity of a product produced by the i-th sector;
Q_{ij} – the quantity of a product of the i-th sector, sold to the j-th sector (flow of product of the i-th sector to the j-th sector);
F_i – the quantity of products produced by the i-th sector, sold to the j-th sector.

Note that since the value = quantity · price, then:

$$\begin{aligned} X_i &= Q_i p_i \\ Y_i &= F_i p_i \\ X_{ji} &= Q_{ij} p_i \end{aligned} \tag{4.5}$$

If the prices of products of the i-th branch were differentiated depending on the recipient, then in the last formula, instead of a uniform price p_i for i-th supplier the p_{ij} symbol would appear, denoting the price of the i-th supplier to the j-th recipient.

By substituting 4.5 to 4.3 and dividing the result on both sides by p_i, we obtain a system of production equations in quantitative terms[3]:

$$Q_i = \sum_{j=1}^{n} Q_{ij} + F_i, \quad for\ i = 1,\ldots,n \,. \tag{4.6}$$

This is the starting point for the construction of the production model. In turn, starting from the system of cost equations, a price model can be constructed. Both models combine one common element, which is the matrix of technical coefficients expressed in quantitative terms.

Production model

According to what has been written above, with the input-output matrix in quantitative terms, the technical coefficients are defined as follows:

$$\tilde{a}_{ij} = \frac{Q_{ij}}{Q_j} \quad for\ i, j = 1,\ldots,n \,. \tag{4.7}$$

Assuming that the technical coefficients are known as well as output of the j-th sector, the formula 4.7 can be converted and used to calculate the flow of product from i-th to j-the sector:

$$Q_{ij} = \tilde{a}_{ij} Q_j \,. \tag{4.8}$$

Now we can write down the system of production equations as:

$$Q_i = \sum_{j=1}^{n} \tilde{a}_{ij} Q_j + F_i, \quad for\ i = 1,\ldots,n \,. \tag{4.9}$$

And in the matrix form as:

$$\mathbf{Q} = \tilde{\mathbf{A}}\mathbf{Q} + \mathbf{F} \,, \tag{4.10}$$

3 The system of cost equations cannot be written down in an analogous manner, because even if it were possible to clearly determine the amount of work and capital in terms of quantity, the flows in the columns of the table would be expressed in different units, and as a result could not be summed up.

where:

$$\tilde{\mathbf{A}} = \begin{bmatrix} \tilde{a}_{11} & \cdots & \tilde{a}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \cdots & \tilde{a}_{nn} \end{bmatrix}, \quad \mathbf{Q} = \begin{bmatrix} Q_1 \\ \dots \\ Q_n \end{bmatrix}, \quad \mathbf{F} = \begin{bmatrix} F_1 \\ \dots \\ F_n \end{bmatrix}. \tag{4.11}$$

The $\tilde{\mathbf{A}}$ matrix is called the matrix of technical coefficients.

Price model

Taking into account the relationship 4.5 between the production measured in monetary and quantity terms, the cost equation 4.4 for the j-th sector can be written in the following form:

$$Q_j p_j = \sum_{i=1}^{n} Q_{ij} p_i + D_j, \quad for\ j = 1, \dots, n. \tag{4.12}$$

In turn, taking into account the relation 4.8, the above equation can be saved in the form:

$$Q_j p_j = \sum_{i=1}^{n} \tilde{a}_{ij} Q_j p_i + D_j, \quad for\ j = 1, \dots, n \tag{4.13}$$

and hence, after dividing both sides by Qj and ordering the equation, we have:

$$p_j = \sum_{i=1}^{n} \tilde{a}_{ij} p_i + d_j, \quad for\ j = 1, \dots, n, \tag{4.14}$$

where d_j is the unit value added in the j-th branch, i.e. the value added per unit of output: $d_j = \frac{D_j}{Q_j}$. Let's save the system 4.14 in the matrix form:

$$\mathbf{p}' = \mathbf{p}'\tilde{\mathbf{A}} + \mathbf{d}', \tag{4.15}$$

where:

$$\mathbf{p} = \begin{bmatrix} p_1 \\ \dots \\ p_n \end{bmatrix}, \quad \mathbf{d} = \begin{bmatrix} d_1 \\ \dots \\ d_n \end{bmatrix}. \tag{4.16}$$

The system of equations 4.15 is called the price model.

Notice that taking into account the relationship between production expressed in the quantity and monetary terms 4.5 and the definition of technical coefficients 4.7, we can write the following relationship:

$$a_{ij} = \tilde{a}_{ij} \frac{p_i}{p_j}. \tag{4.17}$$

The coefficients a_{ij} are called cost coefficients. They are merely technical coefficients expressed in current prices. Formula 4.17 shows the relationship between technical coefficients and cost coefficients.

Model of factors and results of production

Production model and price model show the relationship of primary and secondary factors of production with final production, output and prices. More specifically, the price model links primary and secondary factors with prices, while the production model links secondary factors with production.

Although the production model does not include primary factors (labour and capital), a common assumption in IOA is that labour and capital are proportional to output. This allows to formulate appropriate models showing the factors as a function of volume of output. However, there are more production factors, such as free goods, which are not included in economic accounts and consequently in the production model. On the other hand, output and final production are not the only results of production processes. The other, which are not included in economic accounts, are called external effects of production activities. Below we present a uniform approach to modelling both factors and results of production not included in the production model. It is, therefore, a complement to the production model, allowing for a comprehensive analysis of the production process using I-O methods. It is included in the group of hybrid models[4], i.e. models in which variables can be expressed not only in money terms but also in physical units.

The assumption on proportionality of factors and results of production to output enables construction of coefficients that are analogous to technical coefficients. They show the intensity of using factors used in the production process, as well as the related results. It is not essential whether these factors or results are expressed in terms of quantity or in monetary units. Thus, it may be labour inputs measured as working time, employment or wages. Input of ecological goods,

4 The term *hybrid models* has different meaning depending on the context it is used in. Here we mean that variables of the same model can be measured both in monetary and physical units.

energy inputs and all kinds of external effects, including emissions of pollutants measured in physical units can also be presented in this way.

The proportion mentioned above for the j-th sector can be expressed in the following form:

$$c_j = {C_j}/{Q_j}\ , \tag{4.18}$$

where:
C_j – factor input (production result) in the j-th sector.

Note that the coefficients c_j are defined analogously to the technical coefficients, i.e. as the production factor (production result) per unit of output of the j-th branch. Coefficients of this type are called coefficients of direct factor inputs (production result). It is also worth emphasising that while the output is generally measured in value terms, the factors (results) can be expressed both in value and in physical terms.

The total amount of factor inputs (result sizes) can be written as the following vector equation:

$$C = \mathbf{c}'\mathbf{Q}\ , \tag{4.19}$$

where:
c – vector of coefficients of direct factor inputs (production result).

Any factor inputs or production results can be modelled in this way. We will refer to it as a model of production factors or results.

4.2.2. Applications of fundamental models

Possible solutions of the models

The production and the price model presented in the previous section were expressed in their structural forms. To solve them, a user must make a distinction between endogenous and exogenous variables and then transform the model to the final form[5].

If technical coefficients are known, then the only unknowns in the equation 4.10 are *n*-element vectors: Q and F. To find a unique solution of the system 4.10

5 Because the models are static models, a reduced form does not exist.

of n equations, one must make assumptions on n from the total number of 2n unknowns (variables). The following three sets of assumptions are possible:

All variables of the output vector Q are known – then the system of equations 4.10 will determine the final production (final demand) by sectors:

$$\mathbf{F} = \left(\mathbf{I} - \tilde{\mathbf{A}}\right)\mathbf{Q}\,. \tag{4.20}$$

All variables of the vector of final demand F is known – then the system 4.10 is used to determine the output, ensuring the satisfaction of the final demand:

$$\mathbf{Q} = \left(\mathbf{I} - \tilde{\mathbf{A}}\right)^{-1}\mathbf{F}\,. \tag{4.21}$$

Some variables from the final demand vector and some from the output vector (total of n variables) are known – then the system 4.10 is used to determine the remaining n elements of output and final product vectors[6]:

$$\begin{bmatrix} \mathbf{Q}^{en} \\ \mathbf{Q}^{eg} \end{bmatrix} = \begin{bmatrix} \tilde{\mathbf{A}}_{11} & \tilde{\mathbf{A}}_{12} \\ \tilde{\mathbf{A}}_{21} & \tilde{\mathbf{A}}_{22} \end{bmatrix} \begin{bmatrix} \mathbf{Q}^{en} \\ \mathbf{Q}^{eg} \end{bmatrix} + \begin{bmatrix} \mathbf{F}^{eg} \\ \mathbf{F}^{en} \end{bmatrix} \tag{4.22}$$

or after performing partitioned matrix operations:

$$\begin{bmatrix} \left(\mathbf{I} - \tilde{\mathbf{A}}_{11}\right) & 0 \\ -\tilde{\mathbf{A}}_{21} & -\mathbf{I} \end{bmatrix} \begin{bmatrix} \mathbf{Q}^{en} \\ \mathbf{F}^{en} \end{bmatrix} = \begin{bmatrix} \mathbf{I} & \tilde{\mathbf{A}}_{12} \\ 0 & -\left(\mathbf{I} - \tilde{\mathbf{A}}_{22}\right) \end{bmatrix} \begin{bmatrix} \mathbf{Q}^{eg} \\ \mathbf{F}^{eg} \end{bmatrix}. \tag{4.23}$$

Let us enter the following symbols:

$$\mathbf{M} = \begin{bmatrix} \left(\mathbf{I} - \tilde{\mathbf{A}}_{11}\right) & 0 \\ -\tilde{\mathbf{A}}_{21} & -\mathbf{I} \end{bmatrix} \text{ and } \mathbf{N} = \begin{bmatrix} \mathbf{I} & \tilde{\mathbf{A}}_{12} \\ 0 & -\left(\mathbf{I} - \tilde{\mathbf{A}}_{22}\right) \end{bmatrix}.$$

Using them in 4.23, we get:

$$\mathbf{M} \begin{bmatrix} \mathbf{Q}^{en} \\ \mathbf{F}^{en} \end{bmatrix} = \mathbf{N} \begin{bmatrix} \mathbf{Q}^{eg} \\ \mathbf{F}^{eg} \end{bmatrix} \tag{4.24}$$

6 Models in which endogenous variables consist of both vectors (i.e. output and final production) are known in the literature as mixed models (see Miller, Blair, 2009: 621). For presentation of solution of such kind of models it is convenient to present the structural form using partitioned matrices.

and thus, the solution of the partitioned model is:

$$\begin{bmatrix} \mathbf{Q}^{en} \\ \mathbf{F}^{en} \end{bmatrix} = \mathbf{M}^{-1}\mathbf{N}\begin{bmatrix} \mathbf{Q}^{eg} \\ \mathbf{F}^{eg} \end{bmatrix}. \tag{4.25}$$

Generally, the production model is used to determine the output, ensuring the balance of demand and supply in product markets, taking into account technological production conditions (given in the $\tilde{\mathbf{A}}$ matrix). This is equivalent to the adoption of assumption 2, which reflects the basic principle of the market economy, according to which demand and supply are heading for equilibrium. In some circumstances, however, assumption three is accepted. It concerns situations in which the output of specific sectors is subject to supply-side restrictions. This may happen, for example, in the situation of gradual eliminating of production of specific sectors or the emergence of new technologies or sectors in the economy. In the case of the energy sector, this may refer in particular to the policy of limiting coal supply or demand. This policy can manifest, for instance, by limiting of the modernisation and development investments in the coal industry or by structural changes in the power sector, resulting from replacement of coal-based production capacities with nuclear energy or renewables (RES).

Similar considerations concerning the distinction between endogenous and exogenous variables can be carried out in the case of the price model, with the difference that in place of the output and the final production vectors there are production prices (deflators) and unit value added.

Time series and constant price variables

The production model 4.10 and the price model 4.15 are based on production measured in terms of quantity and a specific price which can be assigned to each product. On the other hand, the models are usually used at national or regional level, and data for them are usually derived from national accounts, which use sectoral "products" which are aggregates expressed in money terms and sectoral prices measured in index form. So, direct application of models 4.10 and 4.15 at this level is therefore impossible. However, the models can be re-written with the use of:

- output at constant prices instead of production in quantitative terms;
- deflators (fixed base price indexes) instead of product prices;
- technical coefficients expressed in constant prices instead of quantities.

By introducing the "0" superscript for the base period, which is the basis for determining deflators and quantities expressed in constant prices, the production model can now be re-written as:

$$\mathbf{X}_t^0 = \tilde{\mathbf{A}}_t^0 \mathbf{X}_t^0 + \mathbf{Y}_t^0 . \tag{4.26}$$

The price model and the model of production factors or results can be presented as:

$$\left(\mathbf{p}_t^0\right)' = \left(\mathbf{p}_t^0\right)' \tilde{\mathbf{A}}_t^0 + \mathbf{d}_t^0 , \tag{4.27}$$

$$C_t = \mathbf{c}_t ' \mathbf{X}_t^0 , \tag{4.28}$$

where subscript t is time. In case of C_t superscript "0" is not required unless C_t is expressed in monetary terms Notice, however, that in the denominator of definition of c_t, output is used, so it should also be expressed in constant prices.

The models 4.26–4.28 are basic models of IOA useful for energy analyses.

It is often assumed in applications that matrix of technical coefficients is constant over time, i.e. it is assumed that tilde accent can be omitted for simplicity, so $\tilde{\mathbf{A}}_t^0 = \mathbf{A}_0$. In such a case, the production model and price model take the following form:

$$\mathbf{X}_t^0 = \mathbf{A}_0 \mathbf{X}_t^0 + \mathbf{Y}_t^0 , \tag{4.29}$$

$$\left(\mathbf{p}_t^0\right)' = \left(\mathbf{p}_t^0\right)' \mathbf{A}_0 + \mathbf{d}_t^0 . \tag{4.30}$$

For simplicity of presentation, the three models under consideration are usually written without explicit specification of a base period for data at constant prices and even without subscript of time, i.e. in the following form:

$$\mathbf{X} = \mathbf{AX} + \mathbf{Y} , \tag{4.31}$$

$$\mathbf{p}' = \mathbf{p}'\mathbf{A} + \mathbf{d}, \tag{4.32}$$

$$C = \mathbf{c}'\mathbf{X} . \tag{4.33}$$

Presentation of models 4.26–4.28 in the form of 4.31–4.33 can lead to misunderstandings involving misinterpretation of variables **X** and **Y** as output and final production in current prices, while **A** as a matrix of cost coefficients. As a result of such an interpretation, the essence of the Leontief approach would be distorted. Model

4.31, in which **X**, **Y** and **A** are understood in this way, can't be referred to as the Leontief model. The formula 4.31 with **X**, **Y** and **A** interpreted in current prices is just a tautology reproducing the relationships occurring in any input-output table in current prices, but should not be treated as a model.

As a final point in the considerations about the fundamental aspects of the basic models, it is worth noting that although it would seem obvious to divide the elements of the model into variables and parameters, this distinction is not particularly strict. In applications, some parameters of basic models are treated as variables. This applies in particular to the situation of rapidly changing technologies or the emergence of new technologies, when it is not possible to assume the stability of some parameters. This takes place, for example, due to the efforts at the global level to reduce the use of non-renewable energy sources in order to achieve the goals of sustainable development. For this reason, sectors using significant amounts of final energy, as well as energy transformation sectors are subject to profound structural changes. They are reflected, among others, in the technological changes, resulting in the energy consumption decrease both in production processes as well as in households, and the efficiency increase in the energy transformation processes. These changes must be reflected in the models. In the case of I-O models, they are introduced by making appropriate modifications in the matrix of technical coefficients. The manner of introducing such kind of changes is discussed in section 4.5.

4.3. Multipliers of IOA

For presentation of IOA multipliers, simplified formulas of the models 4.26–4.28 will be used, given by formulas 4.31–4.33.

Output multipliers

Parameters of the final form of a multi-equation model are called multipliers. They show the reaction of the model (of endogenous variables) on stimuli in the form of change of a single exogenous variable. They are the main characteristics of any model.

Assuming that in the production model given by equation 4.31, the vector of final demand is determined exogenously, the final form (solutions for **X**) can be written as follows:

$$\mathbf{X} = \left(\mathbf{I} - \mathbf{A}\right)^{-1} \mathbf{Y}\,. \tag{4.34}$$

Elements of

$$\left(\mathbf{I}-\mathbf{A}\right)^{-1}$$

matrix are the parameters here, and they are called production multipliers. Let the symbol A_{ij}, mean a single element of this matrix, i.e.:

$$\left(\mathbf{I}-\mathbf{A}\right)^{-1}=\left[A_{ij}\right]. \tag{4.35}$$

It is interpreted as the reaction of output of the j-th sector on the increase of final demand in the i-th sector by one unit.

The sum of the A_{ij} coefficients in the j-th column:

$$\propto_{ij}=\sum_{i=1}^{n}A_{ij} \tag{4.36}$$

is defined as the *simple output multiplier* (production multipliers) of the j-th sector. It is the total value of production in all sectors of the economy that is necessary to satisfy one unit increase in final demand for sector j-th output.

The simple production multiplier consists of three different effects:

1) initial effect, (impulse) or unitary change in final demand, imaged by matrix **I**;
2) direct effect in the form of matrix **A** elements;
3) indirect effect expressed by the sum of consecutive powers of **A** matrix ($\mathbf{A}^2+\mathbf{A}^3+\ldots$).

Production multipliers for all branches of economy can be expressed in the form of a row vector calculated according to the following formula:

$$\propto=\boldsymbol{i}'\left(\mathbf{I}-\mathbf{A}\right)^{-1}. \tag{4.37}$$

In addition to simple output multipliers, *total output multipliers* are also defined in the I-O analysis. Total multipliers are calculated on the basis of the production model closed with respect to households (both income and consumption) by joining it to the I-O table as another production sector. In other words, this means that both household income and household consumption are endogenised. As a result, the total output multipliers contain the three effects of simple multipliers and the so-called induced effect. The induced effect results from the fact that increasing production will increase household incomes which cause additional increase (above the initial effect from the simple multiplier) of final demand.

Let's notice, however, firstly, that the extension of the production model in the way described above is not the only way of closing the I-O model with respect to the household sector, and secondly, that such an extended model is still open due to other sectors creating final demand (mainly investments, government consumption, as well as exports). Thus, induced effects (as well as total multipliers) are ambiguous – their strength may change depending on the method used to close the production model with respect to households. It can also be stated that the "total multipliers" of the I-O analysis are not total multipliers in a general sense, because they contain only one of the possible induced effects, resulting from the feedback between household incomes, expenditures and production. However, they do not contain effects induced by other feedbacks occurring in the economy.

It is worth noting that the models of I-O analysis, and in particular the production model closed with respect to households, are linear models. To determine multipliers, such models can be solved by transformation from the structural form to the final one. However, if the model is closed using nonlinear functions, deriving the appropriate formulas may be too difficult or even impossible. In such cases, the models are solved with numerical methods (simulations), and the appropriate multipliers are calculated by comparing different solutions as so-called generalized multipliers.

Other multipliers

The production multipliers discussed in the previous section do not exhaust the problem of multipliers in I-O analysis. This concept can be generalized to any factor of production or its non-production results, regardless of how they are measured – quantitatively or in value terms. For example, it is possible to analyze labour inputs (in the form of employment, salaries or income), input of ecological goods or energy and external effects (including pollutant emissions).

Substituting vector X in 4.33 by 4.34 we get:

$$C = \left[\mathbf{c}'(\mathbf{I}-\mathbf{A})^{-1}\right]\mathbf{Y}\,. \tag{4.38}$$

The expression enclosed in brackets is a vector of *simple factor (result) multipliers*:

$$\gamma' = \left[\mathbf{c}^{'(\mathbf{I}-\mathbf{A})^{-1}}\right]. \tag{4.39}$$

As in the case of production multipliers, also for factors (results), the term *total multipliers* can be applied to closed models.

The multiplier for the j-th branch is interpreted as a total change in the inputs of the factor (production results) in the entire economy, related to the unit change of the final product of the j-th branch.

Now the so-called *type I multiplier* can be defined as:

$$M_j^I = {}^{\gamma_j}\!/_{c_j} . \tag{4.40}$$

The above multiplier shows the total input of the factor (result of production) in the entire economy, resulting from the unit change of this factor (result) in the j-th sector (and not, as in the case of the simple multiplier, resulting from the unit change of the final product of the j-th sector).

In the case of closed models, the so-called *type II multipliers* are defined, being an analogy to type I, as the quotient of the total multiplier and the direct effect.

4.4. Forecasting of technical coefficients

In the classical approach, the use of technical coefficients is related to the assumption of their constancy. On the other hand, there are many factors due to which production technology can and will change over time for a variety of reasons, such as (Miller, Blair, 2009: 303–304):

- Technological progress as such, manifested by the implementation of production techniques that were previously not used in the economy under consideration. As a result, there are changes in technical coefficients, unit labour inputs, as well as capital. Economies of scale resulting from production growth (subject to capacity constraints) in situations of a significant increase in demand for products from a given sector.
- Emergence of new products (inventions), resulting in – in extreme cases – a creation of new sectors or at least changes in the production structure (and thus in the expenditure structure) of the sector in which the product is included. The new product may also cause changes in production technologies of other sectors, e.g. replacing the old ones, which will cause changes of the coefficients in the row of the table related to the sector in which the product is included. The example could be the use of plastic bottles instead of glass ones.
- Changes in relative prices which may cause substitution of production factors (e.g. substitution of crude oil by natural gas under the influence of a sharp rise in oil prices).

- Classification changes and changes in the level of aggregation of input-output tables – the more aggregated the array, the larger the number of products covering a single sector, which affects the value of technical coefficients (production technology).
- Shifts in the consumption structure between domestic products and imported ones; it may take place as a result of an expansion or a reduction of the production capacity of the sector (e.g. as a result of opening or extending as well as closure or reduction of the capacity of an existing factory).

For these reasons, the matrix of technical coefficients can change over time. Thus, for a modeller, a fundamental question is if, and how the changes can be taken into account in the framework of I-O models. In other words, the question is if the assumption of stability of parameters of I-O models can be accepted or not. In case the answer is negative, some methods of forecasting is needed. The following methods of forecasting of technical coefficients are distinguished in the literature on the subject (Miller, Blair, 2009):

- techniques based on the knowledge of the boundaries of the predicted matrix,
- mathematical programming techniques,
- statistical and econometric techniques,
- heuristic methods.

Methods belonging to the first group are based on the knowledge of the full matrix of technical coefficients for the base year and some balancing sums for a forecasted period. There are two groups of methods of this type. The first consists of proportional scaling methods, concerning only the correction of columns or rows (and at the same time ensuring the balancing only in columns or rows). The second one consists of bi-proportional scaling methods, in which rows and columns are corrected at the same time (ensuring simultaneous balancing in rows and columns). The most commonly known and most often used method of this type is the RAS method (Miller, Blair, 2009).

Mathematical programming techniques used for forecasting of technical coefficients can also be divided into two groups. The first one includes methods based on deterministic models. The idea is based on minimizing the sum of deviations of the forecast values of the coefficients from their initial values. Constraints for the problem are formulated in the way which ensures that the coefficients fulfil the desired properties and sum to specific values. The second category includes techniques based on the least-squares method. The linear programming methods are used to minimize the sum of the squares of deviations of the predicted value of coefficients, resulting from the change function postulated for it, from the value in the base period. Once again, the desirable properties of the value of coefficients are provided by the appropriate formulation of restrictions. It is clear that this group of methods combines linear programming techniques and statistical, or econometric techniques.

The use of econometric and statistical techniques consists in making predictions based on descriptive models or trend models whose parameters are estimated on the basis of time series of technical coefficients. The problem, in this case, is the high labour intensity of research, resulting from the vast number of I-O matrix coefficients, and thus the models to be estimated and analyzed. Therefore, their number is often limited by modelling only the so-called important coefficients (Miller, Blair, 2009), assuming at the same time the stability of other coefficients. Another way to reduce the number of coefficients for forecasting in combination with econometric prediction techniques is to use the *across-the-row* method. It derives from the research trend, which analyzes structural changes based on deviations between empirical values of production and its theoretical values, determined based on the assumption of constancy of I-O coefficients. The name of the method reflects the principle of its use, according to which all the coefficients in a given row change in the same direction and with the same intensity. An essential advantage of the across-the-row method is the fact that its application does not exclude the use of an individual approach in the case of coefficients considered as the important or coefficients determined in a heuristic manner.

The class of ex-ante methods does not have such a rich representation as ex-post methods. It is limited to the use of heuristic methods based on the opinions of experts representing various sectors of the economy (usually the most important or essential from the point of view of the research objective) on the anticipated changes in the sectoral structure of inputs or changes in individual energy-intensity factors. This mainly refers to engineering information characterizing production technologies, which must be "translated" into the language of I-O coefficients (Klein et al., 1999).

4.5. Including a new activity

Let us remind that a j-th column of an A matrix represents the technology of j-th sector within the economy under consideration. Structural changes within the economy cause that technical coefficient's change. As it was stated in section 4.4, several reasons for that can be identified, among them an introduction of new technologies or new products. Both new technology and new product can be interpreted as an introduction of a new activity into the economy. The new activity can be represented in the technological coefficient matrix (A) in two ways.

The most straightforward way to deal with a new activity in an input-output model is to extend the technical coefficient matrix by the new elements in the form of one column and one row. However, in the case of models which are already implemented, technical, software specific problems must be overcome – these are mainly fixed dimensions of vectors and matrices. To avoid the software problems an alternative method, based on mixing (averaging) technical coefficients of the new activity with technical coefficients of an existing sector, can be used[7]. In both approaches, it is assumed that technical coefficients of the new sector are known or can be estimated.

Besides the two above-mentioned methods, i.e. *extension of the technical coefficient matrix* and *averaged technical coefficients*, a third method is also considered in the literature, called the *final demand approach*. The third method is the least demanding in terms of data, compared to the two others. All three methods are presented below in a formalized way.

Extension of technical coefficient matrix

Production model given by formula 4.31 can be re-written to include the new activity in the following way:

$$\begin{bmatrix} \mathbf{X} \\ X_{n+1} \end{bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{A}^{c}_{n+1} \\ \mathbf{A}^{r}_{n+1} & a_{n+1} \end{bmatrix} \begin{bmatrix} \mathbf{X} \\ X_{n+1} \end{bmatrix} + \begin{bmatrix} \mathbf{Y} \\ F_{n+1} \end{bmatrix} \tag{4.41}$$

or after doing partitioned matrix operations

$$\begin{cases} \mathbf{X} = \mathbf{AX} + \mathbf{A}^{c}_{n+1} x_{n+1} + \mathbf{Y} \\ X_{n+1} = \mathbf{A}^{r}_{n+1}\mathbf{X} + a_{n+1} X_{n+1} + Y_{n+1} \end{cases} \tag{4.42}$$

where: subscript $n + 1$ is an index of the new activity, and superscripts r and c mean elements of new row and new column respectively.

The above problem is similar to the one described in section 4.2.2 as mixed models (see assumption 3 in this section). In mixed models, where an output with a new activity (X_{n+1}) is exogenous, we get a recursive system, so after finding the solution for vector X the solution for Y_{n+1} can be easily found:

$$\begin{cases} \mathbf{X} = \left(\mathbf{I} - \mathbf{A}\right)^{-1} \mathbf{Y} + \left(\mathbf{I} - \mathbf{A}\right)^{-1} \mathbf{A}^{c}_{n+1} X_{n+1} \\ Y_{n+1} = \left(1 - a_{n+1}\right) X_{n+1} - \mathbf{A}^{r}_{n+1}\mathbf{X} \end{cases} \tag{4.43}$$

7 Example of the application of this method can be found i.a. in Plich (2016).

Averaged technical coefficients

Again, the production model given by formula 4.31 can be re-written as follows:

$$\mathbf{X} = \mathbf{A}^{*}\mathbf{X} + \mathbf{Y}, \tag{4.44}$$

where $\mathbf{A}^{*}$ matrix differs from **A** with respect to j-th column only ($\mathbf{A}_{j}^{*}$).

The column $\mathbf{A}_{j}^{*}$ is calculated as a weighted average of the old j-th column (of A matrix) and the vector representing technical coefficients of the new activity ($\mathbf{A}_{j}^{cn}$):

$$\mathbf{A}_{j}^{*} = s\mathbf{A}_{j}^{cn} + (1-s)\mathbf{A}_{j}, \tag{4.45}$$

where *s* is an estimated share of the new activity in the output of the j-th sector after the introduction of the new activity.

Final demand approach

This is a less data demanding method compared to the two presented above. It helps to examine the impact of the new sector on the economy, based on final demand vector changes. The idea in the final demand approach is to calculate the impact of the new activity on all sectors while ignoring dependencies in the opposite direction. This is equivalent to ignoring the second equation in the system 4.42. In other words, both $\mathbf{A}_{n+1}^{r} = 0$ and Y_{n+1} is unknown, so X is calculated using only the original model for final demand vector equal to $\mathbf{A}_{n+1}^{c} X_{n+1} + \mathbf{Y}$

$$\mathbf{X} = \mathbf{AX} + \left(\mathbf{A}_{n+1}^{c} X_{n+1} + \mathbf{Y}\right). \tag{4.46}$$

Final demand vector increases by $\Delta\mathbf{Y} = \mathbf{A}_{n+1}^{c} X_{n+1}$ compared to the original solution, so the impact of the new activity is:

$$\Delta\mathbf{X} = (\mathbf{I} - \mathbf{A})^{-1} \Delta\mathbf{Y}. \tag{4.47}$$

We considered three ways of introducing new activities into the production model. Let's add that the other I-O models based on a matrix of technical coefficients can be similarly re-written to include a new activity.

As well as changes of share of imports and domestic production in total demand, new activity can also cause other changes in the technical coefficient matrix. On the one hand, imports of some products can increase if the new activity demands more imported materials compared to the technology used so far, but on the other hand imports of the product of the new activity can decrease if the new activity expands production capacity of the old sector. Appropriate modifications should be made both in domestic and imported matrix in the row corresponding to the sector under consideration, or modifications of imports equations should be introduced (if domestic and imported coefficients are not distinguished in the model).

If the product of the new activity is the same as the product of an existing sector, the row coefficients of this sector can be assumed as the coefficients for the new activity. Another issue to be resolved is the decomposition of the demand for this product between the old, existing and the new sector (assuming that a utility of the new and the old product are the same). This can be determined using the manufacturing costs. In the case where the new activity uses a new technology, production costs may be initially higher and then fall according to a certain learning curve. However, for some products, even non-economic factors may be decisive. For example, this may be the case of a possible start-up of a nuclear power plant (NPP) in Poland. It is not sure that the production cost of electric power in NPP will be lower compared to coal technology, even in the long run. Nevertheless, due to the obligation to limit the emission of air pollutants, the launch of an NPP will be preceded by a closure of coal-fired power plants, which so far have been the baseload power plants in Poland. Thus it can be assumed that an NPP will replace the loss of production of baseload power plants, regardless of the manufacturing costs.

4.6. Modelling energy and emissions

Modelling energy and emissions is in the centre of discussions on climate change mitigation strategies. Two different types of modelling approaches can be identified within this area (see Vogele et al., 2010 or Plich, Skrzypek, 2017). One of them is based on I-O methods and concentrates mainly on demand for energy and interactions between energy system (energy sectors) and other sectors of the economy. The second one focuses more on physical energy flows and technological (engineering) aspects of energy production, like vintage structures, load availability factors or technical parameters of specific installations. Emission levels in both types of models result directly from the amount of energy demand (or energy production), technologies used for the energy production and the ways of satisfying of final consumers' demand for energy.

The two types of models can complement each other when they are linked through a soft or a hard link (see Plich, Skrzypek, 2017). Such hybrid models are hard to construct and maintain because of their high complexity. However, it should be stressed that some kinds of engineering data can be integrated with technological coefficients for sectors of I-O models. Although such an integration causes some loss of details, compared to the use of engineering models, questions on economic and environmental effects of changes in energy mix can still be answered. Therefore this section concerns I-O techniques used for energy and emission modelling.

4.6.1. General approach

The original idea of Leontief production model refers to the table of interindustry flows in physical units. The parameters of the production model are technical coefficients presented in the form of matrix, referring to variables measured just in physical units. On the other hand, the same matrix of technical coefficients is used in the price model. Prices enable transforming variables of the production model (i.e. output and final demand) to the value terms. The use of such an approach, although very attractive in theory, is problematic in practice due to statistical difficulties resulting from the limited ability of aggregation of data expressed in quantitative terms. Therefore, in the applications of the production model, variables in constant prices are usually used as quantitative variables. However, analyses of this type are focused on market goods and services only because their prices are known. The inability to include the modelling of non-market goods would be a severe drawback in the era of such great interest in the issues of sustainable development. The assessment of the size of natural resources and their consumption is carried out in physical units, as in the case of the emission of all kinds of pollutants. This applies especially to fossil fuels and emissions resulting from their combustion in order to transform chemical energy into thermal energy. Therefore, in parallel to improving the methods of collecting statistical data, which increasingly meet the needs of research on sustainable development, analytical methods are continually being developed. These include mathematical models, within which it is possible to combine variables measured both in value and quantitative terms. Thanks to this, I-O methods can be successfully used to track energy consumption and analyze emissions related to the functioning of the economy at the regional, national and global levels.

In the simplest terms, the analysis of energy consumption and emissions can be carried out using one of the classical I-O models discussed in sections 4.2 and 4.3 (see formulas 4.19, 4.33 and 4.38). The versions presented there, concern only one production factor (result). The model can be successfully extended to any number of factors (results):

$$\mathbf{C} = \left[\mathbf{c}'(\mathbf{I} - \mathbf{A})^{-1}\right]\mathbf{Y}, \tag{4.48}$$

where:
C – vector of production factors (results);
c – matrix of direct coefficients of production factors (results);
$\mathbf{c}'(\mathbf{I}-\mathbf{A})^{-1}$ – matrix of simple multipliers of production factors (results).

This form of a model has been and still is often used in energy and emission analysis.

However, in the case of energy, such a formulation may give inconsistencies in the resultant accounting of energy consumption (Miller, Blair, 2009: 403). If energy consumption for a product (energy intensity of a product) is considered, primary and secondary energy (primary and secondary energy sectors) should be distinguished. The total amount of primary energy required for a product must be equal to the total amount of secondary energy required for the same product plus any losses of energy conversion or uses of energy products for non-energy purposes. This condition is called energy conservation condition. The condition is satisfied in another approach to energy I-O modelling, where the production model is based on an I-O table expressed in hybrid units. It refers straightforwardly to the original version of the production model. The original Leontief approach assumes the possibility of measuring products in various units. In particular, it can combine data in value terms and physical terms. So, energy can be expressed in units specific to a kind of carrier or typical energy units like joules, calories, kilowatt-hour, BTU, TOE, and so on. With the appropriate data on production, import and consumption of energy, replacement is possible of rows of energy sectors in the original I-O table to flows measured in energy units. The rows for primary and secondary energy sectors replacing the original flows can be presented as follows:

$$\mathbf{Ui}+\mathbf{u}=\mathbf{q}\,, \tag{4.49}$$

where **U** is m × n matrix of energy flows from energy sectors to all sector of the economy (**i** is a unitary vector), **u** is the vector of energy deliveries to final demand and **q** is the vector of total energy consumption.

Let us denote the matrix of technical coefficients determined on the basis of such a table by $\mathbf{A}^*$, output as $\mathbf{X}^*$ and final demand as $\mathbf{Y}^*$. The production model in the hybrid units will, therefore, take the form:

$$\mathbf{X}^*=\mathbf{A}^*\mathbf{X}^*+\mathbf{Y}^*\,. \tag{4.50}$$

It has all the properties of the production model. The price model can be written similarly. Note, however, that in the price vector, in the case of energy sectors, price levels of particular types appear (in practice, average prices of a given type of energy), but not deflators, as in non-energy sectors.

Using this approach may involve the following difficulties:

- availability of data on energy consumption in the classification of sectors corresponding to the I-O table – usually energy is classified according to industries while the best way of classification of sectors for the I-O table (from the point of view of national economy analyses) is classification by products;
- the relatively high level of I-O tables aggregation does not allow unambiguous assignment of energy sectors to types of energy (there are more types of energy than sectors, and some kinds of energy can be produced by different sectors).

Overcoming these difficulties may be twofold. On the one hand data on energy in energy units can be aggregated to fit I-O table aggregation, and on the other, flows in the I-O table can be disaggregated in order to determine the amount of consumption of particular types of energy in terms of value, in order to fit energy sectors to the energy types. In the first case, the accuracy of analyses decreases because of the necessity for the use of averaged prices and averaged technologies of fuel production, resulting in the lack of unambiguous translation of a specific fuel demand to the production of this fuel. In the second, it is a problem to determine the technology of production of the newly distinguished types of energy. This is analogous to the problem of including a new activity in the I-O model (see section 4.5).

From the point of view of the production function, emissions can be interpreted as both side-effects (unwanted), effects of production activities (production results) as well as a production factor (unwanted but necessary) not included in the economic accounts[8]. Regardless of the interpretation method used, the approach presented at the beginning of the chapter, i.e. based on emission factors determined in relation to the output of the issuer's sector, can be used to model them. In the case of modelling emissions resulting from the energy processing, emission factors may refer directly to the size and type of energy consumed in the transformation processes. In the case of modelling emissions resulting from the energy processing, emission factors may refer directly to the size and type of energy consumed in the transformation processes. The advantage of this approach stems from the

8 Although fees related to emissions, including the price of carbon dioxide in the carbon dioxide emissions trading system, which are determined on market terms, seem to contradict this statement, it must be remembered that this type of valuation does not take into account the scale of the disadvantages resulting from the issue of the value of environment and human health, as well as costs associated with the elimination of the effects of emissions.

fact that it refers directly to the technical parameters of the fuel used (e.g. carbon content) and to the technical parameters of the devices used for its processing instead of the output of the whole sector measured in value terms.

In order to circumvent the previously signalled problems related to the ambiguity of the allocation of energy types to sectors, implied prices are determined, using the lines of energy sector product distribution from the I-O table and the corresponding lines for the distribution of individual types of energy from energy balances. Because the I-O tables, being the basis for the construction of the production model, represent production flows at constant prices, these flows should change in proportion to energy consumption, which means that implied prices should be considered fixed[9].

4.6.2. Equations of air pollution from fuel combustion

The amount of emission of type *z* by sector *j* can be expressed as the sum of emissions resulting from the use of different fuels (f):

$$E_{zj} = \sum_{f} E_{zjf}\ , \tag{4.51}$$

where f means a type of fuel (f = 1, …, F).

Now we can define coefficients e_{zjf}, which express emission of pollutant z resulting from the use of fuel of type f in sector j per unit of output of this sector:

$$e_{zjf} = E_{zjf} / X_j\ . \tag{4.52}$$

If we assume that the coefficients are constant, we have:

$$E_{zjf} = e_{zjf} X_j\ . \tag{4.53}$$

Now we can rewrite equation for emission E_{zj} as:

$$E_{zj} = \sum_{f} e_{zjf} X_j \tag{4.54}$$

9 In practice, however, this is not the case due to imperfections in the process of collecting statistical data within national accounts and energy balances.

or in the equivalent form:

$$E_{zj} = \left(\sum_f e_{zjf} \right) X_j . \tag{4.55}$$

Notice that:

$$e_{zj} = \sum_f e_{zjf} \tag{4.56}$$

i.e., sectoral emission coefficient e_{zj} is equal to the sum of emission coefficients for fuels e_{zjf} (f = 1, …, F). Now, the emission coefficients can be further decomposed. For this purpose, let's multiply e_{zjf} by a factor

$$\frac{U_{fj}}{U_{fj}} \frac{X_{(f)j}}{X_{(f)j}},$$

where:
U_{fj} – amount of fuel f used by sector j (in natural units),
$x_{(f)j}$ – input of products of the energy sector being the producer of fuel f used by sector j.

$$e_{zjf} = \frac{E_{zjf}}{X_j} \frac{U_{fj}}{U_{fj}} \frac{X_{(f)j}}{X_{(f)j}} \tag{4.57}$$

Reordering right-hand side of this formula we obtain:

$$e_{zjf} = \frac{E_{zjf}}{U_{fj}} \frac{U_{fj}}{X_{(f)j}} \frac{X_{(f)j}}{X_j} . \tag{4.58}$$

The above can be written as:

$$e_{zjf} = w_{zjf} v_{fj} a_{(f)j} , \tag{4.59}$$

where:

$w_{zjf} = \frac{E_{zjf}}{U_{fj}}$ – emission coefficient (emission of pollutant z per unit of fuel f used in sector j),

$v_{fj} = \frac{U_{fj}}{X_{(f)j}}$ – coefficient of fuel use (amount of fuel per unit of input of the energy sector being the producer of fuel f used in sector j,

$a_{(f)j} = \frac{X_{(f)j}}{X_j}$ – direct input coefficient of products of the energy sector (f), used in sector j.

Thus, we decomposed the coefficients e_{zjf} into w_{zjf}, v_{fj}, and $a_{(f)j}$. Now, we can rewrite E_{zj} as:

$$E_{zj} = \left(\sum_f w_{zjf} v_{fj} a_{(f)j} \right) X_j . \tag{4.60}$$

Now we can add subscript t to express time and notice that the above equation can be formulated for each pollutant, sector and fuel. Thus we get:

$$E_{zjt} = \left(\sum_f w_{zjft} v_{(f)jt} a_{(f)jt} \right) X_{jt} \ (z = 1,\dots Z)(j = 1,\dots J)(f = 1,\dots F) . \tag{4.61}$$

If we assume that coefficients w_{zjft} and v_{fjt} are constant we get the following emission equations:

$$E_{zjt} = \left(\sum_f w_{zjf0} v_{fj0} a_{(f)jt} \right) X_{jt} \ (z = 1,\dots Z)(j = 1,\dots J)(f = 1,\dots F) . \tag{4.62}$$

5. IAEA Empower model and its properties

This chapter is devoted to the description and properties of the Empower model – one of the many models offered by the International Atomic Energy Agency (IAEA) for energy planning. In section 5.1, the set of models offered by IAEA is succinctly presented. The theoretical properties of the Empower model will be presented in section 5.2. Chapters 5.3 and 5.4 are devoted to the implementation and properties of the model on the example of the Polish economy. It should be borne in mind that the empirical properties can be presented, in fact, only as a case study, because the properties of empirical models based on the same theoretical model depend on the specificity of the considered object – in this case, the national economy. This also applies to the stage of implementation of the model, but the differences are less noticeable in this case because of the standardisation of National Accounts. Referring to the implementation of the Empower model for Poland, we will use the name Empower.pl. The properties of the Empower.pl model will be shown on the example of Polish Nuclear Power Programme (PNPP)[10]. The program is outdated, but the first scenarios for the development of Polish nuclear power, aimed at testing the properties of the model, were based on this program. That is why we decided that the results of these works should also be presented.

5.1. IAEA models for energy planning

International Atomic Energy Agency (IAEA) develops and maintains several models for energy planning:

- Model for Analysis of Energy Demand (MAED) evaluates future energy demands disaggregated into a large number of end-use categories on the base of scenarios of socioeconomic, technological and demographic development.

10 See section 5.4.1 for more explanation.

- Wien Automatic System Planning Package (WASP) determines the optimal expansion plan for a power generating system, minimising total costs under sets of constraints such as limited fuel availability, or emission restrictions.
- Model for Financial Analysis of Electric Sector Expansion Plans (FINPLAN) helps assess the financial viability of plans and projects by calculating cash flows, balance sheet and a set of financial indicators, taking into account various financial sources.
- Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE), is based on a very detailed data on fuels and available technologies and helps in design of long term strategies by analyzing cost-optimal energy mixes, investment needs and other costs for new infrastructure, energy supply security, energy resource utilization, rate of introduction of new technologies (technology learning), environmental constraints.
- Simplified Approach for Estimating Impacts of Electricity Generation (SIMPACTS), estimates and quantifies the health and environmental impacts and external costs of different electricity generation technologies.

The newest one is ***Extended Input-Output Model for the Sustainable* Power** *Generation* (EMPOWER) which was first developed under the IAEA Common Research Project (CRP) 12005 on "Assessing the National and Regional Economic and Social Effects of Nuclear Programmes" (see Kratena, Voigt, 2017; Kratena, Sommer, 2019).

The Empower model consists of two components:

- equation system (a theoretical or empirical model), showing basic multiplier mechanisms occurring within the national economy,
- software for implementing and solving the empirical model, in the form of MS Excel files containing calculation templates and associated Visual Basic for Applications (VBA) programs for running the model.

For referring to the software only, we will use the term *Empower software*. When using the Empower model for the Polish economy[11], we will use the term Empower.pl and Empower.pl software, respectively. Although any software should be general, in case of *Empower*, we had to introduce significant modifications in the calculation templates and VBA codes compared to the original version[12]. Therefore, using a modified name (Empower.pl software) seems to be fully justified.

11 Construction of the first version of the Polish model was supported by financial resources for science in the years 2016–2017, granted for the implementation of the international co-financed project No 3672/IAEA/2017/0 and IAEA Research Contract 18541.

12 The Empower.pl model was implemented in the first version of the Empower software (see Kratena, Voigt, 2017). In June 2019, its new significantly improved version was released.

The idea behind the *Empower* is to propose one model (a theoretical one) with an implementation software, empirical version of which could be built for different countries. The advantage of this approach is the lack of costs associated with the purchase of specialised software and the ability to easily compare results between different countries, and thus the ability to verify them. The software was created based on MS Excel spreadsheet – an intuitive tool used mainly for office calculations – which is an additional advantage guaranteeing that the user will not have to learn a new tool. On the other hand, this approach creates constraints related to the theoretical model. In this approach, the model should have a predetermined analytical form and be limited in size. The software can use only the simplest numerical methods for finding the model solution. The constraints are hard to overcome if software bases on MS Excel.

It is worth noting that there are specialised computer programs dedicated to the implementation of input-output econometric models, which are distributed on a non-commercial basis and do not have such barriers as mentioned above. An example is the Interdyme – a package developed by Inforum[13]. However, the knowledge of the MS Excel environment by the majority of potential users of the Empower model turned out to be a persuasive argument for choosing this path of implementation.

Because the idea of Empower model for Poland goes beyond its original version, so its implementation is possible only after extending the capabilities of the original software. Due to the specificity of Empower software, it can be expected that adding new blocks of equations will extend the time of simulations, which can be a significant problem for its efficiency. Therefore, in parallel with the development of Empower software, work was carried out on the implementation of the model in the Interdyme package.

5.2. Theoretical model

The *Empower* model proposed for the assessment of the effects of the construction and operation of the NPP presented by Kratena and Voigt (2017) and Kratena and Sommer (2019) consists of the sets of equations presented here in Table 5.1 and Figure 5.1.

However, it does not include extensions provided in the Empower.pl.cc. model. Therefore, work on this model continued under the previous version of the software.

13 Inforum is The Interindustry Forcasting Project at the University of Maryland. The Interdyme software is characterized in the webpage http://www.inforum.umd.edu/software/interdyme.html.

Table 5.1. Equations of Empower model

Equations	Symbols
Output (in current nominal terms): $\mathbf{x} = \mathbf{A}^{\mathrm{d}}\mathbf{x} + \mathbf{cp} + \mathbf{f}^{*} + \mathbf{f}^{\mathrm{new}}$ 5.1 Output (in real terms): $\mathbf{x}^{\mathrm{r}} = \mathbf{x} / \mathbf{p}$ 5.2 Disposable income: $YD = \mathbf{l}wf_{\mathrm{w,hh}}\left(1 - t_{\mathrm{hh}}\right)\mathbf{x} + \mathbf{s}f_{\mathrm{s,hh}}\left(1 - t_{\mathrm{hh}}\right)\mathbf{x} + YD_{oth}$ 5.3 Consumption (in current prices): $\mathbf{cp} = [\exp(const_{\mathrm{cp}} + elas(\log(YD))]\mathbf{b}^{\mathrm{d}}_{\mathrm{hh}}$ 5.4 Employment: $L = \mathbf{l}\mathbf{x}^{\mathrm{r}}$ 5.5 Wages: $w = \exp(const_{w} + \beta_{ur}\log(1 - L / LF))$ 5.6 Unit labour costs: $\mathbf{l} = \mathbf{l}_{\mathrm{base}} w / \left(0.5 * w_{\mathrm{base}} + 0.5 * w\right)$ 5.7 Prices: $\mathbf{p} = \mathbf{p}\mathbf{A}^{\mathrm{d}} + \mathbf{p}^{\mathrm{m}}\mathbf{A}^{\mathrm{m}} + \mathbf{l}w + \mathbf{s} + \mathbf{t}^{\mathbf{q}}$ 5.8 Tax rate: $t^{new}_{hh} = \dfrac{r_{pub} i' \mathbf{f}^{\mathrm{new}}}{YD}$ 5.9	Variables: *x* – output *cp* – household consumption *f* – final use (excluding household consumption) *p* – output prices *w* – wage rate *YD* – disposable income (after tax) YD_{oth} – non-wage income *L* – employment *LF* – labour force t^{new}_{hh} – revenue-neutral tax rate Symbols written with variables in the upper or lower index: ^{r} – in real terms ^{d} – domestic ^{m} – foreign * – original data ^{base} – in base year Parameters: *l* – unit labour costs *s* – unit operational surplus *A* – Matrix of input-output coefficients t_{hh} – household tax rate $f_{s,hh}$ – coefficients for harmonization of operational surplus in input=output tables and national accounts $f_{w,hh}$ – coefficients for harmonization of wages in input=output tables and national accounts *const*– constant term *elas* – income elasticity β_{ur} – parameter of wage response to unemployment rate Other symbols: log – natural logarithm exp – exponential function **I** – unit vector ' – symbol of transposition Bold text indicates the vectors containing the appropriate sectoral values.

Source: own elaboration on the base of model equations.

The equations presented above constitute the full version of the model, reflecting the four types of multiplier mechanisms present in the economy, resulting from the following relationships described by the theory of economics:

A. Interindustry (direct and indirect) – equations 5.1 and 5.2.
B. Incomes and consumption – equations 5.3 and 5.4.
C. Employment (unemployment), wages and prices – equations 5.5–5.8.
D. Public sector income revenues and investments – equation 5.9.

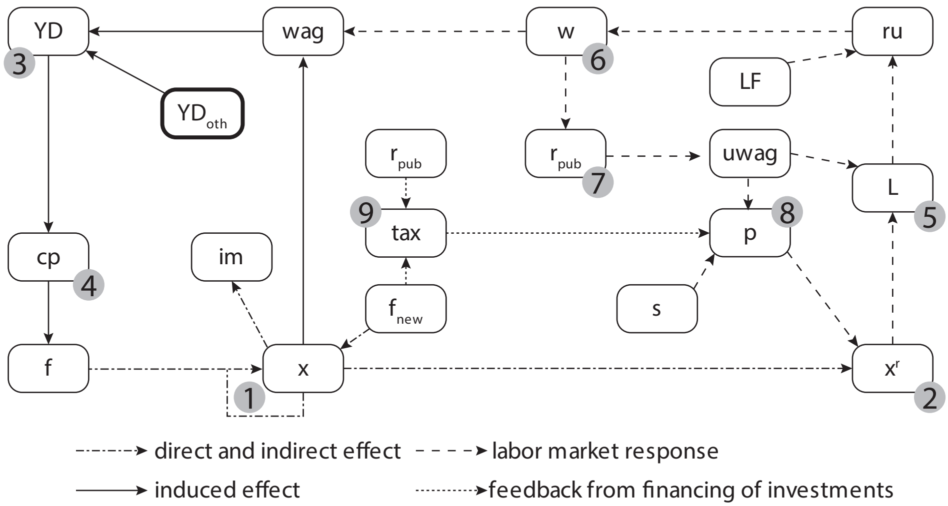

Figure 5.1. Block diagram of Empower model

Source: own elaboration on the base of model equations.

The Empower software enables running of the model in four variants created by adding subsequent sets of equations, so each next variant comprises of more equations. The first and the simplest variant comprises only of the equations of set A, the second – of sets A and B, the third comprises of sets A, B and C, and the last one simulates the use of the full model. The variants are called A, AB, ABC and ABCD, accordingly. This allows drawing conclusions about the impact of specific mechanisms (A, B, C or D) on the economy by comparing the results of the four variants of simulations carried out with the same scenarios.

The mechanisms referred to above may concern both the stage of the construction of an NPP and the stage of its operation. As part of the proposed approach, these two phases are considered separately. In practice, this means that the model can be solved (run) in two different modes:

- NPP construction mode or
- NPP operation mode

and that both variants are mutually exclusive.

Technical coefficients necessary to run the model are calculated based on I-O tables in current prices. Tables for future periods are forecasted based on the assumed rates of sectoral output. Such approach does not take into account an essential problem of technological changes, because sectoral technologies of production represented in the forecasted input-output table are the resultants of technology in the base year and the "boundaries" of the matrix which are forecasted based on assumptions on output in current prices. In such a case, it is hard to say that the changes of the A matrix, i.e. changes in technical coefficients (technologies) are under control and refer to the economic theories – the changes are somewhat accidental and indistinguishable from price changes.

In this model, income flows are presented in a simplified way, as the transfers of part of primary revenues to the budget (taxes and social security burdens) and transfers from the budget to households are presented as one item – net tax burden. The net tax burden is used to designate a total (effective) rate of tax, as uniform for all types of primary income, i.e. wages, operating surplus of households, profits and other incomes.

An analysis of the model equations indicates that there are no intertemporal relationships. This is a static model. Most of its parameters are selected using the calibration method, based on statistical data from the base period. As a result, if the empirical values of the base period are used in the scenario that determines exogenous variables, the endogenous variables at the level of their empirical values from that period will be obtained as a result of the solution of the model, reflecting the state of general equilibrium.

The model is launched by a disturbance of the state of general equilibrium, by introducing an impulse, i.e. a disturbance of the value of one or more exogenous variables or one or more parameters, relative to the equilibrium state. As a result, the model determines the endogenous variables in a new equilibrium.

Interpretation of results is a problem in models of such kind. It is unclear which period the new equilibrium is related to, i.e. at which point the new equilibrium is reached. Because time-lapse is essential in economic analysis, a more straightforward interpretation can be adopted with this type of model: if the impulse size is chosen to reflect changes in the value of exogenous variables between the time periods T and T + t, then the model solution determines the state of general equilibrium in the period T + t. In particular, using this approach in case of annual data, it should be recognized that if the impulse size is for one year only, the model solution concerns precisely this year. In such a case, the model can be solved sequentially for subsequent periods of time for which scenarios of changes in exogenous variables have been prepared. This creates the impression of "dynamizing" the model, although, in essence, the model is static.

5.3. Implementation of the model for Poland

5.3.1. Data collection and adjustment

Production equation 5.1 and price equation 5.8 of *Empower* model are based on classical IOA equations presented in chapter 4.2.1. The basis for their construction are I-O tables. The tables can occur in various forms depending on:

- classifications of industries used for table construction (supply and use tables, symmetric tables),
- level of aggregation (from several to several hundred sectors),
- method of flow of valuation (tables in purchasers' prices and in base prices),
- the way of imports' inclusion (flows with imports and with separation of imports),
- the way prices are treated (tables in current prices and in constant prices).

Since the tables are an integral part of national accounts systems, their preparation and publication are handled by national statistical offices. Since the entry of Poland into the EU, the tables created in Poland have been based on the Eurostat guidelines and are available on the website of Statistics Poland.

Practice shows that, depending on the nature of the tables published by national statistical offices, the use of I-O tables for economic analyses, including the design of economic models, requires some customization. In spite of the standardization of national accounts at an international level, in the case of analyses intended to make international comparisons, it is necessary to harmonize I-O tables for the analyzed countries. Harmonization of tables is usually carried out by international institutions that provide the results on a commercial basis or free of charge. The world's most popular commercial input-output database is elaborated by GTAP (Global Trade Analysis Project), coordinated by Purdue University (Indiana, USA). Among the non-commercial databases, the most known are the following:

- EXIOBASE, Extended Input-Output Base, created by several scientific institutions of different European countries – www.exiobase.eu;
- WIOD, World Input-Output Database constructed within the WIOD Project, funded by the European Commission as part of the 7th Framework Programme (www.wiod.org);
- OECD – www.oecd.org/trade/input-outputtables.htm.

By default, *Empower software* is configured for a classification of 35 sectors[14] for which WIOD database is available (see Timmer et al., 2015). The database covers

14 This concerns the 2013 release of WIOD, where sectors are classified according to the International Standard Industrial Classification revision 3 (ISIC Rev. 3). In the newest release of 2016 there are 56 sectors classified according to the ISIC Rev. 4.

the years 1995–2011 and includes not only I-O tables but also socio-economic accounts as well as environmental data harmonized with the I-O tables for 43 countries, including Poland.

Taking the above into account, there was no reason to use other databases for implementing the *Empower* model for Poland. The latest table (i.e. for 2011) was used to build the model. It was decided that the model variables will be expressed in US dollars. Where source data was not available in that currency, conversions were made at the applicable exchange rate.

Empower software assumes that the first sector in the I-O table is the electricity-producing sector. In the WIOD classification, however, it is in position 17, so the source matrix has been transformed adequately[15].

5.3.2. Implementation and launch of the model

Model parameters

The I-O coefficients for the production and price equations (5.1 and 5.8) have been calculated as well as other parameters which are created on the basis of the input-output table.

Equations 5.4 and 5.6 contain parameters essential for the performance of the *Empower* model – income elasticity (*elas*) and wage response power for the unemployment rate (β_{ur}). Usually, they are estimated with econometric methods. In the *Empower* model, as in other models, which concentrate on the state of economic equilibrium, it is possible to determine these parameters in other ways, such as on the basis of other theories, theoretical assumptions or expert methods. In this study, the parameters were determined based on suggestions by the authors of the *Empower* model (Kratena, Voigt, 2017), which were combined with the research of Polish authors (Doszyń, 2004; Utzig, 2008; Bartosik, Mycielski, 2015). Finally, in the simulations, the *elas* parameter was set to 0.8, while the β_{ur} parameter was set to –0.2.

Common part of simulation scenarios

As mentioned earlier, *Empower* makes it possible to conduct separate simulations concerning the stage of construction of an NPP and the stage of its operation, each in four variants. The basis for the simulation is a suitable simulation scenario containing the values of exogenous variables for the simulation period. Besides, consideration may be given to incorporating selected model parameters into the scenarios. In the classic approach, model parameters are predetermined

15 The Interdyme software does not have such restrictions, however, to facilitate comparisons, the same convention is also maintained in this case.

constants. However, there may be good reasons to treat them as exogenous variables[16] and include them when building scenarios for simulations, for example, when testing the sensitivity of the model's results to changes in parameters or when predicting the future under the assumption of technological changes.

Simulation scenarios are built by assuming paths of changes of exogenous variables. Usually, several scenarios are prepared. For a more comfortable control of all scenarios and clarity of results' analysis, only the paths of chosen exogenous variables differ between scenarios while others are the same, forming a "fixed part" for all scenarios. Therefore, considering the scenarios envisaged in the study, one can distinguish their "fixed part" consisting of variables and parameters with unchanging paths or adopted at a constant level, as well as their "variable part".

For the Empower.pl model, the fixed part of scenarios is related to forecasted I-O tables since the run of the model starts with forecasting of input-output table in current prices for a target year, based on the base year table and assumptions about changes of its boundaries. The forecasting is done using the RAS method. The "fixed part" of scenarios is at the same time, the baseline solution (see section 5.4.1).

Table 5.2. Scenarios of changes of boundaries of input-output table assumed for the example simulations – annual growth rates (%)

No.	Sector name	Output	Prices	outP	No.	Sector name	Output	Prices	outP
1	Electricity	1.2	1.1	2.3	19	Sale & repair of motoveh.	1.9	1.0	3.0
2	Agriculture	0.7	–2.1	–1.4	20	Wholesale trade	1.9	1.0	3.0
3	Mining and quarrying	–1.2	–3.7	–4.8	21	Retail trade	1.9	1.0	3.0
4	Food, beverages & tobacco	3.2	0.6	3.8	22	Hotels and Restaurants	2.7	3.2	6.0
5	Textiles & textile products	5.5	0.3	5.8	23	Inland Transport	3.8	2.7	6.6
6	Leather & footwear	3.5	2.5	6.0	24	Water Transport	3.8	2.7	6.6
7	Wood & products & cork	4.0	0.9	5.0	25	Air Transport	3.8	2.7	6.6
8	Pulp, paper, print. & publ.	5.2	0.6	5.8	26	Oth. transport & travel ag.	3.8	2.7	6.6
9	Coke, petrol. & nucl. fuel	–3.4	–5.9	–9.1	27	Post and telecommunic.	6.3	–0.4	5.8

16 In paragraph 1.4 a possibility of treating parameters as endogenous variables were also considered.

Table 5.2 (cont.)

No.	Sector name	Output	Prices	outP	No.	Sector name	Output	Prices	outP
10	Chemicals & products	1.6	0.9	2.5	28	Financial intermediation	4.7	–1.3	3.3
11	Rubber and plastics	4.9	0.6	5.5	29	Real estate activities	1.0	1.6	2.6
12	Other non-metallic mineral	2.5	–0.8	1.7	30	Renting of mach. & equip.	4.5	1.4	6.0
13	Basic & fabricated metals	3.7	–0.6	3.1	31	Public administration	0.6	4.0	4.6
14	Machinery, nec	3.7	0.7	4.5	32	Education	0.2	4.3	4.6
15	Electrical & optical equip.	4.3	–0.6	3.7	33	Health and social work	4.1	3.9	8.1
16	Transport equipment	4.4	0.8	5.2	34	Other services	3.2	–2.5	0.6
17	Manufactur. nec; recycl.	6.2	1.0	7.2	35	Private HH empl. Persons	3.2	–2.5	0.6
18	Construction	0.1	0.5	0.6		Total	2.6	0.6	3.2

Source: own elaboration.

In this chapter, when building example scenarios for the development of the Polish economy for the coming years, the rate of annual change of the input-output matrix boundaries were assumed to be equal to the average annual growth rates for the period 2011–2016, i.e. during last 6 years for which historical data are available. Table 5.2 presents three variables characterizing output of 35 sectors of the Polish economy according to WIOD classification: output in real terms (output), prices, and output in nominal terms (outP).

Model solving

Let's recall that the Empower.pl model is constructed to reproduce the general equilibrium of the base period (the period which the input-output table used for the model parameters calibration). In the case of the model for Poland, this is the year 2011. In general, running models of this type requires the following:

- introduction of an impulse (scenario) in the form of changes in exogenous variables or parameters; impulse precipitates the model from equilibrium; for the Empower model, scenario content is related to the construction and operation of NPPs;
- definition of the state of the economy in the initial period; because in the case of the *Em-power.pl* model scenarios are related to future events rather

(i.e. construction, and even more, the functioning of NPPs) than the base period the model predicts the state of the economy for years to come; so if the scenario is for example for 2020 and the base year for the model is 2011 (as it is the case for the model for Poland), before the launch of the model, the state of the Polish economy in 2020 should be forecasted; for this purpose *plRAS* file is used;
- finding a new state of equilibrium by solving the model with the user-defined scenario.

5.4. Exploring properties of the model

5.4.1. Scenarios

General concept of the performed simulations

The Empower.pl model is a static model, so the assumptions for the simulations can be adopted independently for each year. For each year the model determines the state of equilibrium. To use the model, a set of assumptions for a baseline simulation (baseline assumptions) presenting the states of equilibrium for subsequent years must be determined first. Then some disturbances (impulses) can be introduced to the baseline assumptions and solve again the model to get results of disturbed simulation. The deviations of the results of the disturbed simulation from the baseline simulation show the impact of the disturbances.

As we have already mentioned in Section 5.3.2, the baseline scenario for Empower.pl is at the same time, the "fixed part" of all scenarios for Empower.pl. The baseline scenario was the example simulations presented in this chapter, was constructed using the assumption of constant growth rates of nominal output for each of the 35 sectors of the economy. The growth rates are assumed to be equal to the average growth rates for the period 2011–2016, and they are shown in Table 5.2.

Let us recall that this scenario determines Poland's economic growth rate until 2030, by determining the growth rate of output at current prices of each of the 35 sectors that have been distinguished in the model. It is therefore crucial that both the scenario and the model do not explicitly determine the pace of inflationary processes. If therefore, the results of the simulation refer to changes in prices, they relate to deviations from unknown price levels formed in the base solution. It is therefore not possible to determine the inflation rates on the basis of the model results. However, one can determine to what extent the price change indices will bounce up or down from their (unknown) level from the base solution. It is also possible to cumulate and interpret such price changes. Accordingly, the interpretation of fixed-price variables resulting from the model solution should also be adapted to the specifics of the model.

Two basic types of disturbances are introduced into the baseline scenario:

- increase of investment expenditures by the cost of construction of an NPP, and
- changes in the technological structure of electricity generation, resulting in changes in input-output coefficients for the sector producing this type of energy; these disturbances concern the stage of operation of an NPP (i.e. after completion of an NPP construction and the activation of at least one nuclear unit).

A detailed discussion of the method of introducing disturbances and the resulting example scenarios regarding both the construction and operation stages for Poland are presented below in this section.

An important aspect of the construction stage of a power plant, which can affect the economy, is the way of financing the construction. In the simulation scenarios, the following three funding options are considered:

- solely from private resources (scenario labelled as prv),
- half from private and half from public resources (scenario labelled as half),
- solely from public resources (scenario labelled as pub).

Due to the fact that the most likely solution is to finance the construction of an NPP from the private sector resources (i.e. by power companies), the prv scenario should be regarded as "central" in this analysis (see Ministerstwo Gospodarki, 2014; Antoszewski, 2017).

The authors of the Empower software have envisaged the possibility of running the model in four variants, including the following types of multipliers (see Chapter 1.1 of this paper):

a) interindustry,
b) interindustry and induced,
c) interindustry, induced and labour market response,
d) interindustry, induced, labour market response and involving public funds in investment.

As we have already seen when comparing the results of different variants with unchanged impulses, one can track the effects of these economic mechanisms. Therefore, the results of the simulation presented in section 3.2 are presented also using the Empower model.

Please note that the C and D variants are the same if the financing of a power plant is from private sources (prv scenario). The only difference between variants C and

D is taking into account the partial (half scenario) or full (pub scenario) financing of construction from public funds (neutral for the state budget). This distinction is irrelevant for simulations concerning the operation mode of *Empower* simulations.

A summary of the simulations performed during the study is presented in Table 5.3.

Table 5.3. Types of simulations used to study the impact of construction and operation of an NPP on the economy of Poland

<table>
<tr><th colspan="2">Type of simulation</th><th>NPP construction</th><th>NPP operation</th></tr>
<tr><td colspan="2">Base – no NPP</td><td>–</td><td>–</td></tr>
<tr><td>Leontief multiplier</td><td>prv</td><td>+</td><td>+</td></tr>
<tr><td>plus income and consumption multiplier</td><td>prv</td><td>+</td><td>+</td></tr>
<tr><td>plus wage and price multiplier</td><td rowspan="2">prv</td><td rowspan="2">+</td><td>+</td></tr>
<tr><td rowspan="3">NPP financing
(budget revenue neutral multiplier)</td><td>–</td></tr>
<tr><td>half</td><td>+</td><td>–</td></tr>
<tr><td>pub</td><td>+</td><td>–</td></tr>
</table>

Source: own elaboration.

Scenario of NPP construction mode

The construction of the scenario for the development of the Polish nuclear power industry is based on the information presented in the *Polish Nuclear Power Program* (see Ministerstwo Gospodarki, 2014), adopted by the Resolution of the Council of Ministers in January 2014 (PNPP)[17]. The program covers the period up to 2035 and envisages the construction of two power plants of up to 6000 MW (Table 5.4).

Table 5.4. Assumptions of the PNPP concerning the construction of an NPP

Issue	Assumptions of the PNPP/problems of modelling			
When	2020	2024	2030	2035
Power (in MW)	0	>= 1000	>= 3000	<= 6000
Technology	Unknown			
Share of Polish funds	10%	30%	...	60%

17 In the recent days a new governmental proposal has been submitted for consultation (see Ministerstwo Energii, 2018). It includes plans for the building of the first NPP only in 2033.

Construction costs per MW	Power station 1 (3000 MW)	PLN 40 – 60 bln (USD 3,3 – 5 mln/MWh) Time distribution unknown	
	Power station 2		Commencement date and costs unknown

Source: own elaboration based on PNPP.

According to this program the blocks of the first NPP with a capacity of 1000–1500 MW, will be launched successively between 2024 and 2030 and the cost of its construction are estimated at 40–60 billion PLN. However, because the implementation of the PNPP is severely delayed[18] the example scenario presented in this section assumes that the first block of the NPP will be launched in 2029 and the second on in 2033 (each with the capacity of 1500 MW).

In order to adapt these assumptions to Empower.pl NPP construction scenario, a module is included with the existing software to process the above information into the scenario form contained in the model. The module was inserted into the *IOpl* sheet in the *plData* file. Within the model, the changes to the total amount of investment for Poland are distributed between the years of construction (in per cent) and sectors.

Comparing PNPP information with information requirements that should be met in order to build a scenario for Empower.pl points to the following gaps and uncertainties:

- uncertainty about the cost of building a power plant, related, among others, to the lack of decision on the type of reactor technology, contractor, location, etc.;
- no tips on-time schedule of the construction;
- no information on the costs of NPP blocks;
- uncertainty about the year of construction commencement;
- the assumptions concerning the construction of the second power plant are unknown.

We, therefore, conclude that at this stage neither the amounts nor the distribution of construction costs for the next few years and between the blocks of power plants can be unequivocally identified, so the scenario currently included in the model (see Table 5.5) should be treated as an example.

A scenario concerning the first stage of PNPP implementation is presented in Table 5.5. It concerns the construction of the first NPP with a total capacity of 3 GWh

18 In the beginning of 2018 The Supreme Audit Office (NIK) negatively assessed the implementation of activities specified in the PNPP, related to the preparation of the construction of the first Polish nuclear power plant (see Najwyższa Izba Kontroli, 2018). For the results of simulations based on the original plans see Plich, Konopielko, 2018.

(two blocks of 1.5 GWh each). It is assumed that the first and the second block will be launched respectively in the tenth and thirteenth year of the PNPP implementation. In the first years, the expenditure will be relatively small but growing – during the first three years, the outlays will amount to 6% of the total amount envisaged for the program. The maximum expenditure incurred in this scenario take place in the eighth year and will amount to 2,100 mln. dollars, which, i.e. 14% of the total cost, and then start to fall gradually.

Table 5.5. The assumed distribution of expenditures for PNPP implementation

Year No.	Amount (in mln)		% of the total	
	PLN	USD		Cumulated
1	600	150	1	1
2	1,200	300	2	3
3	1,800	450	3	6
4	3,600	900	6	12
5	4,800	1,200	8	20
6	6,000	1,500	10	30
7	7,200	1,800	12	42
8	8,400	2,100	14	56
9	7,800	1,950	13	69
10	7,200	1,800	12	81
11	4,800	1,200	8	89
12	3,600	900	6	95
13	3,000	750	5	100
Total	60,000	15,000	100	

Source: own elaboration based on PNPP.

The NPP construction scenario consists of the following elements:
- number indicating the year of construction of the power plant;
- the amount of capital expenditure for subsequent years;
- the exchange rate to convert the scenario from the currency in which it is expressed to the currency in which the monetary variables are expressed.

Scenario of NPP operation mode

In the *Empower* model, changes in the technological coefficients matrix $\mathbf{A}^d$ (see the formula 5.1), particularly those concerning the electricity sector, play the primary role running the model in NPP operation mode. Values of the coefficients for the electricity sector depend on several factors, the most important of which are:

- volumes of electricity supply by technologies, which in turn depend on production capacities and capacity utilisation factors,
- unit production costs of different technologies of electricity generation,
- the classification of technologies of electricity production used in the Empower.pl model is presented in Table 5.6; the Empower model uses a classification of electricity generation by 7 different technologies, applied in the IEA, in publications presenting the average unit costs of electricity production; these data are used in the *Empower* model to estimate changes in technological factors in the electricity sector.

Table 5.6. Classifications of electricity production technologies according to IEA and Empower.pl

<table>
<tr><th>Empower.pl</th><th>IEA</th></tr>
<tr><td>Hard coal</td><td rowspan="2">Coal</td></tr>
<tr><td>Lignite</td></tr>
<tr><td colspan="2">Oil products</td></tr>
<tr><td colspan="2">Gas</td></tr>
<tr><td colspan="2">Nuclear</td></tr>
<tr><td colspan="2">Hydropower</td></tr>
<tr><td>Wind</td><td rowspan="2">Wind/solar</td></tr>
<tr><td>Solar</td></tr>
<tr><td>Not used</td><td>Wave/tidal</td></tr>
</table>

Source: own elaboration.

Let us notice that within the IEA classification, technologies based on hard coal and lignite are not distinguished. The same concerns solar and wind technologies. All these technologies are very important for the Polish energy system predictions, mainly due to the fact that the two different types of coal play a vital role within the Polish energy system and also due to different growth rates of wind and solar technologies production capacities, both observed in the past and projected for the Polish economy in the future. This is why in the Empower.pl, power production is forecasted for 9[19] types of technologies (see Table 5.6) following forecasts of power generation capacities, and next the production is aggregated to the IEA classification, distinguishing 7 technologies, to estimate changes in technological factors on the base of data delivered in the IEA publications (IEA, NEA, 2010; 2015).

19 In practice, only 8 categories are used, because wave/tidal are not included in the scenarios for Poland.

Table 5.7. Scenario of electricity supply by technology (in GWh)

Year	Technology								
	Wind	Solar	Gas	Hard coal	Lignite	Oil prod.	Nuclear	Hydro	Total energy
2010	1.7	0.0	6.7	92.0	50.9	2.9	0.0	3.5	157.7
2011	3.2	0.0	7.6	92.1	55.4	2.5	0.0	2.8	163.5
2012	4.7	0.0	8.1	86.6	58.2	2.0	0.0	2.5	162.1
2013	6.0	0.0	7.3	86.8	59.7	1.8	0.0	3.0	164.6
2014	7.7	0.0	7.4	82.1	57.6	1.6	0.0	2.7	159.1
2015	10.9	0.1	8.8	83.7	56.9	2.1	0.0	2.4	164.9
2016	12.6	0.1	10.4	82.5	56.1	2.3	0.0	2.6	166.6
2017	13.0	0.1	11.0	82.6	56.2	2.4	0.0	2.7	167.9
2018	13.4	0.2	11.6	82.8	56.3	2.4	0.0	2.7	169.2
2019	13.8	0.2	12.1	82.9	56.4	2.5	0.0	2.7	170.5
2020	14.3	0.2	12.8	83.0	56.4	2.5	0.0	2.7	171.9
2021	14.7	0.2	13.4	83.1	56.5	2.6	0.0	2.8	173.2
2022	15.1	0.2	14.1	83.1	56.5	2.6	0.0	2.8	174.5
2023	15.6	0.2	14.8	83.2	56.5	2.7	0.0	2.8	175.9
2024	16.1	0.3	15.6	83.2	56.6	2.7	0.0	2.9	177.3
2025	16.6	0.3	16.3	83.2	56.6	2.8	0.0	2.9	178.6
2026	17.1	0.3	17.2	83.2	56.6	2.8	0.0	2.9	180.0
2027	17.6	0.4	18.0	83.1	56.5	2.9	0.0	2.9	181.4
2028	18.1	0.4	18.9	83.1	56.5	2.9	0.0	3.0	182.8
2029	18.6	0.4	19.8	83.0	56.4	3.0	0.0	3.0	184.2
2030	18.5	0.5	20.1	80.0	54.4	2.9	6.4	2.9	185.7
2031	18.9	0.5	20.9	79.4	54.0	3.0	7.6	2.9	187.1
2032	19.3	0.5	21.8	78.7	53.5	3.0	8.8	2.9	188.6
2033	18.9	0.6	21.8	75.1	51.1	2.9	16.8	2.8	190.0
2034	19.5	0.6	22.8	75.0	51.0	3.0	16.7	2.9	191.5
2035	20.5	0.7	24.5	76.7	46.2	3.1	18.3	2.9	193.0

Source: own elaboration.

Table 5.7 and Figure 5.2 show the scenario of electricity supply by technology, by 2035 (in GWh and %). The scenario was constructed on the basis of the following sets of data published by Eurostat:

- General Energy Statistics[20],

20 See the link https://ec.europa.eu/energy/sites/ener/files/documents/countrydatasheets_june2018.xlsx.

- supply, transformation and consumption of electricity – annual data (nrg_105a)[21].

They contain time series covering the period 1990–2016 for 28 EU countries. The data were used for analyses of demand and supply of electricity as well as technology mix understood as the size of production capacities by technology and the degree of the capacity utilisation. Results of the analyses combined with the PNPP assumptions allowed for the formulation of the scenario.

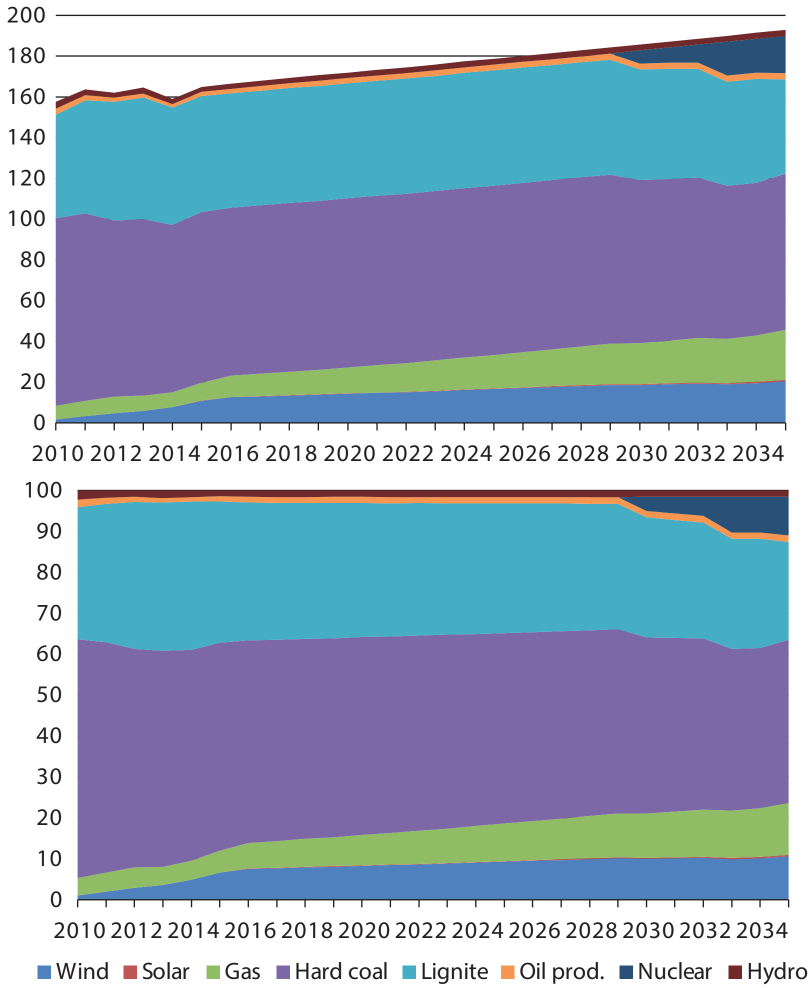

Figure 5.2. Scenario of electricity supply by technology, by 2035 (in GWh and in %)

Source: own elaboration based on Table 5.7.

21 See the link http://ec.europa.eu/eurostat/product?code=nrg_105a&language=en&mode=view.

The second factor influencing the electricity sector represented in the coefficients of $\mathbf{A}^d$ matrix, apart from the volumes of electricity supply by technologies, is unit production costs of technologies used for electricity production. Since they will be used to develop a projection of changes in technological factors in a model for the electricity sector, it is desirable that these costs be further disaggregated by type. Such information is published by the IEA but in a breakdown limited to several items only (see IEA, NEA, 2015):

- capital,
- labour,
- fossil fuels,
- coke, crude oil, nuclear fuels,
- other operational costs.

The original IEA data for 2010 are shown in Table 5.8. They do not include capital costs, as they are not used in the estimation of coefficients.

Table 5.8. Average unit costs of electricity production by technology in 2010, 2025 and 2035 (USD/MWh)

Year 2010	Wave/ tidal	Wind/ solar	Gas	Coal	Oil prod- ucts	Nuclear	Hydro- power
Year 2010							
Labour cost	14.5	11.0	2.5	3.5	2.5	3.5	6.5
Mining and Quarrying	0.0	0.0	84.0	43.0	0.0	0.0	0.0
Coke, petrol. & nucl. fuel	0.0	0.0	0.0	0.0	84.0	9.5	0.0
Other costs (operational)	35.0	25.0	6.0	7.5	6.0	10.0	20.0
Year 2025							
Labour cost	15.6	11.9	2.7	3.8	2.7	3.8	7.0
Mining and Quarrying	0.0	0.0	90.5	46.3	0.0	0.0	0.0
Coke, petrol. & nucl. fuel	0.0	0.0	0.0	0.0	90.5	10.2	0.0
Other costs (operational)	37.7	26.9	6.5	8.1	6.5	10.8	21.6
Year 2035							
Labour cost	16.7	12.6	2.9	4.0	2.9	4.0	7.5
Mining and Quarrying	0.0	0.0	96.6	49.4	0.0	0.0	0.0
Coke, petrol. & nucl. fuel	0.0	0.0	0.0	0.0	96.6	10.9	0.0
Other costs (operational)	40.2	28.7	6.9	8.6	6.9	11.5	23.0

Source: IEA, NEA (2010) and own elaboration based on results of Empower.pl

This information, combined with the energy mix projections of the electricity sector mentioned earlier, allows for estimating of the future technological parameters of the electricity generation sector. So, the estimation procedure runs in the following three steps:

- Preparing energy mix projections for electricity generation, with seven technologies (primary sources): Wave / tidal; Wind / solar; Gas; Coal; Oil products; Nuclear; Hydro-power.
- Extrapolation of average unit costs of electricity production, for each cost type and technology, based on assumptions on average annual growth rates and changes in electricity prices (see Table 5.8 for the example results, for years 2025 and 2035).
- Determination of future changes in input-output coefficients in the electricity sector, based on the energy mix projections and the average unit costs of electricity.

5.4.2. Analysis of the results

The example scenario presented in previous section assumes that the first block of the NPP will be launched in 2029 and the second on in 2033 (each with the capacity of 1500 MW) and the assumed distribution of expenditures for PNPP implementation is presented in Table 5.5. The cost of the construction is estimated at 40–60 billion PLN (see Table 5.5). This investment triggers a disturbance in the baseline scenario in the years 2018–2030, when the investment outlay in the economy is increasing. The distribution of these outlays is shown in Figure 5.3. They rise from USD 150 million in 2020 and reach a maximum of USD 2,100 million in 2027. The following they start to decline gradually, to reach the USD 750 million in 2032. Total expenditure is USD 15 billion.

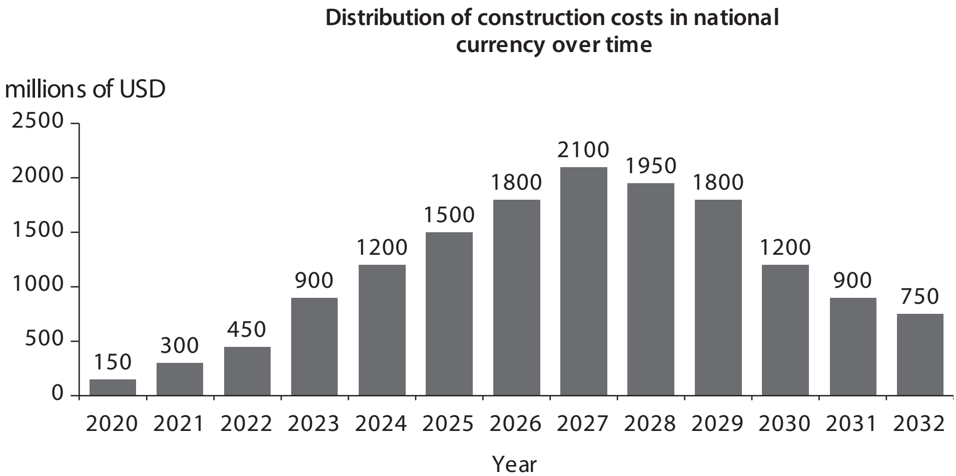

Figure 5.3. Distribution of expenditures for PNPP implementation

Source: own elaboration based on Table 5.5.

Evaluating the impact of the construction of an NPP will start with the evaluation of its impact on the macroeconomic variables, and then we will present sectoral variables. Unless otherwise stated, the presented quantities are expressed in terms of the percentage deviation of the outcome of the scenario from the baseline. We will initially focus on the nuclear scenario based on private investment (prv) and then selectively discuss the results of other scenarios. Figure 5.4 shows five graphs of prv simulations that assume the development of NPPs based on private investment. They represent successively changes in gross domestic product (GDP), emp, gross income, personal income (Income) and public savings (PubSav). When interpreting the results for the latter variable, keep in mind that public savings in Poland are negative. This means that there is a public finance deficit in Poland. So, if the percentage deviation for this variable is positive, then it means increasing the deficit and vice versa – negative deviations mean deficit reduction. All of these graphs include the four types of simulation – A, B, C and D – listed in Table 5.3. For all presented variables, the results of C and D simulations overlap. This is because, in the prv scenario, the C and D simulations do not differ from each other (by definition). The occurrence of this effect was already signalled earlier when discussing the concept of the simulations.

In the case of Gross Domestic Product, results of simulation B are also very close to the path of C and D simulations. On the other hand, if we compare the results for GDP variable in nominal terms, the results differ significantly (see the graph on the right in the first row of Figure 5.4) – the deviations from base simulation in variants C (equivalent to D) are significantly higher than in the B variant.

It follows that the rise of prices in variants C and D do not affect real GDP significantly. Notice that in the case of variant B results no differences between variables in real and nominal terms can be observed because in this variant *Empower* model does not include price equations.

The characteristic feature of all the results presented in Figure 5.4 is the time distribution of the effects of the disturbances introduced into the baseline scenario. These effects increase until the year 2027, and then they decrease gradually until the last year of the simulation. This is not surprising. It is related to the distribution of investment expenditures for the construction of the NPP and in some way "repeats" it (see Figure 5.3). The strength of the impact of this disturbance on the analysed variables is, however, varied. Besides, differentiation of this strength is observed, depending on the simulation variant considered (A, B, C, and D).

The maximum change in GDP amounts to approximately 0.11–0.12% in 2027 and concerns variants B, C and D. For variant A, this change is approximately 0.08%. Looking at the employment (*emp* variable) and income (*income* variable), a similarity of behaviour of the two variables can be observed. This applies not only to their distribution over time but also to the magnitude of deviations. Although the deviations from the baseline for the two variables are not equal, but they differ very little in the individual variants (A, B, C, D), approximately by 0.02 p.p. For example, the maximum deviation in variant B is approximately 0.13% for income and 0.11% for employment. Let us recall that, in this variant, the effect of output multipliers is amplified compared to variant A by the addition of the equation of income and consumption (consumption multiplier). This can be easily observed on the graphs, where the deviations from the baseline are much higher in variant B compared to A. However results of the two remaining simulations are placed significantly below the lines both A and B variant. This is because the market response represented by variants C and D corrects sharply the deviations, which decrease by half compared to variant B.

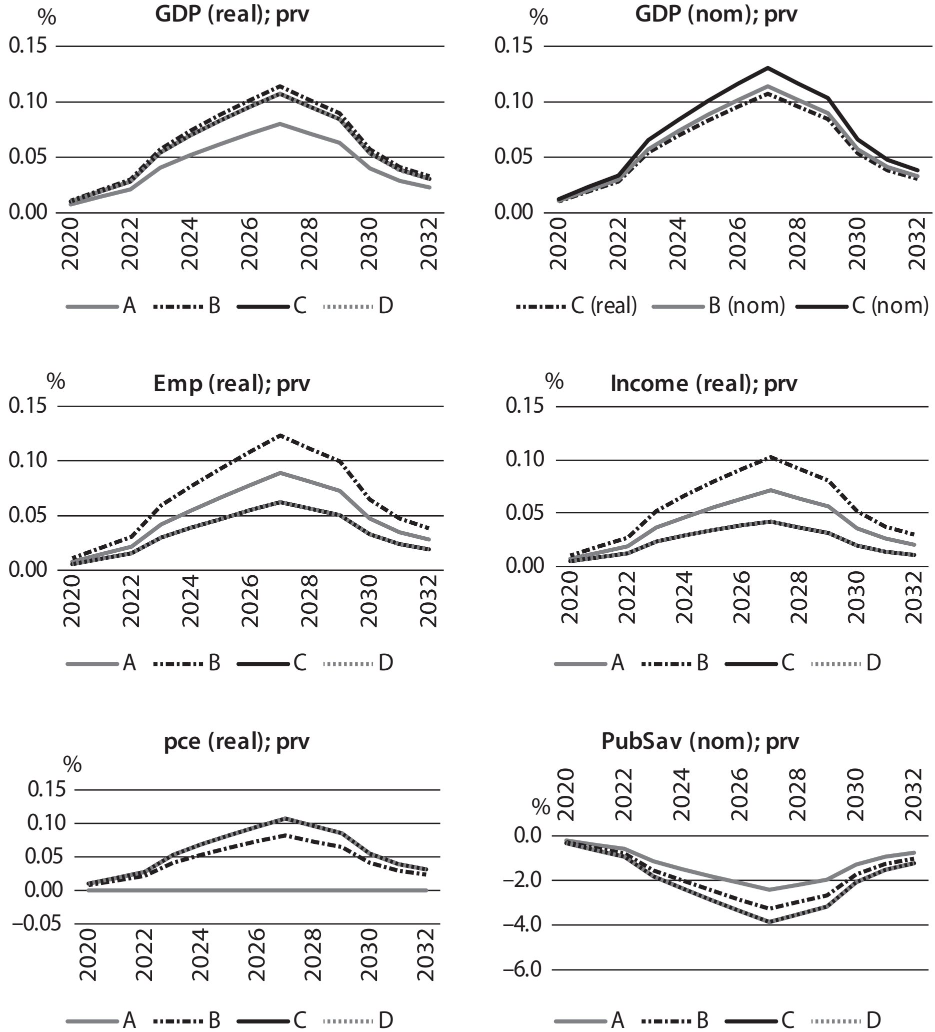

Figure 5.4. Results of the simulation of macroeconomic variables for the financing option prv

Source: own elaboration.

The last graph in Figure 5.4 shows the deviations of public savings (PubSav). Here, unlike in the other variables, the effect in the simulation period is negative. As noted above (in the initial commentary on Figure 5.4), this should not be a surprise. The negative value of the PubSav variable deviation means the reduction of the public finance deficit by approximately 3.9% in 2027 for the D (and C) variant. The effects in simulations B and A are lower and are (respectively) about 3.1% and 2.2%. Reducing the deficit is connected with the increase in economic activity resulting from the construction of the NPP. Let us remind that we are considering a situation where public funds do not support the investment.

In the next part of our analysis, we will focus on the results of simulation D, which takes into account changes in the financing method of the nuclear power plant construction, within the economy. Figure 5.5 presents a set of graphs for the macroeconomic variables considered so far, i.e., gross domestic product (GDP), emp, personal income (Income), personal consumption expenditures income (pce) and public savings (PubSav). This time, however, the charts include results for variants of the following simulations:

- *Pub*, in the case of funding the NPP construction exclusively from public funds,
- *Prv*, in the case of financing the NPP construction entirely from private funds,
- *Half*, where the burden of investment financing is distributed equally between private and public funds.

Recall that the use of public funds in pubs and half variants would take place in a neutral manner for the public sector revenues provided for in the baseline solution. In practice, this means that tax rates should be increased to an extent to facilitate the covering of the completion costs of the next stages of PNPP implementation using the extra revenues.

In Figure 5.5, the deviation from the base solution corresponds to what we observed for variant D in Figure 5.4. The characteristic feature of the variant graphs for the *pub* variant shown in Figure 5.5 is that, with the exception of income, they show negative deviations from the baseline – they are a kind of symmetrical reflection of the plots for the variant *prv* with respect to the time axis. The line denoting deviations for the *half* variant lays between these two.

The general conclusion of the deviation analysis is therefore clear and quite distinct – it is better for the economy when the funds for the construction of the PNPP come from the private sector. However, the specificity of the disturbances introduced in the prv variant is that the funds for investment come from the outside of the economy – these are additional measures that were not included in the baseline. If new, previously "non-existent" resources appear in the economy, it is no wonder that the economy derives additional benefits.

Financing of the NPP construction from public funds, without changing the amount and structure of existing expenditures, means the need to limit and reallocate resources previously allocated (in the baseline solution) for consumption. They must be shifted and allocated to investment (consumption falls below the baseline). In the long run, this can have a positive effect because additional consumption growth and gross domestic product – over the baseline solution – could be observed. However, the *Empower* model has no built-in mechanisms that could illustrate this.

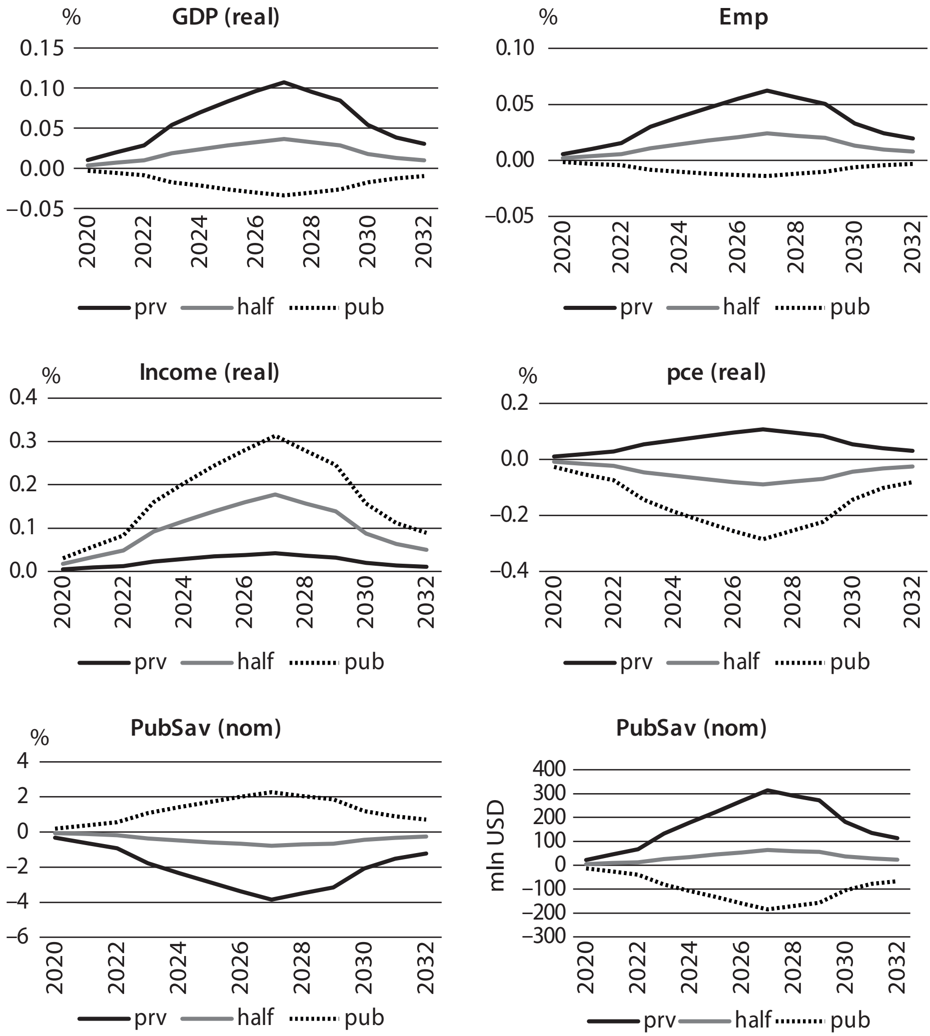

Figure 5.5. Results of simulation of macroeconomic variables for variant D

Source: own elaboration.

Also, in the case of financing of the NPP construction from private sources, the *Empower* model is unable to reflect some critical economic mechanisms. They are connected with the so-called pushing-out effect, which results from resource constraints such as capital or labour. In the case where the limited resources are already allocated to specific tasks (the state of equilibrium in baseline is reached), a new task, such as an NPP construction, creates the necessity of resources reallocation, and, in practice, withdrawal of some tasks that have been planned previously. Incorporating these additional mechanisms would develop the *Empower* model towards CGE and WMM models[22].

Empower, as a multisectoral model, provides insights not only on macroeconomic indicators but also on the influence of impulses on sectors of the economy. In Table 5.9, we present the sectoral results on the example of employment. Results for all of the 35 sectors distinguished in the model are shown in rows. The columns show the changes in employment in subsequent years compared to the baseline. This time the differences are not expressed in percentage deviations, but in absolute deviations measured by the number of employees (in thousands). In order to allow and facilitate a more comprehensive interpretation of the results presented in Table 5.9, they are supplemented by two graphs presented in Figure 5.6. The first of the graphs concerns the changes in total employment, while the other – the structure of employment changes by sectors.

When analyzing the results of employment changes, it is essential to remember that the primary sectoral beneficiaries of the growing investment for the construction of an NPP are the sectors providing investment products. The classification used in the WIOD tables includes the following 3 sectors as producers of investment goods and services: machinery industry, the electrical and optical industry and construction. The effects that occur in other sectors are the result of the economic mechanisms described in the subsequent variants of the model.

The confrontation of the results in Table 5.9 with the content of the graphs makes it easy to see that in the year of incurring the maximum investment outlays (2027), employment in the whole economy is higher than the base variant by over 12 thousand employees (variant D of the simulations). The most significant contributors to this growth are the sectors providing investment products and services, that is:

- construction (6.5 thousand),
- machinery industry (1.3 thousand),
- electro-technical industry (0.8 thousands).

22 WMM stands for Multisectoral Macroeconomic Models, such as Inforum Model (see e.g. Almon, 1991; Plich, 2002 or Bardazzi, 2013).

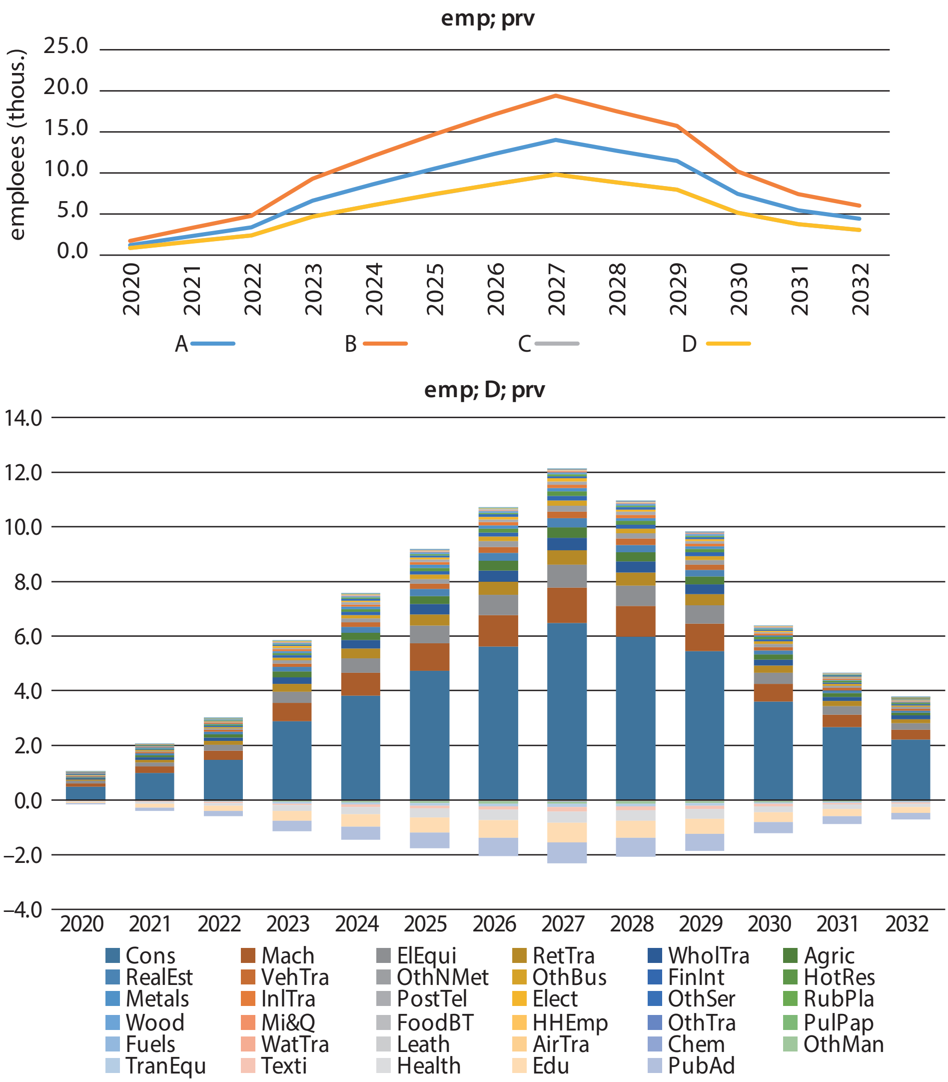

Figure 5.6. Employment – results of simulation for D variant (in thousands)

Source: own elaboration.

Table 5.9. Changes in employment in D-prv simulation (in thousands employed)

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Elect	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0
Agric	0.0	0.1	0.1	0.2	0.3	0.3	0.3	0.4	0.3	0.3	0.2	0.1	0.1
Mi&Q	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FoodBT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Texti	0.0	0.0	0.0	–0.1	–0.1	–0.1	–0.1	–0.1	–0.1	–0.1	–0.1	–0.1	0.0
Leath	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wood	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0
PulPap	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fuels	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Chem	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RubPla	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0
OthNMet	0.0	0.0	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1
Metals	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0
Mach	0.1	0.2	0.3	0.7	0.8	1.0	1.2	1.3	1.1	1.0	0.6	0.5	0.4
ElEqui	0.1	0.1	0.2	0.4	0.5	0.6	0.7	0.8	0.7	0.7	0.4	0.3	0.2
TranEqu	0.0	0.0	0.0	–0.1	–0.1	–0.1	–0.1	–0.1	–0.1	–0.1	–0.1	0.0	0.0
OthMan	0.0	0.0	0.0	0.0	–0.1	–0.1	–0.1	–0.1	–0.1	–0.1	0.0	0.0	0.0
Cons	0.5	1.0	1.5	2.9	3.8	4.7	5.6	6.5	6.0	5.5	3.6	2.7	2.2
VehTra	0.0	0.0	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1
WholTra	0.0	0.1	0.1	0.2	0.3	0.4	0.4	0.5	0.4	0.4	0.2	0.2	0.1
RetTra	0.1	0.1	0.1	0.3	0.4	0.4	0.5	0.5	0.5	0.4	0.3	0.2	0.1
HotRes	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.0
InlTra	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0
WatTra	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AirTra	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OthTra	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PostTel	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0
FinInt	0.0	0.0	0.0	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.0
RealEst	0.0	0.1	0.1	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.2	0.1	0.1
OthBus	0.0	0.0	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1
PubAd	–0.1	–0.1	–0.2	–0.4	–0.5	–0.6	–0.7	–0.8	–0.7	–0.6	–0.4	–0.3	–0.2
Edu	0.0	–0.1	–0.2	–0.4	–0.5	–0.5	–0.6	–0.7	–0.6	–0.6	–0.4	–0.3	–0.2
Health	0.0	–0.1	–0.1	–0.2	–0.3	–0.3	–0.4	–0.4	–0.4	–0.3	–0.2	–0.2	–0.1
OthSer	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0
HHEmp	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Source: own elaboration.

6. Impact of Nuclear Power on CO2 Emissions in Poland

6.1. Empower.pl.cc

The basic properties of the Empower model are presented in the previous chapter, in particular regarding the effects of the multiplier mechanisms A, B, C and D described in the same chapter, based on the example of Poland. The simulations were carried out using the first version of the Empower software, which was appropriately modified for the use of the Empower.pl model (see Appendix). The simulation assumptions were based on PNPP.

This chapter presents the results of the simulation on the Empower.pl.cc model. Compared to the previous version, the model has been expanded to contain an energy block and a pollutant emissions block and installed in the Interdyme package. The assumptions adopted for the simulation are based on the EPP2040 project[23]. Adopting this document in its current form would be tantamount to withdrawal from the plans contained in the PNPP, and although this document has not been formally withdrawn, it has become outdated, at least regarding the date of the first Polish nuclear power plant unit launch. When presenting the results, we do not focus on separate multiplier mechanisms, as was the case in chapter 5 because the purpose of the simulations is a comprehensive assessment of the effects of structural changes in the power sector resulting from the EPP2040 project provisions, from the discussion on climate change perspective. Nevertheless, in order to maintain comparability with the results of the original Empower model proposed by IAEA (the Empower.pl.cc model goes far beyond these frameworks), obtained by teams from other countries, we also present simulation results in which we split the impact of the nuclear power plant construction stage from the nuclear power plant operation stage.

The Empower.pl.cc model is an extension of the Empower.pl model, whose design and properties are described in chapters 5.3 and 5.4. Here, we present its

23 See section 6.2.1 for more explanations.

version with the added energy and pollutant emissions blocks. The general principles of the extension are presented in chapter 4.6.

6.2. Simulation Assumptions

The assumptions necessary to perform simulations on the Empower model can be divided into three groups:

- economy,
- nuclear program costs,
- demand and power generation mix.

They are discussed below.

6.2.1. Economy

Economic assumptions relate to:

- sectoral change rates of global output,
- wage reaction to the unemployment rate,
- income elasticity of consumption,
- export price elasticity,
- the change rate in productivity per output growth,
- productivity pass-through parameter.

The design of the base solution in the Empower model is based on the use of the RAS method to design I-O tables for subsequent years based on the assumed rates of change in global output in nominal terms for all sectors[24]. The Empower.pl.cc model interprets these assumptions differently and, what follows, it also interprets the results of the RAS method differently. It is assumed that the assumed rates of change concern production in real and not nominal terms. If we additionally assume that the output changes at the same pace in all sectors, it is tantamount to the assumption that the technologies of production (technical coefficients) are constant. Therefore, the Empower model in this approach directly refers to the classic Leontief model, in which it was additionally assumed that final output of all sectors changes at the same pace, which implies an identical pace of change in global output[25].

24 It is important to remember that the effect of this approach is the inability to determine the changes taking place within the production technologies, as the IO coefficients result here from mathematical dependencies, and not from processes observed in the economy.

25 In this approach, one can successfully abandon the RAS method, and thus assumptions about the rates of change in global output, in favour of assumptions about the rate of change in the final demand category, which is usually adopted in the classic Leontief model.

For the purposes of this study, it was assumed that the rate of change in output, in real terms is 2%. Comparing this figure with the average rate of change in total output in the 1990–2018 time period, which is close to 4.1%[26], the adopted rate should be considered moderate. It is difficult to conclude that within the next 40 years, the economy will develop at as fast a pace as before. The adopted assumption is in line with the growth path developed by the Ministry of Finance in May 2019 (see Ministry of Finance, 2019)[27].

The range for the *wage reaction* to the unemployment rate is between −0.05 and −0.09 for different groups of European countries – the more competitive the labour market, the higher the value of the parameter should be chosen (see Kratena, Sommer, 2019). The value of this parameter determined for the needs of the Empower.pl.cc model is −0.7, i.e. it was determined in the middle of the variability range resulting from research conducted for EU countries. An analysis of the sensitivity of the model results was also conducted, determining the size of the wage reaction to the unemployment rate parameter for the ends of the range indicated above.

Based on literature, Kratena and Sommer (2019)[28] suggest assuming the income elasticity of demand between 0.6−0.9%. The assumption of high-income elasticity of demand emphasizes the importance of current income in shaping current consumption. On the other hand, low elasticity means that demand is shaped in accordance with the life cycle model with liquidity constraints, in which current income plays a significant role only for poor consumers (Mariger, 1987). In the Empower.pl.cc model, this parameter was adopted at 0.8%, and a sensitivity analysis was carried out, determining its size for the ends of the range indicated above.

The model uses export price elasticity of –1% (export price elasticity). In the literature, this level is usually considered as the lower limit of the variability of export elasticity. The upper limit is difficult to determine as it may depend on the type of good and the country being considered. Kratena and Sommer (2019) recognize that it can reach –2% in small countries.

26 The calculations were made on the basis of the Statistics Poland study (GUS, 2019).

27 The guidelines of the Ministry of Finance assume that the GDP rate will be systematically decreasing from 4% in 2019 to 1.6% over the next 40 years, which translates into an average growth rate of 2.07%. The forecast of electricity and power demand presented in the document of the Ministry of Energy (2018) was based on the same guidelines.

28 In Kratena and Sommer's study, the parameter of wage reaction to unemployment rate is mistakenly defined as marginal propensity of consumption. It is easy to notice that the consumption equation expressed in their paper with formula (3) has an exponential form, so the parameter specified by the mpc symbol is – in fact – income elasticity and not a marginal change in consumption. However, this does not undermine the validity of the conclusions drawn by the authors.

Changes in employment within the sectors are determined on the basis of demand for global output and sector labour productivity. Global output is an endogenous variable within the model, while labour productivity is determined exogenously by adopting assumptions about the rate of its change. Similarly, i.e. by adopting assumptions about the rate of change, it is possible to introduce scenarios for changes in the number of labour force into the model. The rate of change in labour productivity and labour force, combined with changes in output, indirectly determine the unemployment rate in the base solution of the model. In the presented simulations, it was assumed that the rate of change in sector labour productivity is the same and equal to the rate of change in global output. It was also assumed that the number of the labour force does not change (the rate of change is 0%). In this way, these variables were, de facto, excluded from the study to simplify the analysis of its results.

The last of the model's essential parameters – the productivity pass-through coefficient, determining the increase in wages, and thus the remaining part of the added value, in the form of operating surplus, as suggested by Kratena and Sommer (2019) was adopted at the 0.5 level.

6.2.2. Nuclear program costs

In Poland, energy policy is established over the span of several decades, as part of documents updated every few years under the common name: Polish Energy Policy. Currently, public consultations of the *Energy Policy of Poland until 2040*, which was presented in December 2018, are taking place (see Ministry of Energy, 2018). Assumptions presented in the draft (EPP2040) and in particular, those regarding the power generation mix, were adopted as a starting point for the impact assessment of nuclear energy on greenhouse gas emissions.

EPP2040 suggests the following eight strategic directions of operation (Ministry of Energy, 2018):

- optimal use of domestic energy resources,
- development of the power capacity and transmission infrastructure,
- diversification of natural gas and oil supply and network infrastructure development,
- development of energy markets,
- launch of nuclear energy,
- development of renewable energy sources,
- development of heating and cogeneration,
- improving energy efficiency.

The assumptions presented for the strategic direction no 5 anticipate the implementation of a much broader nuclear energy program, compared to the 2014 plans included in PNPP (see chapter 5.4), but postpone the prospect of commencing the operation of the first nuclear power plant until the next decade. Initially, PNPP anticipated the first block of the nuclear power plant in Poland to launch in 2024, and the cost of building the entire 3 GW power plant was estimated at PLN 40–60 billion, i.e. PLN 13.3–20 billion/GW. In the case of EPP2040, it is assumed that two power plants will be built to contain six power blocks, each with a capacity of 1–1.5 GW, which will give a total capacity of 6–9 GW. It is also expected that the first block will be launched by 2033, and the next ones will be created every two years from then, which means that the entire program will be completed by 2043. The government estimates the cost of the entire program at PLN 100–135 billion[29]. This means that construction costs per 1 GW of installed capacity are estimated at PLN 16.7 billion, in the case of implementing the option of constructing a power plant with a lower total capacity (6 GW) and PLN 15 billion for the 9 GW variant.

In order for these plans to be included in the model, additional assumptions need to be made regarding the distribution of investment outlays over the 20-year period of the nuclear program envisaged in the EPP2040 document. To this end, the construction period of the power plant was divided into the preparatory stage, lasting 3 years and the construction stage. It was assumed that the construction of one power plant block would take 7 years (cf. ARE, 2016), which means that the construction of the power plant, including the preparatory period would take at least 10 years. In the case where the construction of subsequent power plant blocks takes place at different times, as was assumed in EPP2040, the power plant construction period will be correspondingly longer. The information contained in the ARE 2016 study was used to develop the payment schedule, which is presented in a chart form, on the left-hand side, in Figure 6.1.

As can be easily seen by analysing the chart, the preparatory period consumes relatively small amounts of money (it was assumed that it would be 5% of the total expenditure on the power plants construction), as do the first two years of construction of each block. The most considerable outlays, covering a total of approx. 93% of the block construction costs (excluding the 3-year preparatory period, which applies to the entire power plant) are incurred in the second half of the entire 10-year investment cycle.

The chart on the right-hand side shows the payment schedule in the case of three-block power plant construction, where the construction of each block starts every two years, i.e. as envisioned by EPP2040. The symbol NPP.0 used in the legend denotes the period of preparation for the power plant construction, while NPP.1,

29 This information was provided during a press conference which took place in January 2019 (see https://gramwzielone.pl/trendy/34156/program-jadrowy-ma-kosztowac-przynajmniej-100-mld-zl, accessed: 4.09.2019).

NPP.2 and NPP.3 denote the construction of the subsequent blocks. In this case, also, there is an asymmetry in the distribution of expenditure – over 80% of the cost falls on the second half of the entire 14-year investment cycle.

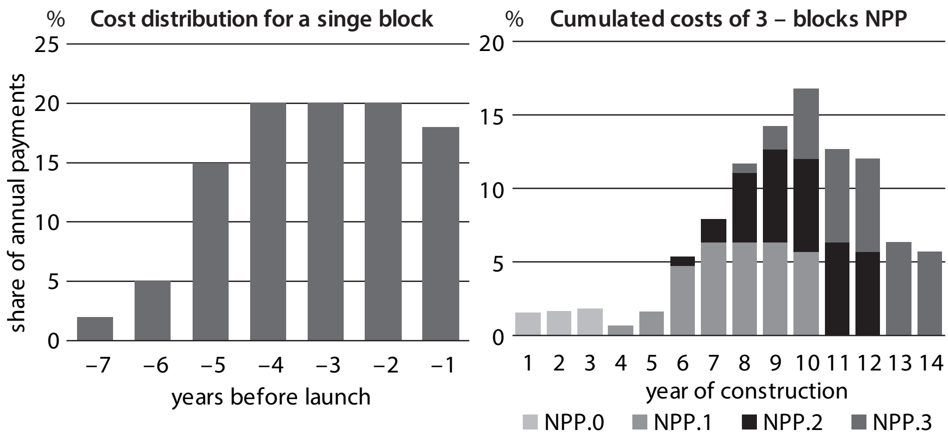

Figure 6.1. Construction cycle and payment schedule for the construction of a nuclear power plant

Source: ARE, 2016; Tracz, 2014 and own elaboration.

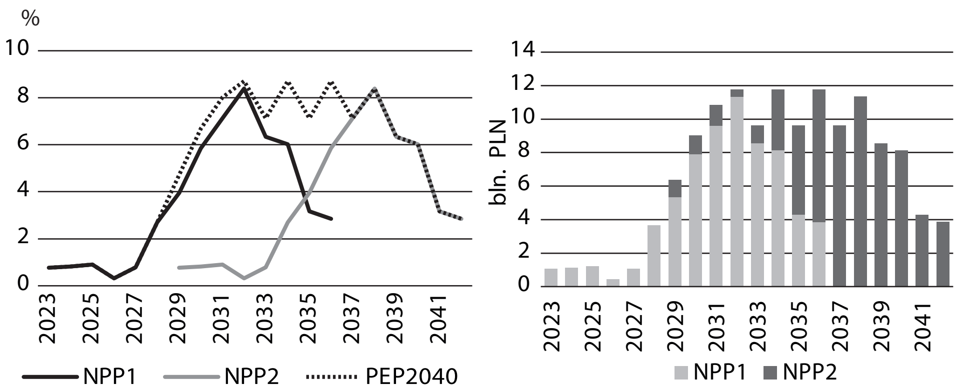

Figure 6.2. Assumed distribution of outlays on the implementation of the nuclear program in Poland

Source: own elaboration.

In the scenarios for the Empower.pl.cc model, it was assumed that the nuclear program outlined in EPP2040 will be implemented in 2023–2043 and will consume PLN 135 billion. It was assumed that by 2043 six nuclear blocks, each with 1.4 GW capacity, would be built and installed in two power plants. The construction of the first block will be completed in 2032, and in 2033 the block will be included into the power grid. Subsequent blocks will be launched every two years. The stage of preparation for the construction of each power plant will last 3 years and will consume 5% of the total expenditure. The construction stage will commence in 2023 and 2029, respectively.

The distribution of outlays for each of the power plants (NPP1 and NPP2), resulting from the above assumptions and for the whole program (EPP2040) is shown in Figure 6.2. These result from the sum of expenditures incurred during the preparatory stages and the expenditures incurred directly in connection with the construction of each block. It turns out that the most significant expenditure on the implementation of the EPP2040 nuclear program will occur in 2030–2040, constituting nearly 83% of the entire program costs. Expenses in these years will reach the level of PLN 9 to almost 12 billion annually.

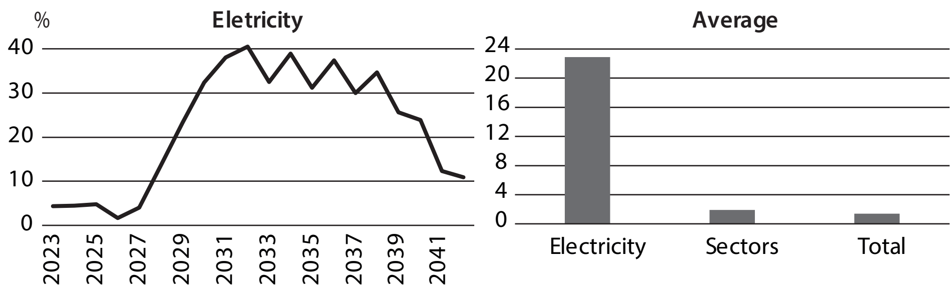

Figure 6.3. Shares of outlays on the implementation of the nuclear program in Poland

Source: own elaboration.

Figure 6.3 shows the relative size of the investment effort for implementation of the nuclear power programme compared to the investment outlays in the baseline scenario. It can be seen there that investment outlays in the electricity sector increase even by 40% over the baseline in 2032, and by almost 23% during the 20 years of the programme realization. In the case of production sectors of the economy and the economy as a whole, this share equal 1.9% and 1.4% adequately.

6.2.3. Demand for electricity and power generation mix

Historical characteristics of supply and demand

Before presenting projections for electricity demand and the structure of its generation for the next few decades, let's take a look at the current trends. Figure 6.4 shows:

on the left-hand side chart:
– production,
– useful power,
– domestic demand,
– distribution losses (in% – right scale).

on the right-hand side chart:
– export,
– import.
– exchange balance (in% – right scale).

The difference between production and useful power results from energy losses occurring in the distribution process. It is worth noting that since 1995 the share of losses has been steadily decreasing. In the analysed period, it fell from almost 13% to 5.7% in 2016. The volume of useful power was initially higher than domestic demand. Surplus energy could, therefore, be exported to neighbouring countries[30]. In the time period of 2003–2006, the share of exports ranged from 7% to 8% of useful power. In recent years, however, this trend has reversed – domestic demand has outstripped electricity production, and its shortages have to be met by imports.

Figure 6.5 shows the rate of change in electricity production and domestic demand. The chart on the left shows the year-to-year rates, while the right-hand chart shows the average annual rates for ten-year periods. One can observe a large amplitude of fluctuations in production and demand – from –5% to +5% – which makes it difficult to draw conclusions about change trends. However, it appears that production has shown an upward trend over the past quarter of the century. The average production rate in the time period 1990–2016 was 0.78%, which is well below the GDP growth rate for the same period, which average was 4.1% (see chapter 6.2.1). This apparent difference can be explained by the slow increase in electricity demand due to the increase in electricity use efficiency, which, in turn, was caused by:

- the reduction of consumption resulting from an increase in relative energy prices, and
- the improvement of energy efficiency of electrically powered processes and devices, which took place across the entire economy.

Demand grew slowly over the period considered, but in 1990–2016 its average rate was 0.94%, which was slightly higher than the production rate. Moreover, the changes in net exports mentioned earlier (in recent years imports exceeded

30 It should be noted that in the power sector electricity exports and imports are of a regulatory, and therefore, limited nature. Their purpose is to ensure system stability and supply stability. On the other hand, permanent shortages or permanent surplus are not a positive phenomenon either, as they can contribute to losses or periodic reduction of demand.

exports) suggest that the need to import electricity may be structural in nature. This is confirmed by the analysis of the graph showing the average ten-year rate of change in production and demand, as since 2003 production has risen too slowly in relation to demand, and this unfavourable difference is continuously increasing. Within the last few years, the difference in these rates exceeds 1 percentage point per year.

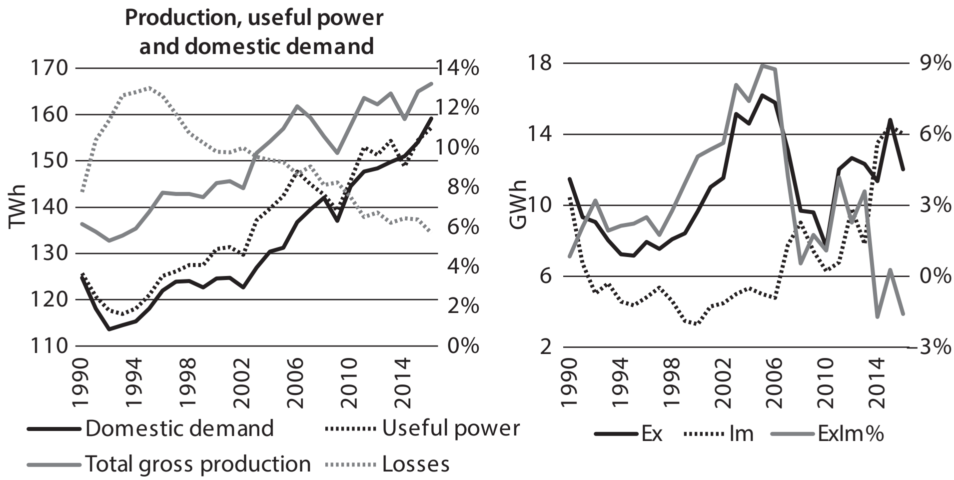

Figure 6.4. Demand and production of electricity in 1990–2016

Source: own elaboration based on Eurostat data.

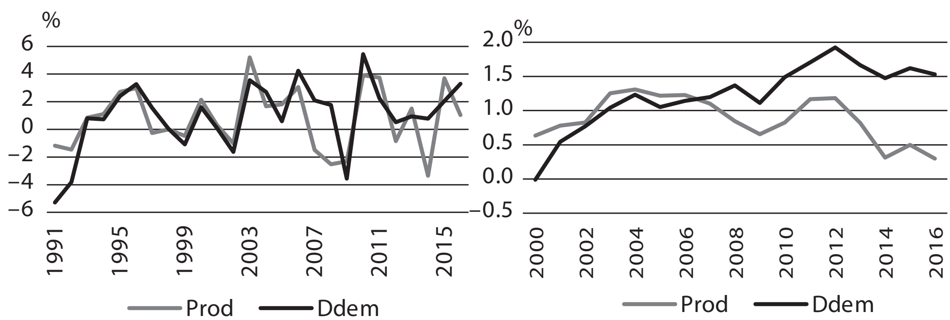

Figure 6.5. The rate of change in electricity production and demand

Source: own elaboration.

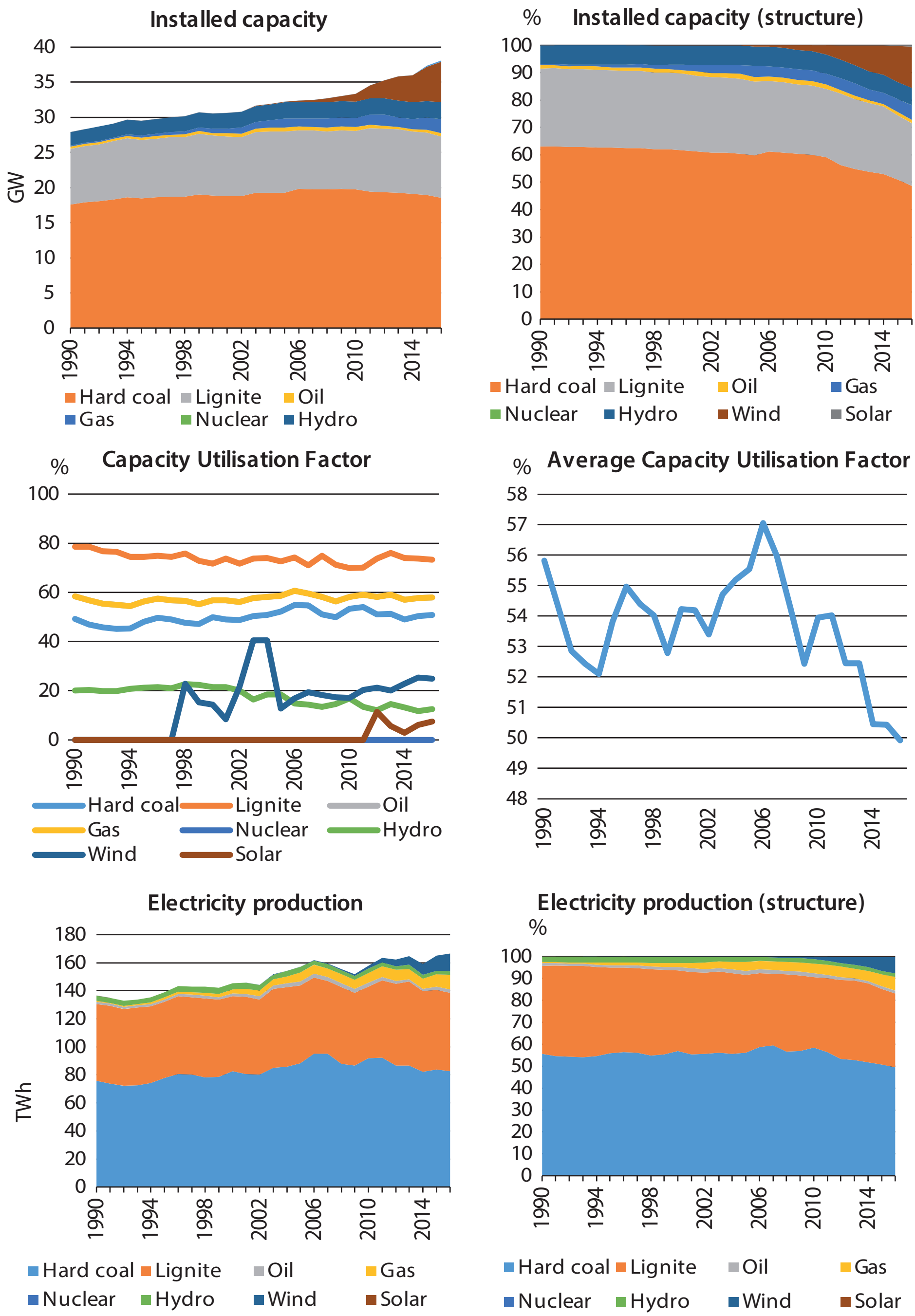

Figure 6.6. Power and its use as well as electricity production in 1990–2016

Source: own elaboration.

The next charts in Figure 6.6 present necessary information about power plants in Poland by types of technologies used for electricity production:

- installed capacity,
- average capacity utilization factors,
- electricity production.

Particularly noteworthy is the slow reduction of the role of hard coal technology (from 63% at the beginning of the analysed period to 48% in 2016) and the very rapid increase in the share of installed capacity in wind farms in recent years. The first wind turbines appeared in Poland as early as 1997, and their share in 2016 was 15%. However, this does not translate fully into production, because the degree of use of these capacities measured by CUF does not exceed 30% – which is much lower compared to hard coal power plants. The exceptions are the years 2002 and 2003 when the power utilization ratio of the wind farms exceeded 40%. As a result, the share of wind farms in electricity production in 2016 was only 7.5%.

Generally, renewable energy sources satisfy the demand for electricity in Poland to a small extent in comparison with other EU countries. The share of solar energy in the energy mix is, so far, almost unnoticeable in Poland, and the degree of utilization of installed capacity is the lowest in comparison with other technologies. This is related not only to the small amount of installed capacity but also to the climate conditions prevailing in Poland. In turn, the power produced by wind farms is usually used as an additional source of electricity – during intermediate load or peak load periods. So far, baseload is the domain of coal power plants. It is not without significance that so far all wind turbines in Poland have been built on land. Offshore wind farms have an advantage over the onshore ones due to the higher stability of the winds blowing there. Most likely, for this reason, the EPP2040 project anticipates a reduction in the construction of onshore wind farms to support the construction of offshore farms, which is discussed in the next point of consideration.

EPP2040 Forecasts

The EPP2040 project includes an attachment in the form of *Conclusions from prognostic analyses for the energy sector*. It presents, among others, forecasts regarding the demand for electricity, installed capacity and electricity generation until 2040 (see Table 6.1 and Figure 6.7). They form the basis of prognostic assumptions adopted in the simulations on the Empower.pl.cc model.

Table 6.1. Forecast of demand, maximum power and electricity production

Demand increase in time		2018–2020	2020–2025	2025–2030	2030–2035	2035–2040
Electricity (in %)		1.9	1.9	1.9	1.5	1.5
Maximum power (in %)		2.1	1.9	1.6	1.3	1.3
Demand		2020	2025	2030	2035	2040
Electricity (TWh)		165	181.2	198.8	214.3	230.1
Maximum power (MW)		25 487	27 963	30 226	32 301	34 535
Installed capacity (MW)		2020	2025	2030	2035	2040
Lignite power plants		7 400	7 600	7 600	3 800	1 500
Hard coal power plants and heat and power plants – existing and new		20 650	19 710	17 830	13 810	11 985
Nuclear power plants		0	0	0	2 800	5 600
Gas		2850	3520	6900	10230	12445
Photovoltaic power plants		900	5 200	10 200	15 200	20 200
Wind farms		6400	7000	10600	8200	11100
Other RES power plants (biomass, water, biogas)		3 400	3 800	4 100	4 300	4 300
Other combined heat and power plants		400	470	470	460	470
Reserve power plants (OCGT*/diesel)		0	0	0	3 600	5 000
TOTAL	MW	42 000	47 300	57 700	62 400	72 600
	Average pace (%)	–	2.4	4.1	1.6	3.1
Production (TWh)		2020	2025	2030	2035	2040
Lignite power plants		54.3	58.4	56.9	30.3	11.7
Hard coal power plants and heat and power plants – existing and new		74.5	73.8	67.4	69.0	62.9
Nuclear power plants		0.0	0.0	0.0	20.8	41.5
Gas		9.5	15.8	19.0	34.7	38.0
Photovoltaic power plants		0.8	4.8	9.6	14.7	19.9
Wind farms		14.7	16.0	30.8	28.2	42.9
Other RES power plants (biomass, water, biogas)		9.5	11.0	14.1	15.9	13.0
Other combined heat and power plants		1.7	2.0	2.0	2.0	1.9
Reserve power plants (OCGT/diesel)		0.0	0.0	0.0	0.0	0.0
TOTAL	TWh	165.0	181.8	199.8	215.6	231.8
	Average pace (%)	–	2.0	1.9	1.5	1.5
* OCGT – open cycle gas turbines.						

Source: Ministry of Energy, 2018.

The forecasts for installed capacity and power generation presented in the EPP2040 project were prepared so as to ensure that the demand is met, taking into account the power reserve at the required level of 9% and without taking into account cross-border exchange.

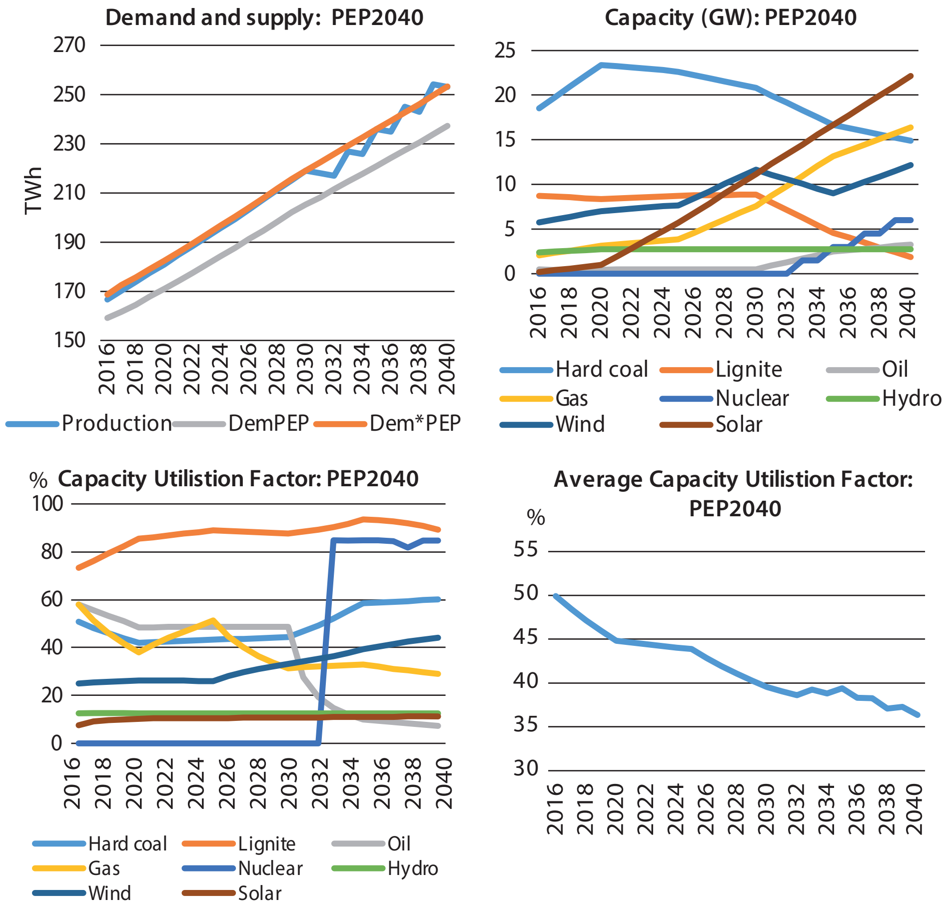

Figure 6.7. Electricity demand and production in the EPP2040 scenario

Source: own elaboration.

According to the EPP2040 forecast, the rate of change in demand in the first decade of the forecast period is 1.9% and then falls to 1.5%. This difference can be explained by the rapid increase of the electro-mobility needs and heat pumps resulting from the implementation of government programs. As the authors emphasize, without this stimulus the average rate of change in electricity demand by 2040 would be lower and would be 1.5%, therefore close to the average rate of change in demand over the last 10 years (cf. Figure 6.7).

In the years covered by the EPP2040 forecast, the installed capacity in power plants increases faster than the demand (the average rate is 2.8% and 1.7%, respectively). Therefore, it seems that the problem of unfavourable trends in energy demand and supply, resulting from power shortages, can be solved[31].

The first nuclear block will be included in the power grid not earlier than in 2033. Importantly, the "Conclusions" state that "Assumptions for the model introduce the possibility and not the necessity to build a nuclear power plant. Therefore, its presence in the energy mix is economically justified".

Important decisions affecting the shape of the power generation mix also apply to wind farms. The offshore wind farm construction program will be implemented starting from 2030. At the same time, the construction of new onshore wind farms would be discontinued, except for those being built as part of the RES auctions, which means that in 2040 their participation in the mix will be unnoticeable. The dynamic increase in the capacity of offshore wind farms will mean, however, that after a slight slump in 2035, the share of wind farms in electricity generation will increase. As a result, in 2040 the share of wind power will not decrease (it will remain at around 15%), and at the same time, their share in electricity production will double – it will increase from 9 to over 18%. This is due to the higher efficiency of offshore power plants and the assumption of an increase in the capacity utilization factor of wind power plants from the current 25% to nearly 45% in 2040. Despite that, the average capacity utilization factor drops from 50% to 36% over the forecasted period.

Forecast up to 2060

For the purposes of this study, a power market forecast up to the year 2060 has been prepared. For the period up to 2040, the forecast is based on the EPP2040 papers, while for 2040–2060 a stable economic growth rate of 2% is assumed and an increase in electricity demand is assumed at a rate of 1.5%, i.e. as in the final years of the EPP2040 forecast.

Since EPP2040 uses the production of electricity in net terms[32], while the assumptions formulated for the needs of the model represent gross production, it was

31 The only concern is that the forecasted production does not go hand in hand with the forecasted increase in capacity, whose average pace in the same period is 1.7%, and therefore equals the forecasted increase in demand. One can conclude from this, that the shortages of production and the need to import electricity observed in recent years will persist in the forecasted period, despite the clearly faster increase in installed capacity. This is probably the result of the decreasing average power utilization rate, which in turn is due to the systematic liquidation of coal-based technology, characterized by relatively high indicators. The indicators of RES usage (wind and solar power) are clearly lower. The inclusion of further nuclear blocks in the system only slightly improves the situation (cf. Figure 6.7).

32 It is gross production reduced by the consumption of electricity for energy transformation needs.

necessary to introduce appropriate calculations. The left-hand side chart of Figure 6.8 shows the historical values of electricity consumption for energy transformation needs within the power plants, in percentage of gross production. Note the slight variability of this difference – the variability coefficient calculated on the basis of this data for the last 12 years does not exceed 2%. Therefore, it seems reasonable to assume that in the perspective of 2060, gross and net production in percentage terms will be at a level equal to the average from the last 12 years. The right-hand side chart presents losses related to the transmission and distribution of electricity in percentage of gross production. In recent years they have fallen to a level below 7%, the average from the last six years is 6.3%. This amount of losses was assumed in the presented forecasts.

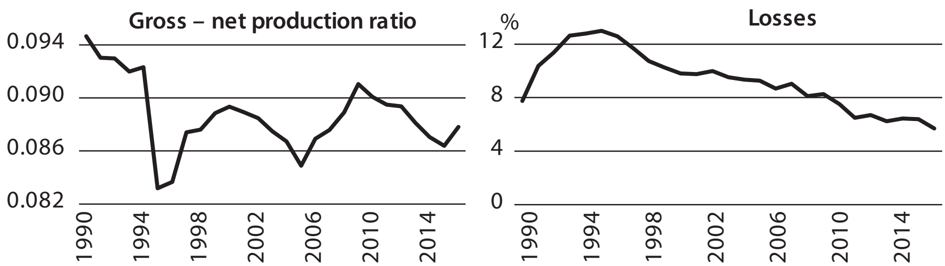

Figure 6.8. Production and losses of electricity

Source: own elaboration.

The power market forecast is presented in Table 6.2, Figure 6.9 and Figure 6.10.

The Polish nuclear power development program in will start in 2023 and will be completed in 2043, i.e. as forecasted under EPP2040. Lignite and hard coal power plants will be phased out, and it was assumed that they would cease to function in 2044 and 2053, respectively.

Table 6.2. Forecast for electricity demand and production until 2060

Year	Dem* PEP	Production (TWh)									Surplus(deficit)	
		Total	Hard coal	Lignite	Oil	Gas	Nuclear	Hydro	Wind	Solar	Prod – Dem* PEP	
												%
2016	168.6	166.6	82.5	56.1	2.3	10.4	0.0	2.6	12.6	0.1	−2.0	−1.2
2017	172.4	170.2	83.4	57.7	2.2	10.4	0.0	2.7	13.5	0.3	−2.2	−1.3
2018	175.7	173.8	84.2	59.4	2.1	10.4	0.0	2.8	14.4	0.5	−1.9	−1.1
2019	179.0	177.4	85.1	61.0	2.0	10.4	0.0	2.9	15.2	0.7	−1.7	−0.9
2020	182.4	180.9	86.0	62.7	1.9	10.4	0.0	3.0	16.1	0.9	−1.5	−0.8
2021	185.9	184.6	86.0	63.7	1.9	11.8	0.0	3.0	16.4	1.8	−1.3	−0.7
2022	189.4	188.3	86.0	64.8	2.0	13.2	0.0	3.0	16.7	2.6	−1.1	−0.6
2023	193.0	192.0	86.0	65.9	2.1	14.6	0.0	3.0	17.0	3.5	−1.0	−0.5

Table 6.2 (continiued)

Year	Dem* PEP	Production (TWh)									Surplus(deficit)	
		Total	Hard coal	Lignite	Oil	Gas	Nuclear	Hydro	Wind	Solar	Prod – Dem* PEP	
												%
2024	196.6	195.7	86.0	67.0	2.1	15.9	0.0	3.0	17.3	4.4	–0.9	–0.5
2025	200.3	199.4	86.0	68.0	2.2	17.3	0.0	3.0	17.5	5.3	–0.9	–0.5
2026	204.1	203.3	84.9	68.1	2.2	18.0	0.0	3.0	20.8	6.3	–0.7	–0.4
2027	207.9	207.3	83.9	68.1	2.2	18.7	0.0	3.0	24.0	7.4	–0.6	–0.3
2028	211.8	211.2	82.8	68.1	2.2	19.4	0.0	3.0	27.3	8.4	–0.6	–0.3
2029	215.7	215.2	81.7	68.1	2.2	20.1	0.0	3.0	30.5	9.5	–0.6	–0.3
2030	219.0	219.1	80.7	68.1	2.2	20.8	0.0	3.0	33.8	10.5	0.1	0.1
2031	222.3	218.0	81.7	62.0	2.2	24.3	0.0	3.0	33.2	11.6	–4.3	–1.9
2032	225.7	216.9	82.7	55.9	2.2	27.7	0.0	3.0	32.6	12.8	–8.8	–3.9
2033	229.1	227.0	83.7	49.8	2.2	31.2	11.1	3.0	32.1	13.9	–2.1	–0.9
2034	232.5	225.9	84.7	43.7	2.2	34.6	11.1	3.0	31.5	15.0	–6.7	–2.9
2035	235.9	235.9	85.7	37.6	2.2	38.1	22.3	3.0	30.9	16.1	0.0	0.0
2036	239.3	234.9	84.2	33.0	2.2	38.8	22.3	3.0	34.1	17.3	–4.3	–1.8
2037	242.7	245.0	82.8	28.4	2.1	39.5	33.3	3.0	37.4	18.4	2.3	0.9
2038	246.2	242.9	81.4	23.8	2.1	40.2	32.3	3.0	40.6	19.5	–3.3	–1.3
2039	249.7	254.1	79.9	19.2	2.1	40.9	44.5	3.0	43.8	20.7	4.4	1.8
2040	253.3	253.2	78.5	14.6	2.1	41.7	44.5	3.0	47.0	21.8	–0.1	0.0
2041	256.9	262.9	73.2	10.7	2.1	45.5	55.6	3.0	48.6	24.3	6.0	2.3
2042	260.6	261.6	67.9	6.8	2.1	49.4	55.6	3.0	50.0	26.8	1.0	0.4
2043	264.3	272.4	62.7	2.9	2.1	53.5	67.9	3.0	51.0	29.4	8.1	3.1
2044	268.1	272.7	57.4	0.0	2.1	57.7	68.3	3.0	52.1	32.1	4.6	1.7
2045	271.9	276.1	52.1	0.0	2.1	62.1	68.7	3.0	53.2	34.9	4.1	1.5
2046	275.8	279.7	46.9	0.0	2.1	66.6	69.1	3.0	54.3	37.8	3.9	1.4
2047	279.8	283.7	41.6	0.0	2.1	71.3	69.5	3.0	55.4	40.9	3.9	1.4
2048	283.8	288.0	36.3	0.0	2.1	76.2	69.9	3.0	56.5	44.0	4.2	1.5
2049	287.9	292.0	31.1	0.0	2.1	81.2	70.2	3.0	57.7	46.7	4.1	1.4
2050	292.0	294.5	25.8	0.0	2.1	86.4	70.6	3.0	58.9	47.6	2.5	0.8
2051	296.2	297.1	20.5	0.0	2.1	91.8	71.0	3.0	60.1	48.6	0.9	0.3
2052	300.4	299.7	15.3	0.0	2.1	97.4	71.0	3.0	61.4	49.6	–0.7	–0.2
2053	304.7	302.5	10.0	0.0	2.1	103.1	71.0	3.0	62.6	50.7	–2.3	–0.7
2054	309.1	305.5	4.7	0.0	2.1	109.1	71.0	3.0	63.9	51.7	–3.6	–1.2
2055	313.5	309.3	0.0	0.0	2.1	115.3	71.0	3.0	65.3	52.8	–4.2	–1.3
2056	318.0	316.1	0.0	0.0	2.1	119.6	71.0	3.0	66.6	53.9	–1.9	–0.6
2057	322.6	321.1	0.0	0.0	2.1	122.1	71.0	3.0	68.0	55.0	–1.5	–0.5
2058	327.2	326.2	0.0	0.0	2.1	124.6	71.0	3.0	69.4	56.1	–1.0	–0.3
2059	331.9	331.3	0.0	0.0	2.1	127.2	71.0	3.0	70.8	57.3	–0.5	–0.2
2060	336.6	336.6	0.0	0.0	2.1	129.8	71.0	3.0	72.3	58.5	0.0	0.0

Source: own elaboration, based on Eurostat and EPP2040 data.

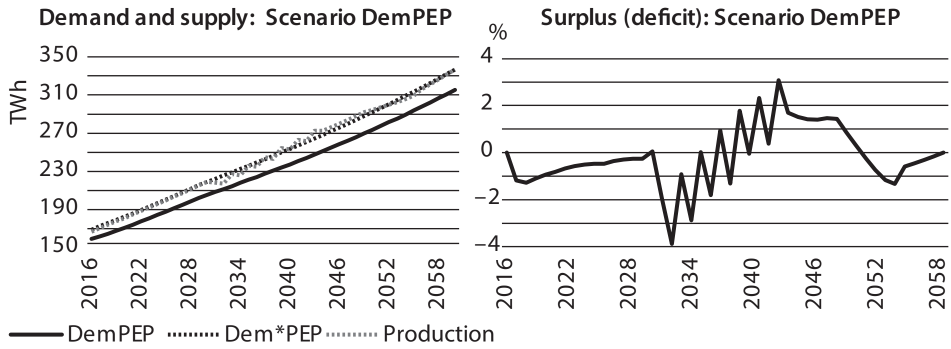

Figure 6.9. Forecast for electricity demand and production until 2060

Source: own elaboration, based on Eurostat and EPP2040 data.

Satisfying the growing demand after 2040 will be possible thanks to the development of energy production based on renewable sources (wind and solar) and gas. The capacity of RES power plants is increasing at a pace which will assure meeting the demand in 2060. The capacity of hydro and oil-based power plants will be maintained at their current low level. With the above assumptions, the gaps between the demand and supply in the forecast period oscillate around 0, not exceeding 4% and can be balanced by cross-border exchange (cf. Figure 6.9).

The forecast of installed capacity, its utilisation factor and the production of electricity until 2060 is presented in Figure 6.10. As a result of the assumptions made, in 2060, solar and wind power have the largest share in the installed capacity of all power plants – approx. 37% and 20% respectively. This will be due to the advantages of distributed energy systems and the falling costs of photovoltaic power plants (70% cheaper compared to the current level) and wind farms (60% cheaper). In the event of resignation from further development of nuclear power after the completion of the project envisaged in EPP2040, its share will slowly decline. However, the share of gas will increase – from 20% in 2040 to 27% at the end of the forecast period. As far as the assumptions for CUF are concerned, it is worth mentioning an increase in wind (up to 45%) and solar (20%) power. The average CUF value for the entire sector, after falling from the current level of 50% to 37% in 2040, will increase to 42% in 2060. This will be mainly due to the growing share of gas power plants and their use as part of the baseload, which will increase the CUF for this technology to 60% (after a period of decline to 30% before 2040).

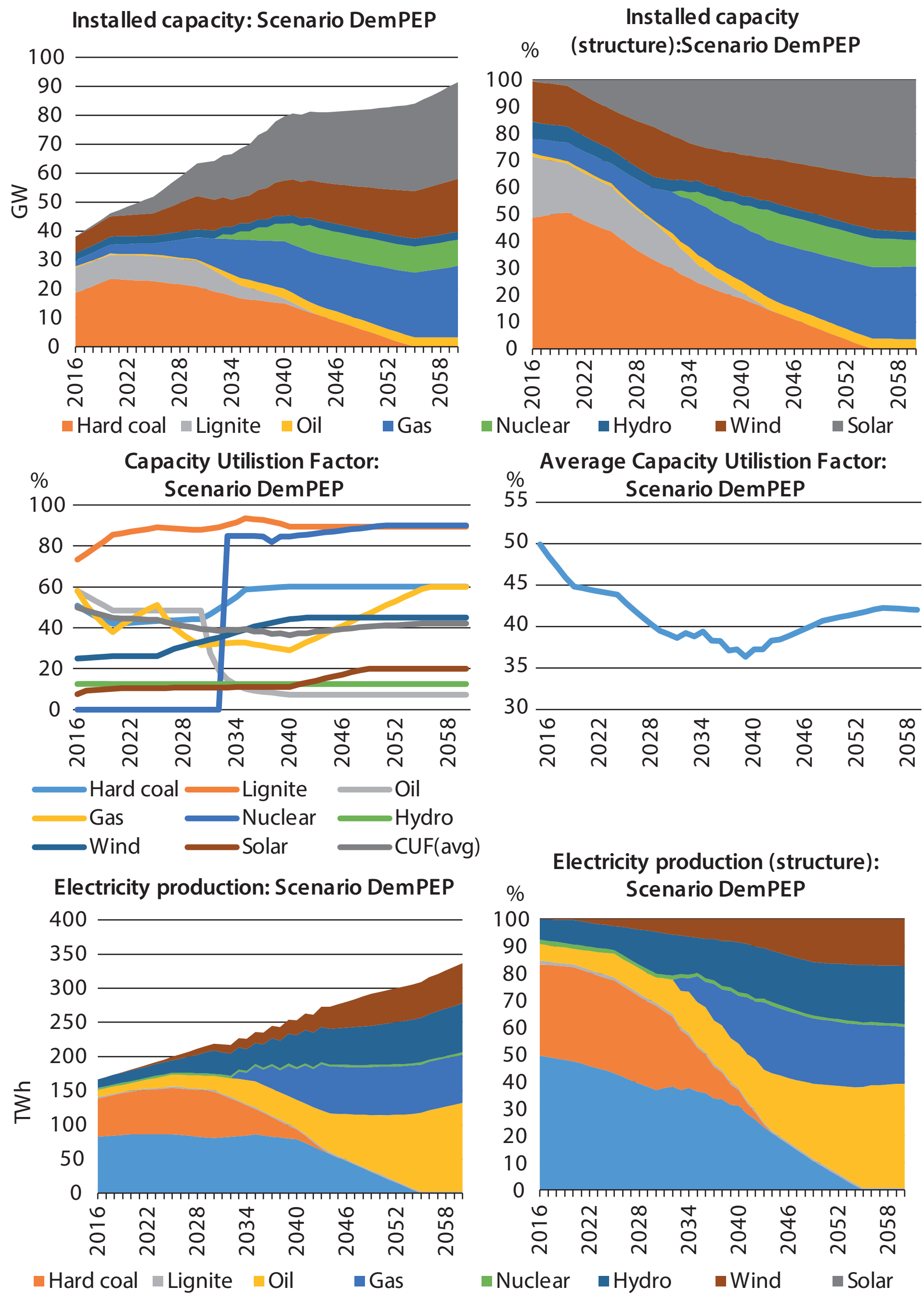

Figure 6.10. Forecast of capacity, its utilization factor and electricity production up to 2060

Source: own elaboration.

The increase in capacity and utilization factor of RES and gas power plants, as well as the closure of coal power plants, will contribute to fundamental changes in the structure of electricity production. The main components of the power mix in 2060 will be:

- gas (39%),
- wind (22%),
- solar (17%),
- nuclear (21%).

This forecast meets the forecasts for the global economy, cited by Kassenberg (2018) after *Bloomberg New Energy Outlook*, according to which, in 2050, half of the electricity supplied will be generated from wind and solar power. In the case of Poland, this share in 2060 is slightly lower – at 43%. The reason for the less dynamic development of renewable technologies in Poland may be the implementation of the nuclear power development program in 2023–2043. Although the installed capacity of nuclear power plants would be relatively small (it would not exceed 10% in 2060), the condition for the operation of nuclear power plants is a relatively high load (above 60%). Therefore, the share of nuclear power plants in electricity production in Poland would be correspondingly high. In addition, the estimated lifetime of nuclear power plants is currently 60–80 years. Therefore, the implementation of the nuclear program in Poland could be seen as a form of limitation imposed on the possibility of solar and wind power production development.

6.3. Scenarios and results

The base solution was created assuming that the demand for electricity changes at the rate assumed in EPP2040 and the installed capacity increases at the same rate, but its structure and capacity utilization factors are frozen at the level of 2033, i.e. the year in which the first block of the nuclear power plant is to be launched.

The Empower.pl.cc model enables the introduction of very complex scenarios that reflect various aspects of economic decisions taken by institutions operating within the economy. In this study, we focused only on two aspects:

- changes in the technological structure of the sector's production capacity (including the emergence of the new, nuclear technology) resulting in changes in the power mix;
- changes in the utilisation efficiency of various types of energy (including those not used to generate electricity) by its recipients (here: other sectors and households); this will make it possible to assess the role of the future nuclear power plant, in the context of other measures, in the reduction of greenhouse gas emissions.

Below, we propose related scenarios.

6.3.1. Change of power structure and power mix

Impact of power mix on electricity prices

One should note that any changes in the technological structure of installed capacity lead to a change in the power mix. Each technology can be characterized by its characteristic structure of unit material inputs. As part of the Empower model, the electricity production technology is presented in the form of an appropriate column of the input-output coefficient matrix, which may change when the power mix changes. These changes result in a change in the average costs per unit in the electricity sector and thus affect changes in electricity prices and the functioning of the economy.

The average unit costs of electricity production by technology published periodically by IEA (cf. Table 5.8. Average unit costs of electricity production by technology in 2010, 2025 and 2035 (USD/MWh)), constitute the basis for the assessment of average costs changes in the Empower model, and thus the assessment of the impact of changes in this sector on the economy. Based on this data and in connection with the power mix assumptions, the cost change index is calculated for the electricity sector, taking the form of a fixed-base index. This variable (marked as IPel) is shown in Figure 6.11, in the form of four lines, the values of which vary, depending on the observation (year) used as the basis for the calculation of the index. The choice of the basis depends on the type of simulation – the variable affects price changes starting from the year indicated in the scenario, which is also the basis for the calculation of the index. The lines in the graph show the course of the IPel variable for the following scenarios:

a) baseline, assuming that the nuclear power plant will not be built,
b) basic (covering the period of the nuclear power plant construction and its operation),
c) construction, excluding the operation stage,
d) operation, excluding the construction stage.

For scenarios b and d, the IPel variable assumes the same values and operates starting in 2033 when, according to EPP2040's assumptions, the first nuclear block will be launched. After that point, we can observe a downward trend in prices as, according to IEA data, the unit costs of electricity production in nuclear power plants are the lowest compared to other technologies. The intensity of the changes depends on the participation of the nuclear power plant in the power mix. Costs start to rise in 2043, i.e. with the completion of the nuclear power plant construction program envisaged in EPP2040.

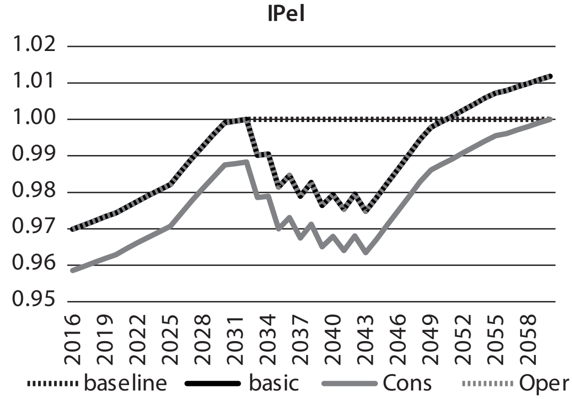

Figure 6.11. The course of the IPel variable in simulations

Source: own elaboration.

In the baseline scenario (*a*) it is assumed that by 2032 the power mix will have changed in accordance with EPP2040, and then will remain unchanged – although the installed capacity increases, the production structure from 2032 is sustained until 2060. Finally, in scenario *c* in order to exclude the impact of the operation of a nuclear power plant on the economy, as this scenario concerns only the construction stage, it was assumed that in the forecast horizon (2060) the IPel variable does not affect the cost changes (and thus also prices) of electricity. For this purpose, it was assumed that the variable might affect the costs only beyond the forecast horizon (after 2060).

The Financing of the nuclear program

It is assumed that all changes in the structure of installed capacity within the power sector are taken into consideration in the investment funds provided for this sector in the base solution. The nuclear program is an exception, and it is implemented with the use of other sources of financing. Similarly to how it was done in the simulations described in chapter 5, the following three funding options are considered:

- solely from private resources (scenario labelled as *pub0*; previously called *prv*);
- half from private and half from public resources (scenario labelled as *pub05*; previously *half*);
- solely from public resources (scenario labelled as *pub1*; previously *pub*).

6.3.2. Changes in energy efficiency

As part of the discussion on the EPP2040 project, Kassenberg (2018) presented his opinion on the matter, raising many important issues, of which one is particularly worth exploring. Citing the International Renewable Energy Agency (IRENA), Kassenberg (2018: 4) noted that:

> The energy intensity of the global economy is expected to fall by about two-thirds, reducing energy demand in 2050 to a level slightly lower than in 2015. Together, RES and the improvement in the energy efficiency can – by using safe, reliable, affordable and widely available technologies – reduce CO2 emissions from the energy sector by 90%.

This remark served as a starting point for building a scenario of changes in energy efficiency. The goal of the scenario is not to verify the above opinion within the Polish economy – this would require a separate study. Instead, we would like to highlight the capabilities of the Empower.pl.cc model and show the role of the nuclear program planned under EPP2040 in the broader context of measures to reduce greenhouse gas emissions (how significant is the effect of building an NPP compared to other projects aimed at reducing emissions).

In models using the Leontief approach to modelling of production and prices, changes in the utilisation efficiency of resources that are products of the economy can be analysed using the rows of input-output factor tables. They present the outlays of a given type of product per unit of production of other sectors. This approach can be extended to final consumption, and in particular, to determine the consumption of these products per unit of household expenditure. For energy consumption considerations, the sectors that supply it should be identified. In the classification used for the construction of the Empower.pl.cc model (also used in WIOD), among the 35 sectors, there are those which produce energy (cf. Table 5.2). These sectors are:

Number in the classification		Name	Symbol in Empower.pl
Empower.pl	WIOD		
1	17	Electricity, Gas and Water Supply	ElecGasWatSup
3	2	Mining and Quarrying	MinQuarrying
9	8	Coke, Refined Petroleum and Nuclear Fuel	RefPetCokeNuc

Scenarios of changes in efficiency relate to the use of energy of products supplied for intermediate and final purposes by these sectors. As part of this study, we are considering two scenarios which differ in the rate of efficiency improvement (the rate at which the relevant factors are reduced):

- AM1 – efficiency improvement at a rate of 1% per year, starting from 2020,
- AM3 – efficiency improvement at a rate of 3% per year, starting from 2020.

These can be combined with all previously presented scenarios. However, due to the repetitiveness of conclusions resulting from the analyses, we will limit ourselves only to selected combinations.

6.4. Simulation results

This chapter presents the results of the following simulations (the names used in the graph legends are listed in bold):

- **Baseline**: *no NPP* (up to 2060),
- *EPP2040 and beyond* (up to 2060):
  - *Construction*:
    - **ConsPub0**,
    - **ConsPub05**,
    - **ConsPub1**,
  - **Operation**,
  - **Basic**[33] (Construction and Operation),
  - **AM1** (basic + energy efficiency increase by 1% per year),
  - **AM3** (basic + energy efficiency increase by 3% per year).

Figure 6.13 contains the results of simulations carried out in the Construction (left column) and Operation (right column) modes for selected economic variables. The charts for the Construction mode contain three lines depicting different financing options for the power plant construction program: pub0 pub05 and pub1, for selected macroeconomic variables. The remaining charts in Figure 6.13 relate to the following variables:

- gdp – gross domestic product,
- empT – total employment,
- pns – public net saving.

In the case of simulations for the construction phase, the results confirm previous observations regarding the properties of the model[34], presented in Chapter 5.4.2. They show, in particular, that additional investments – above the baseline solution path[35] – cause deviations of gross domestic product, employment and public debt from the baseline solution path. However, the strength and direction of these changes depend on the financing method used. In the case of financing

33 If the financing method of the investment is important for the results of the Basic simulation, we refer to it using the following names: BasicPub0, BasicPubn05 and BasicPub1.

34 The differences result from a different starting point of the simulation, the scale of the project and the distribution of outlays over time.

35 The scenarios in the current version do not include the crowding out effect.

from private sources, additional investments become an incentive for GDP growth (maximum by 0.2% above the basic solution path), employment growth (maximum by 34 thousand people) and a decrease in public net savings of about 4% during the times of the highest outlays incurred. Financing from public funds, carried out as a result of increased taxes, causes a decrease in economic activity (a decrease in GDP by a maximum of about 0.08% and a decrease in employment (by about 15 thousand people), but an increase in public debt (by a maximum of 1.4%). In the pub05 variant, one should expect an increase in economic growth, but clearly lower compared to the pub0 variant (three times lower deviations from the baseline solution).

Interesting observations are provided by the analysis of simulation results carried out in the Operation mode. It turns out that the launch of the NPP blocks envisioned by EPP2040 will contribute to the increase in economic activity. In 2043, when the last block is launched, the additional GDP increase will amount to 0.3%. This will be followed by an increase in employment and a decrease in public debt. It is worth emphasizing that the employment in the economy as a whole is increasing despite it being dominated by a steep decline of employment in the mining and quarrying sector, resulting from the limited activity of lignite and hard coal mines, related, of course, to changes in the power mix. The below baseline decrease in employment in the mining sector reaches even 21 thousand people per year (see Figure 6.12).

The Empower.pl.cc model (unlike the original version of the Empower model) enables one not only to divide the simulations into the construction and the operation phases of a nuclear power plant but also to obtain results from the entire development program In the case of EPP2040, it has been established that the investment program will be implemented for 20 years. During this period, the blocks of the nuclear power plant will be successively built and put into service. The simulation results for selected macroeconomic variables throughout the program implementation period and over the next several years are presented in Figure 6.13.

Analysing the charts, we note that by 2033, when the first nuclear power plant block is launched, and after 2043 – after the completion of the nuclear power development program, the results of the baseline simulation coincide with the results of the simulations for the Construction and Operation stages. In the years of program implementation (2033–2043), the results are a combination of both of these stages[36].

36 Due to the non-linearity of the model, there may be differences between the sum of Construction and Operation deviations from baseline and the results of the Base simulation.

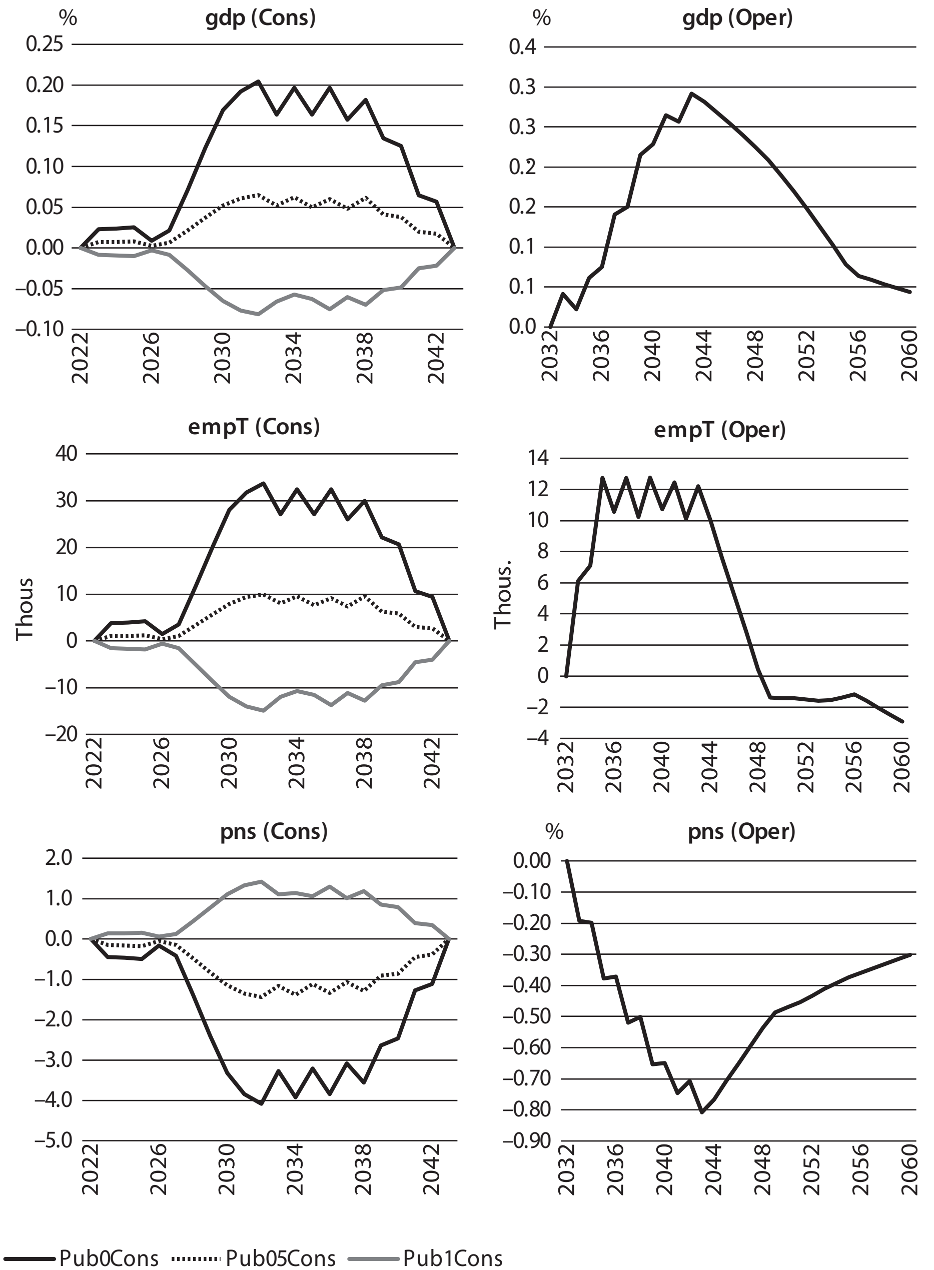

Figure 6.12. Results of simulations for construction and operation mode

Source: own elaboration.

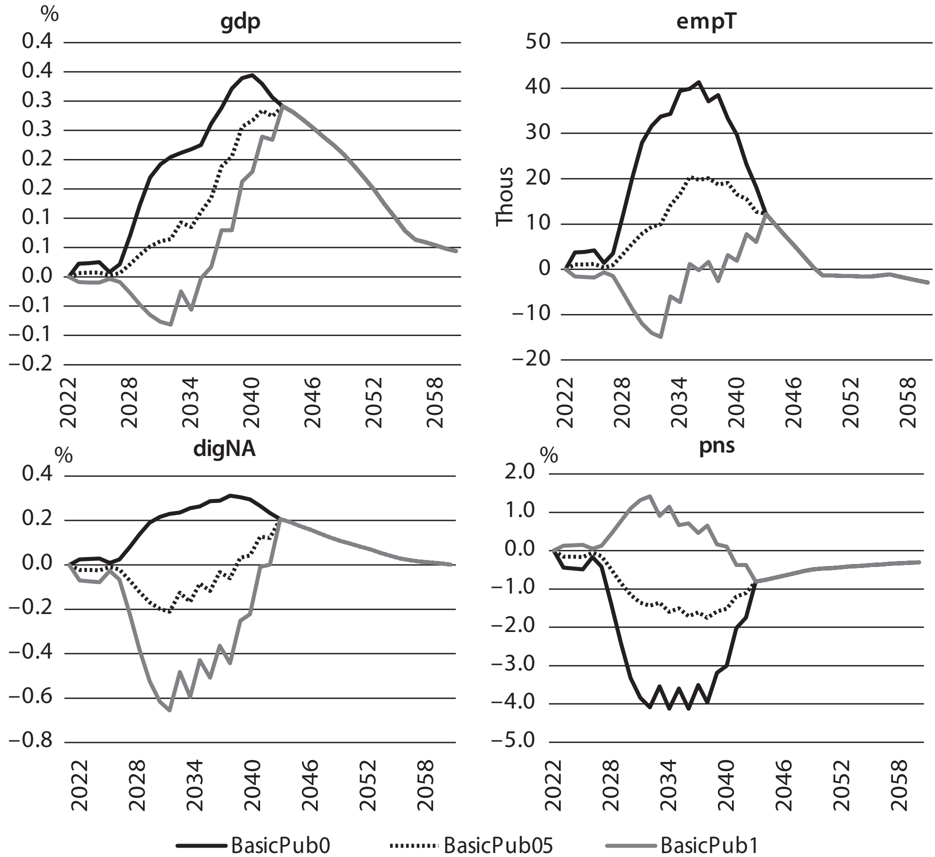

Figure 6.13. Results of simulation for GDP, employment and public net savings

Source: own elaboration.

Based on the results of the simulations, it can be concluded that the implementation period of the nuclear energy development program brings economic benefits in the form of GDP growth above the baseline path. Although the financing of the program from public sources initially contributes to the decrease of the GDP below the baseline path, since 2036 the benefits from the implementation of its subsequent stages (commissioning of subsequent blocks) outweigh the losses resulting from the increase in taxes to finance the construction of the NPP. This is due to the reduction of average electricity production costs as a result of the growing share of nuclear energy in the power mix (see Figure 6.11). After the completion of the program, we observe a gradual reduction of these benefits, due to the growing share of electricity generated from solar wind and gas sources, for which unit production costs are higher (see Table 5.8). Despite this, GDP in 2060 is still higher (by approx. 0.1% from the baseline level). Changes in GDP are followed by changes in employment. It is easy to observe the apparent differences between the various simulation variants, which are the result of different rules for the financing of the construction phase. Financing from private sources is a potent stimulus, which, combined with the benefits of lower electricity production costs, causes employment to increase by nearly 40,000 people above the baseline in 2034–2038.

The significant impact of employment reduction in mining, starting in 2033, on total employment, should be noted. We have already pointed it out in the commentary on the results of the Operation stage. This effect is presented in the chart titled Employment (see Figure 6.13), where the simulation results for the following three values[37] are shown:

- empT – total employment,
- emp3 – employment in the mining and quarrying sectors,
- empT* – total employment, excluding the mining and quarrying (emp3) sectors.

The stage of substantial reduction of lignite and hard coal production will begin in 2033, with the launch of the first nuclear power plant block[38]. As a result, employment in the mining and quarrying sector will be reduced compared to baseline and will reach 20,000 people in 2043. In coal mining itself, this decline can be even more noticeable, but it can't be fully foreseen for the operations of the entire mining and quarrying sector, as it will be counterweighted by the growing share of gas in the power mix, causing a slowdown of the decrease within the entire sector. After 2043, the employment growth effect associated with the increased gas production is manifested in a pause of the decline in employment in the entire mining and quarrying sector at the level of 10 people compared to baseline.

Changes in the average electricity generation costs resulting from changes in power mix (see Figure 6.11) are a direct result of changes in material costs, labour costs and profits per production unit. Unit material costs are included in the Empower model within the technical coefficient matrix[39], marked with the AM symbol. Figure 6.14 illustrates changes in selected coefficients from the first column of this matrix:

- AM1.1 – Electricity, Gas and Water Supply,
- AM3.1 – Mining and Quarrying,
- AM9.1 – Coke, Refined Petroleum and Nuclear Fuel.

37 In the form of deviations from baseline.

38 This can be observed in the chart showing the power mix structure scenario (see Figure 6.9).

39 Matrix of direct material input at constant prices.

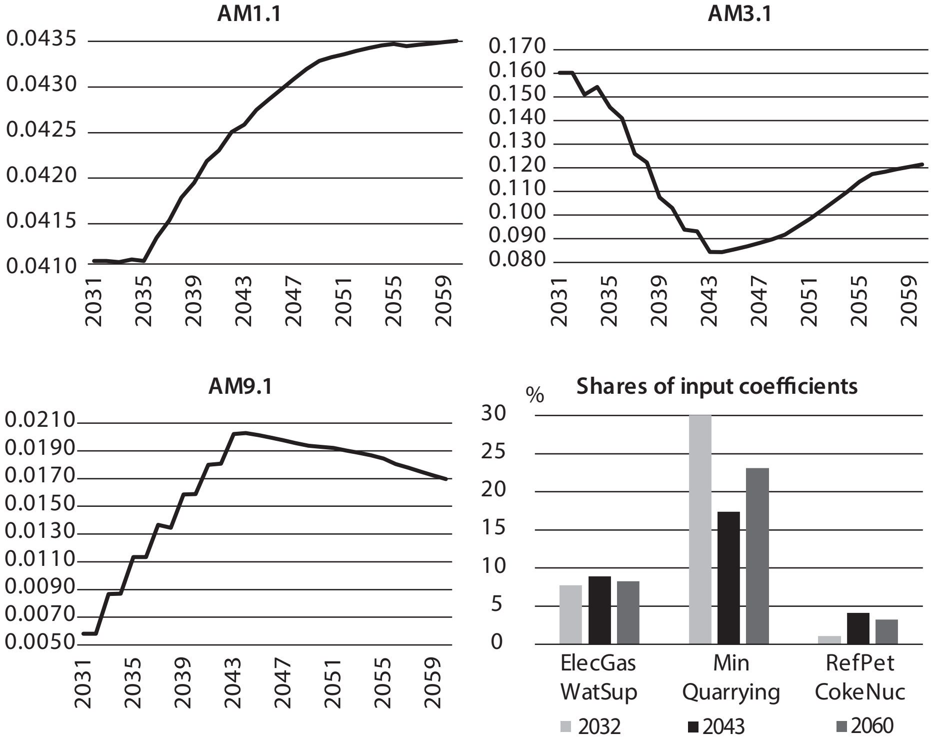

Figure 6.14. Chosen input out coefficients for the electricity sector

Source: own elaboration.

These are the coefficients for various types of energy supplied for the purposes of electricity production[40] (by sectors number 1, 3 and 9 respectively). The values of the coefficients themselves and the scale of their changes vary, which can be observed by analysing the charts of subsequent coefficients and their shares in total material costs. The AM3.1 coefficient representing coal and gas supplies has the highest value (with a 30% share in material costs in 2032), but in 2043 it is almost half the value of 2032 (about 17% of total material costs). This is related to the process of launching the subsequent nuclear blocks discussed above and the simultaneous decommissioning of lignite and hard coal mines. The subsequent gradual increase in value of the discussed coefficient results from the growing role of gas in the power mix. At the same time, in the years 2033–2043, the unit consumption of the AM9.1 coefficient will more than triple due to the demand for nuclear fuel. The slight decrease in value of this coefficient after 2043 results from the need to meet the growing demand for electricity while stabilizing the installed capacity in nuclear blocks.

40 Total energy input (total input), which consists of direct input and consumption of transformations input.

It is undisputed that the gradual reduction of the use of coal for electricity production while implementing the nuclear power plant construction program envisaged under EPP2040 will reduce CO2 emissions to the atmosphere. The scale of this reduction can be determined using the Empower.cc.pl model. Please note, however, that changing the power mix structure towards low- or zero-emission energy sources is just one of two elements of the energy transformation that aims to provide the conditions necessary for sustainable development. The second, equally important, is the increase in energy efficiency, consisting in the reduction of energy consumption without limiting the utility values resulting from the use of energy (for production or broadly understood consumption). Therefore, an increase in energy efficiency leads to energy savings, but energy savings do not have to occur solely due to an increase in energy efficiency.

The Empower.pl.cc model has been prepared so that it is possible to take into account undertakings leading to changes in the energy efficiency of production processes in individual sectors of the economy, as well as of consumption processes. These possibilities are illustrated by the AM1 and AM3 scenarios, which assume that the energy efficiency of the sectors and households, measured with the values of the AM coefficients and energy shares in consumption, increases by 1% in the AM1 scenario and 3% in the AM3 scenario[41].

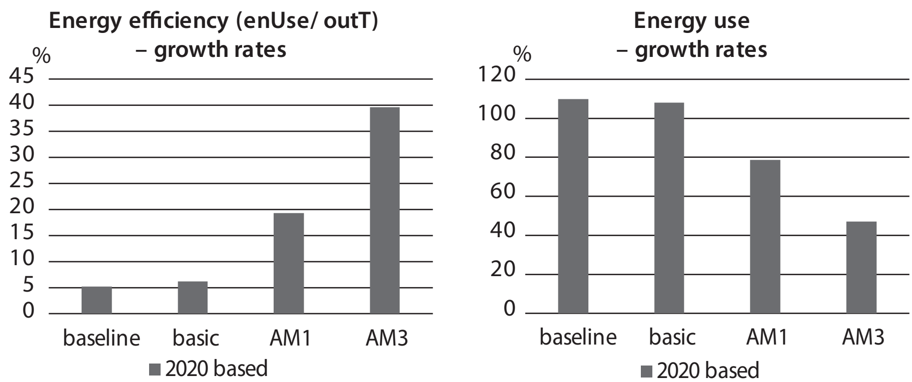

Figure 6.15. Changes in energy efficiency and energy use

Source: own elaboration.

Figure 6.15 presents changes in energy efficiency in the entire economy and changes in energy consumption in 2060 compared to 2020 for baseline, basic, AM1 and AM3 scenarios. It turns out that in the case of the first two, energy efficiency in the period under consideration increases only slightly,

41 These are the coefficients and shares in the rows corresponding to the sectors supplying various types of energy: ElecGasWatSup (1), MinQuarrying (3) and RefPetCokeNuc (9).

by about 5%. The effect of systematic increase of energy efficiency over the years studied is an increase in efficiency by 19% in the AM1 scenario and 39% in the AM3 scenario. Observed changes in efficiency result in energy savings. While in the case of the baseline and basic scenarios, energy consumption in the period under review has more than doubled (by approx. 110%), in the other two scenarios it is clearly lower – 79% and 47% in the AM1 and AM3 scenarios respectively.

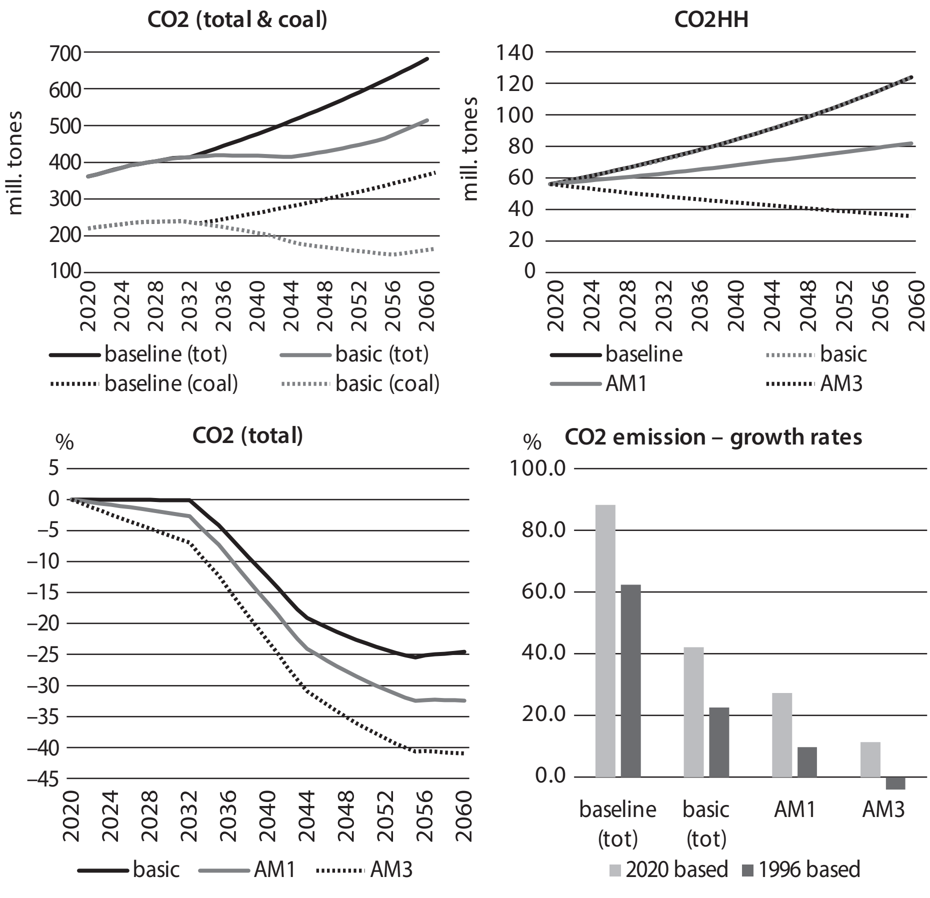

Figure 6.16. Results of simulations for CO2 emissions

Source: own elaboration.

The last figure (Figure 6.16) contains simulation results for carbon dioxide emissions. They relate to total emissions, i.e. related to all energy sources (total), emissions resulting exclusively from coal combustion, as well as emissions caused exclusively by households (HH).

Comparison of baseline emissions with basic simulation indicates that as a result of launching subsequent nuclear blocks, not only the marked increase in emissions resulting from coal combustion is inhibited, but even a decrease from 233 mill. tones in 2032 to 139 mill. tones in 2056, so by 36%. Considering the total emissions, however, the situation looks less optimistic, because despite the noticeable reduction, CO2 emissions are still rising, and the increase in the period 2032–2056 reaches 12%). This is due to the fact that in the basic simulation, measures to reduce emissions concern the exclusion of the electricity production sector, and therefore does not include other sectors of the economy (households and other sectors producing goods and services). This is illustrated by the graph showing carbon dioxide emissions from households (CO2HH), in which the line showing emissions in baseline coincides with the results of the basic simulation.

The Empower.pl.cc model makes it possible to carry out simulations that also reflect other activities for climate protection; for example, those aimed at increasing energy efficiency. Figure 6.16 presents examples of the results of this type of scenarios (AM1 and AM2). It turns out that in the case of households, a 1% increase in energy efficiency per year is only sufficient to reduce CO2 emissions compared to baseline, but not to reduce them absolutely – in 2020–2060 emissions increase by nearly 50%. If household energy efficiency increased at a rate of 3% per year, there would be an absolute reduction in household emissions from 56 to 36 million. tones, so by about 36%. The impact of the basic, AM1 and AM3 scenarios on reducing CO2 emissions compared to the baseline is presented in the bottom left corner of Figure 6.16 entitled CO2 (total). As expected, emissions fall in all simulations. In the basic scenario, the decline begins in 2033, i.e. when the first nuclear unit is launched. In the final years of the simulation, the reduction reaches 25%[42].

According to the adopted assumptions, in the variants AM1 and AM3 the reduction starts already in 2021 and reaches respectively 32% and 41%. These deep declines compared to the baseline, however, do not translate into absolute declines if we take 2020 as the basis for comparisons – even in the AM3 variant, we can see an 11% increase in emissions (see CO2 emission – growth rates). If the basis for comparisons is 1996, the volume of emissions in this variant may drop, but only by 4%. Nationally Determined Contributions (NDCs) for EU countries under the Paris Agreement, requires that by 2030 greenhouse gas emissions in Poland be reduced by 40% compared to 1990. With this in mind, it can be concluded that the implementation of the AM3 scenario is far insufficient to achieve this goal.

42 Although the simulation results presented on the Empower.pl.cc model refer to 1996 (this is the first year of the emissions data bank in the model) and not 1990, as in the case of the NDC, the application remains valid, because according to CO2 emissions from KOBIZE in 1996 differ from those in 1990 by just under 1%.

7. Conclusions and recommendations

In the light of the agreements reached at the United Nations Conference on the issue of climate change, the change of the energy sector's structure will be unavoidable, regardless of the USA withdrawal from the Paris Treaty. Therefore, the structure of electricity production in Poland should, among other transformations, aim at discontinuing coal-based production in favour of low-carbon sources. This necessity is not only due to the depletion of domestic resources of coal. In the medium term, expensive coal imports can easily replace domestic production[43]. However, policy measures undertaken both at the global and the EU level, aiming at reducing GHG emissions, cause an increase of the costs of traditional mix of electricity production, based on combustible fossil fuels, as the result of:

- growing costs of investment in modern coal blocks, equipped with additional CO2 capture systems (which negatively affect the business efficiency of projects),
- parallel systems of improvement of their efficiency,
- increasing costs of emissions permits with each new EU ETS perspective.

All of this causes the profitability of traditional energy sources based on fossil fuels to decrease, compared to renewable resources and nuclear energy. Majority of the scenarios considered in this book, assumed a significant reduction of CO2 emissions in Poland based on the increasing share of wind and solar energy. Resistance to the construction of new nuclear power plants in many countries, including Poland, is very high, which is a derivative of historical conditions and political stereotypes but also changes in consumer preferences, as well as lack of public awareness both on nuclear energy and consequences of GHG emissions. Despite this, the inclusion of nuclear energy in the Polish energy mix seems to have been decided in the perspective of the next two decades. It will operate at a base-load, replacing energy from coal. This leads to several issues raised in the body of our study.

43 In 2018 roughly ¼ of domestic demand for coal was imported, mainly from Russia (see Interpelacja nr 29680, 2019).

The way to compare the overall costs of electricity production with different technologies is to calculate Levelized Costs of Electricity. It takes into account capital costs, including site preparation, construction costs and financial costs as well as operational comprising of the cost of fuel, operation, maintenance, including waste management, decommissioning the plant, and finally other costs like those related to environmental concerns, system costs or specific taxes. Although the calculations of LCOE for NPP construction have been presented in chapter 3, the following conclusions are even more up to date, and so, worth highlighting:

- Capital cost, financial model and net installed capacity have the most substantial impact on LCOE.
- Scale effect can be achieved, manifested in a decrease of LCOE in the case of construction of several blocks simultaneously. Bearing this in mind, the increase in NPP's capacity planned in EPP2040 compared to the previous PNPP is a positive change.
- Financing through the means of contract for difference provides overall the lowest LCOE and total as-spent cost. However, financing via power purchase agreements is only a slightly less desirable option.

The presented estimates may be further calibrated, taking into account the details of financial models and the actual development of the Polish nuclear program. However, methods presented in this monograph can provide a starting point for further investigations as well as useful data source.

The implementation of plans to change the power mix structure creates a big challenge for the energy sector and the Polish economy. The EPP2040 envisages building two NPPs, which will absorb around 20% of the total investment outlays of the electricity sector for the period 2023–2042. The large scale of the investments in the electricity sector will affect the entire economy, both during the construction and the operation period of the NPPs, and replacing coal with nuclear energy in power mix will cause reduction of CO2 emission. Estimation of the effects is feasible with the use of a mathematical model reflecting the links between electricity sector and other sectors of the economy, i.e. a model constructed at a meso-economic level. There are different approaches to the construction of such class of models, but all of them use input-output tables as the source for modelling, which opens a possibility of using input-output methods for the model construction.

The advantage of the input-output approach to modelling economies is the elasticity enabling different kind of extensions not envisioned in the standard approach. The extensions necessary for this research include adding a new technology (nuclear) to an existing sector of economy (electricity production) and the model extension with new blocks of equations, namely energy and emission blocks in order to investigate effects on GHG emission reduction.

Some economists criticise the methods, including the Leontief production model, for rigidity, particularly its assumption of fixed coefficients and the failure to explain factor rewards (ten Raa, 1994). However, this criticism seems to be unjustified if the modeller combines the Leontief model with econometric methods to explain variability of technical coefficients or factor rewards as well as other critical economic processes. Endogenising demand categories of the standard input-output model and including price-quantity interactions leads to construction of fully-fledged CGE models or macroeconomic multisectoral models. IAEA Empower model extends the standard input-output approach to modelling production and prices by including wage and unemployment equations, whose parameters are estimated econometrically. The extensions allow for the assessment of not only direct and indirect effects of changes in final demand but also the induced effects, labour market response, as well as the effects of changes of power mix. The idea of Empower model for Poland (Empower.cc.pl) extends the original version with energy and emission blocks of equations, thus enabling tracing GHG emissions resulting from the changing structure of the power mix. Another deviation from the original version is the replacement of the Excel-based software for model implementation with Interdyme – a package designed for multi-sectoral macro models which allows to run a model in a faster and more efficient manner.

Within the research, Empower.cc.pl model was applied to examine macroeconomic and sectoral effects of a power mix against a baseline scenario, which assumed a moderate growth of the Polish economy until 2060. The power mix structure followed the assumptions of EPP2040 project until 2042 when the 20-year nuclear energy development program ends. In the next years, the growing demand for electricity is satisfied with the construction of further wind and solar farms as well as gas power plants. The scenario assumes successive elimination of the coal power plants.

The results of the simulations indicate that the nuclear energy development program will have a varying impact on the economy. In the construction stage, the results depend on the method of financing the program. Public financing causes a slowdown by less than 0.1% compared to baseline, while financing by private entities accelerates the growth even by 0.2%[44]. The results for the operation mode show a positive impact of NPPs on the economy, mainly due to lower electricity

44 The model does not take into account the crowding-out effects caused by the vast scale of the nuclear program, which can cause weakening of the growth compared to the presented results. However, it is worth noting here, that estimates of the crowding-out effect for studies on the impact of increased investments related to other larger project, e.g. the organization of Euro2012 by Poland and Ukraine, show a rather moderate impact, offset by a reduction in prices after the end of the investment (Borowski et al., 2013).

costs. The effects are decreasing, but they are still positive in the last decade of the simulation period when the share of nuclear energy in the energy mix is decreasing. Both in construction and operation period, the results are sector-specific. However, the overall conclusion is that the implementation of the nuclear energy development program brings economic benefits in the form of GDP increase above the baseline path, followed by changes in employment, and public net savings.

Analysis of the results of CO2 simulations shows that the power mix assumed in EPP2040 does not assure the fulfilment of Poland's obligations under the Paris Agreement. Measures to be introduced have to be much more radical because the simulation results show that even a systematic increase in efficiency of 3% per year over the years covered by the simulation (in conjunction with the change in the power mix structure envisaged in the EPP2040 project) is insufficient to achieve the required emission reduction. Therefore, a significant increase in the share of low-carbon energy sources in the power mix compared to EPP20450 seems to be the necessary condition. The increase should parallel faster liquidation of coal-based energy, and maybe even a limitation of the role of gas. The capacity market could play an essential role in this process[45]. However, it turns out that the first capacity market auctions have only consolidated the strong position of coal in the Polish energy sector (Gawlikowska-Fyk, 2019). The situation may change only after 2025, when the impassable emission limit for the capacity market participants, of 550 g CO2/kWh, will come into force. Nevertheless, this does not eliminate gas power plants from the capacity market.

Technical progress and a noticeable increase in wholesale electricity prices are conducive to the development of renewable energy. Prices of electricity from renewable sources are increasingly approaching market prices and are often already lower than the cost of production in coal-fired power plants. This applies especially to wind energy (see Derski, 2019). It turns out that onshore wind farms can develop even without government support and contrary to the EPP2040 government scenario, which marginalises them. If the trends that have emerged lately are maintained, the share of renewable sources in the power mix will increase by itself above the level provided for in the official documents, which will contribute to the fulfilment of Poland's obligations on the international stage. Last, but not least, as it proved to happen already in history, disruptive innovations may occur, which could be game-changers not only for the industry but for the whole economy; however the probability of such a phenomenon is beyond the scope of the models presented in this book.

45 The capacity market is a mechanism that provides support to power plants for maintaining "spare capacity", which can be used during periods of peak power consumption, and the resulting additional revenues would be allocated (potentially) to the modernization or construction of new units.

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Appendix

Empower.pl software

1. Structure and modifications compared to the original version

The *Empower software* provided by the IAEA is stored in seven MS Excel files with VBA routines, which are designed to automate the preparation of the model, where possible, and to run the model (see Kratena, Voigt, 2017). In this section, a modified version of the software is presented. Although it was prepared for the implementation of *Empower.pl* – the model for Poland – it is still general, which means that the introduced modifications do not relate to the model for Poland only, but are general in nature and can be used to implement the model for any country's economy*. Moreover, modifications do not alter the essence of the model nor the main principles of the software use. However, they remove some of the shortcomings and inconveniences noticed when working with the original version. The modifications were designed to facilitate the use of the model by the end-user, inter alia by providing better control over the process of model solving. They aimed to increase the flexibility of this tool so that the launching of the model in any period should not be a severe problem for the end-user as it was in the original version. It is also more comfortable for the user to maintain control over the process of model solving.

Each file of the *Empower software* consists of several to a dozen sheets, containing a specific set of data/formulas necessary for the operation of the model. Tables 1–4 below, show the contents of the templates and, in some cases, also their structure.

Before the implementation of the model for Poland, the names of files and sheets were significantly simplified (shortened). In the Tables, the original names are presented in parenthesis. Also, some of the original files of the *Empower software* were extended by adding new sheets. Generally, files' and sheets' names have been shortened and simplified.

* The *Emower.PL* software is available on the request sent to email address plich@uni.lodz.pl.

Table 1. Names and contents of Empower.pl template files

Filename*	Contents
plData.xlsm (*Model2015-ABCD_data_NEW.xlsm*)	All necessary data (source and processed) needed to run the model. Source data processing involves adjusting aggregation of source data to model needs, harmonizing data from different sources, and estimating or calibrating model parameters.
Aggregation_final.xlsm	Aggregation of an input-output table to the Empower model requirements, which are: no more than 35 sectors, 5 categories of final demand and 5 components of added value. This procedure was prepared by M.
Aggregation_code1.xls	Aggregation codes for standard input-output tables to the form required in the Empower model (for use within the *Aggregation_final* template).
plRAS.xlsm (*Model2015-ABCD_RAS.xlsm*)	Forecasting of input-output tables at current prices for subsequent years, based on the base year table and assumptions for changes in its boundaries.
plConstr.xlm *(Model2015-ABCD_construction_NEW.xlsm)*	Model equations saved in spreadsheet formulas, as well as VBA procedures to run the model in various variants. The equations are adapted to the impulses (scenarios) associated with the construction of an NPP.
plOperation (*Model2015-ABCD_operation_NEW.xlsm*)	Model equations saved in spreadsheet formulas, as well as VBA procedures to run the model in various variants. The equations are adapted to the impulses (scenarios) associated with the operation of an NPP after its startup.
plResults.xlm (*Model2015-results.xlsm*)	Summary of macroeconomic and sectoral results of simulations. Although a Results template is listed in the documentation provided by the IAEA, it was not delivered as a file to the participants of the project. Therefore, it was designed specifically for the *Empower.pl* model.

* When using a different name in the *Empower.pl* software, the original name is typed below in grey font.

Source: own elaboration.

Both the files' names and the sheets' names retain the essential elements of the original names to facilitate comparisons with the original version. This was done for purely practical reasons – to make it easier to analyze the formulas in spreadsheets, especially the spreadsheets that are very complex or contain links to other spreadsheets and files. It should be emphasized that neither the file structure of the files and sheets nor its purpose has been changed. Only in the case of the *plData* file, several new sheets have been added to enter Polish source data and to adjust them to *Empower software* requirements.

Table 2. Content of plData.xlsm template

Sheet name	Content/purpose
SEApl	Socio-economic data for Poland, including data on labour expenditure and sectoral wages.
seaNotes	Explanation of data in the *SEApl* sheet (symbols, units of measurement, etc.).
IOpl	The year 2011 I-O table for Poland of 2011; current prices; imports separated from domestic flows; labour market data (from the *SEApl* sheet); account of the distribution and use of household income (GUS, 2015); the amount and distribution of expenditures related to the development of nuclear power in Poland (Ministerstwo Gospodarki, 2014) over fifteen consecutive years.
IOpl1	Table from the *IOpl* sheet transformed to enable its use in *Empower.pl*.
MiscPL	Data on exchange rates, labour market in Poland and costs of construction of NPPs in the USA and Europe.
ioBaseY	Data from sheet pl1 with formulas checking matrix balancing.
ioTargetY	A balanced I-O table forecast for the target year ("current" year for model solving), from the *[plRAS]Ras_Control* file, and formulas for checking the formal correctness of the table. "Current" year is the year entered in the *[plRAS]Ras_Control!D10* cell.
Emp	Employment in sectors; salaries in sectors; labour force; the growth rate of exogenous variables is entered in rows 29–31 of the *[plData]Emp* file; the growth rate of exogenous variables is introduced in *[plData]Emp!I20:I26* range.
HH	Wages (Compensation of employees); OperatingSurplusHH; ProfitIncome; TaxesGovHH; SocContGovHH; TransfersGovHH-OtherIncomeHH.
Gov	Net taxes on income; net taxes on products; public consumption; other expenditure; other revenue; public net saving.
Fin	Construction; external financing; ex-ante revenue; neutral tax increase; transfer cut; revenue target; in % of YD; new tax rate.
Param	Marginal propensity of consumption; wage reaction to unemployment rate; export price elasticity (unique).
ConstrCosts	Estimates of costs of construction of a new NPP – distribution of capital expenditures for the construction of an NPP in Poland.
ConstrBySector	Distribution of investment expenditures for the construction of an NPP from the *ConstrCosts* sheet decomposed by sectors and with the distinction between inputs of domestic production and imports.
OperOut	Energy mix projections for electricity generation, with 7 technologies (primary sources): Wave/tidal; Wind/solar; Gas; Coal; Oil products; Nuclear; Hydropower
OperTechCosts	Current and anticipated production costs of 1 MWh of electricity (according to IEA) broken down by technology.
OperTechCostsMap	Determination of changes in the input-output coefficients of the electricity generation sector for the selected year.

Source: own elaboration.

Table 3. Content of plRAS.xlsm template

Name		Content/purpose
Sheet	*data*	Scenario of growth rates of output. On this basis, the input-output table is forecasted for successive years, including components of added value and final demand.
	IOT	Input-output table for the base year taken from *[PLdata]!ioBase* sheet.
	RAS_Control	Forecasting of input-output table for the target year (year number is entered in cell *D13*) The forecasting procedure is started with the *Start_RAS* button.
	RAS_Calc	RAS calculation template run by VBA *Start_RAS_Main*.
VBA	*Start_RAS_Main*	Runs RAS calculations based on the base year input-output table and its boundaries for the target year specified in the data template.
	Reset	Runs RAS calculations for base year.

Source: own elaboration.

Table 4. Content of plConstr.xlsm and plOperation.xlsm template

Name		Content/purpose
Sheet	*Ctrl&Res*	Running simulations in four variants for a single year or for many years. Saving the results of the simulation.
	Results	Preparation of simulation results for a single year for saving (the sheet added under the *Empower.pl* model).
	ResultsBD	Simulation results for subsequent years taken from the *Results* sheet are saved in this sheet; the content of this sheet is prepared so that it can be used for database creation in a separate file and then used to analyze the results of the simulation based on pivot tables or pivot charts.
	dataIO	Data from the input-output table for the target year, retrieved from the *[pl.RAS]ioTargetY* sheet.
	HH&GovFin	Income and expenditures of households and government as well as assumptions concerning the way of financing of an NPP construction.
	model	Parameters of Leontief production and prices' models and model of households' consumption and wages.
	?	Where *?* is one of the 4 letters: A, B, C, D. These are the calculation templates used to solve the model in one of four variants. Calculations are run using the *Start* or *RunAll* procedure.
	p?	Where *?* is one of the 2 letters: C, D. Calculation templates for price loops of C and D variants.
	Param	Parameters of the econometric equations of *Empower* model: income elasticity of consumption (*elas*), wage response on the unemployment rate (β_{ur}), price elasticity of export.
	Names	An auxiliary sheet that contains the names of the ranges used by the VBA procedures in the template.
	OneSecLoop	An auxiliary sheet (example), containing an example of calculations for a single-sector model, helps to understand how a full model works.

Name		Content/purpose
VBA	*Start?*	Where *?* is one of the 4 letters: A, B, C, D. Runs the specified variant of the simulation.
	Reset?	Where *?* is one of the 4 letters: A, B, C, D. Starts the base simulation (the NPP is not built or does not work).
	RunAll	Runs all simulation variants one after another and saves results in the *ResultsBD* sheet.
	EraseAll	Deletes simulation results from the *Results* sheet.

Source: own elaboration.

The content of these tables does not require separate comments except for Table 4. It presents the structure of *plConstruction* and *plOperation* templates. We discuss them together because they have a similar purpose – they are used to perform simulation on the model. The only difference is in the *plConstruction* template, the calculations are performed on the base of a scenario of a power plant construction, while in the *plOperation* a scenario of an operation phase is used. In both cases, the same model is used, so the same types of sector and macroeconomic multipliers are calculated. In *EmpowerPL* the two templates have been standardized. After these changes, the calculation systems in sheets called A, B, C, D, and pC and pD are identical. The modifications made the tracing of the Empower calculations much easier compared to the original version, so, now their analysis is also much easier compared to the original software version. Now the only difference between them is that they use two different scenarios. For the *plConstruction* template, a scenario determining the distribution of capital expenditures for the construction of an NPP is used. It is taken from the *CostsConstr* sheet. The *plOperation* template uses a scenario for the future energy mix for electricity generation resulting in changes of technical coefficients for the energy sector.

2. Other modifications

In addition to the above changes to the *Empower.pl software* a number of other changes have been introduced compared to the original version, with the aim of standardizing the templates and improving the functionality of the software. The most significant improvements are the following:

- Programming of automatic transfer of necessary information between templates (files), consisting of software – usually templates in the original version worked independently. In particular, the parameters of the *plData* file have been associated with *plConstruction* and *plOperation* templates, as this is the basis for the automation of the calculations.
- Analysis and improvement of the existing VBA routines for model solving. The purpose of these actions was to increase the efficiency of these procedures

by reducing the time needed to complete the calculation. The two following improvements were made: (1) reduction of the number of iterations by introduction of the convergence "stop criterion", in addition to the iteration number, (2) installation of the iteration counter which allows visual validation of the model solving process by the user.

- In order to study the effects year after year, the software has been expanded so that the results of the solution are automatically saved.
- Construction of procedures to automate the simulation process. Their introduction allows for the automatic solution of the model (i.e. without user intervention) for subsequent variants and subsequent years and saves the results.
- Preparation of the simulation results' reporting module (model results presentation standards). They allow comparisons over the time period under review (from the start of construction to its completion and during any time period of operation of an NPP). They also open the way for comparing Empower results for different countries.
- Flexible defining of the base year. Previously, the base year was set to "rigid" (2005), and the user had to adjust to it. If the base year were defined differently for a country, the users had to reconcile the shortening of the simulation horizon. At present, the users select the base year by themselves and always have a 25-year horizon available.
- In all files and sheets that are valid for the users, both the base year and the target year are clearly visible. This greatly facilitates the analysis of the results of the model as well as its solution.
- Model variables have been arranged and grouped within the templates. Model diagram was prepared, which makes it easier to analyze its functioning.

3. Aggregation

The aggregation procedure (*Aggregation_final.xlsm* template) was proposed by Plich (2017), after reviewing the Empower software structure. Its purpose is to make it easier for users to work on the data preparation stage of the model. It is incorporated as a permanent element of *Empower.pl*. The procedure was supplemented with aggregation codes to automatically aggregate the source input-output tables to the Empower software standard (*Aggregation_codes1.xls* file).

The template can be used for aggregation of input-output tables to required dimensions. Data matrix cannot exceed 1200 rows and 600 columns, including all parts of I-O table, i.e. industries, final demand flows and value added.

Aggregation procedure uses an idea of "aggregation codes", which are numbers of row/col (respectively) of new matrix (i.e. matrix after aggregation) to which the "old" row/col will be added. Code "0" (or an empty cell) causes the row or column to be skipped during the aggregation (not taken into account). Excel procedures for solving *Empower* assume that number of industries equals to 35. In case number of industries after aggregation is less than 35, extra "0" rows and columns can be added to the original I-O matrix. Assigning appropriate aggregation codes to the "0" industries causes "artificial" industries with 0 flows to appear in aggregated matrix.

To aggregate a matrix, do the following:

- delete previous matrix from *Matrix* sheet (if there was any) as well as aggregation codes from Codes sheet (manually or by clicking on 'From scratch' button in the *Matrix* sheet);
- copy (as values) an input matrix to *Matrix* sheet, placing the left-upper corner of the matrix in cell C3;
- enter aggregation codes for rows and columns in *Codes* sheet in column A and B respectively (in columns E&F, H&I, K&L copies of aggregation codes which are ready to use can be kept, if necessary);
- click on 'Aggregation' button in *Matrix* sheet;
- results are given in the *Col* sheet and can be copied to another file;
- check=0 in *Col* sheet means that all data from the original matrix (before aggregation) was used in the new one (after aggregation); if one or more rows/columns are skipped the check does not equal 0;
- split total flows to domestic and imported.

In the case where the original matrix contains total flows (domestic and imports), maximum number of industries in the original matrix should not exceed (1200-VA)/2, where VA is number of rows below last industry.

The results of the aggregation procedure (which are given in *Col* sheet) are the input for the splitting procedure. For the splitting procedure, last row in *Col* sheet must contain imports and last column – exports.

To split total flows into domestic and imports components do the following:

- check if in *Col* sheet imports and exports are given in last row and column (adequately);
- put number of industries to A2 cell in *ImpShares* sheet and click on 'Create Imports Shares' button;
- results are given in the Imports sheet and can be copied to another file (as values);
- one can change manually values of import shares in *ImpShares* sheet and the result matrix in Imports sheet will be adjusted automatically; in the case of manual adjustments of imports shares, one should ensure that the sum of shares in m rows equals 1 (they are shown in column A of *ImpShare* sheet).

List of Figures

List of Tables