GOSPODARKA SUROWCAMI MINERALNYMI – MINERAL RESOURCES MANAGEMENT

2025 Volume 41 Issue 4 Pages 5–32

DOI: 10.24425/gsm.2025.155882

MONIKA PEPŁOWSKA[1]

Modelling the substitution of hard coal in input–output tables: implications for the Polish energy market

Introduction

The Polish economy is entering a phase of accelerated energy transition, in which the gradual reduction of hard coal mining constitutes one of the key vectors of change. In light of national political commitments and long-term mine closure schedules, the shrinking supply of domestic hard coal for energy use translates into a deficit of energy in coal-consuming sectors, thereby forcing the substitution of the missing fuel with other sources. In such a situation, it becomes essential not only to assess the scale of the reduction but also to propose realistic substitution pathways that can compensate for the lost energy input, while maintaining the stability of inter-sectoral flows in the economy. The scale and direction of this substitution, however, are not arbitrary: they are determined by constraints on import capacity, technical and efficiency parameters of available technologies, capital expenditure (CAPEX), and operating costs (OPEX), as well as the actual structure of inter-sectoral linkages in the economy.

✉ Corresponding Author: Monika Pepłowska; e-mail: monika@min-pan.krakow.pl
[1] Mineral and Energy Economy Research Institute, Polish Academy of Sciences, Kraków, Poland; ORCID iD: 0000-0001-9150-7525; e-mail: monika@min-pan.krakow.pl

In parallel, Poland has been experiencing a rapid expansion of renewable energy capacity, particularly photovoltaics, as well as shifts in electricity demand patterns (Olczak and Matuszewska 2023). These changes provide an important context for the country's energy transition.

The purpose of this article is to demonstrate the substitution potential of hard coal in the Polish energy market, based on input–output flows within the Polish economy. The updated inter-industry flows incorporate variants of domestic coal production reduction as well as substitution variants under different price scenarios. Unlike analyses based solely on energy balances or engineering models, the input–output (I–O) approach makes it possible to connect the energy deficit, the costs of technological change, and the real relationships between sectors. This, in turn, allows for the calculation of the substitution consequences at the level of the I–O table (parts I–III), including depreciation, taxes, and operating surplus.

Input–output tables are a classical tool for analyzing sectoral linkages in the economy. In their complete form, they are divided into four parts. In practice, publications by Statistics Poland (GUS) present only the first three parts. Part I – the intermediate consumption matrix (ICM), also called the transaction matrix, which includes mutual transactions between sectors. The rows present the flow of intermediate demand, i.e., purchases of products (services) intended for further processing. The columns, in turn, are interpreted as the structure of impersonal costs of individual sectors. Part II – the final demand matrix (FDM), which consists of: consumption in the household sector, in the sector of non-profit institutions serving households, and in the government and local government sector; gross fixed capital formation; changes in inventories and valuables; and exports. Part III – the gross value added matrix (GVAM), which consists of: employment-related costs; other taxes less subsidies on production; depreciation; net operating surplus/mixed income; and gross operating surplus/gross mixed income (GUS 2019).

In this study, the author uses a Decomposed Input–Output Table (TPMD), developed on the basis of GUS tables. In order to determine the loss of domestic hard coal for energy use, it was necessary to perform a decomposition of the official table and create the TPMD. This is because in the GUS input–output table, all domestic coal – both hard coal, coking coal, and lignite – is classified into a single industry ("Hard coal and lignite"), as described in a separate article.

The first step was to define Reduction Variants (WR), representing possible gradual losses or a complete lack of domestic thermal coal on the Polish market. Four levels of reduction were adopted: 24%, 50%, 75% and 100%. The analysis also considers the effect of coal reduction on employment in the coal industry and proposes a worker migration model. These aspects are discussed in detail in Pepłowska (2024).

Consequently, the identification of feasible substitution pathways becomes a crucial element of this study, as it enables the formulation of a comprehensive model that links coal reduction with the practical possibilities of replacing it with alternative energy sources.

1. Substitution model

In the context of achieving the objective of this article, a key stage is to demonstrate the substitution potential of hard coal in the Polish energy market. A reduction or complete lack of domestic hard coal may result in the necessity of switching either to the same fuel but imported, or to alternative carriers such as natural gas and electricity.

This study adopts a dual-track approach, assuming that domestic hard coal may be replaced either by imported coal or by other sources of energy – specifically, imported natural gas and imported electricity. For the calculations presented in this section, the reference parameters are based on the most up-to-date data (2020–2023).

1.1. Assumptions of the substitution model

In order to calculate the extent of substituting hard coal with other sources of electricity and heat (fuels), the first step was to ensure the comparability of energy values by estimating the amount of energy loss resulting from the reduction or elimination of hard coal in Poland.

The use of hard coal in individual branches is treated as the amount of energy required by a given sector. Accordingly, in the event of a reduction in the availability of hard coal on the Polish market (caused by the introduction of Reduction Variants), it is assumed that substitution will be possible.

As a result of applying the Reduction Variants, inter-industry flows in coal-consuming branches change (these Reduction Variants are described in detail in Pepłowska, 2024). To quantify this change, the shortage of hard coal in each branch was calculated and converted from units of coal mass (Mg, metric tonnes) into energy units, gigajoules (GJ), using appropriate conversion factors. When converting coal mass into energy, these coefficients determine how much energy is produced from a given mass of coal.

This procedure made it possible to establish the scale of energy loss in the branches caused by the lack of domestic supply (implementation of Reduction Variants), and, consequently, to determine the amount of energy that must be imported in order to achieve substitution (implementation of Substitution Variants – WS).

The article adopts a procedure based on accurately estimating the amount of energy lost by each activity due to reduced supplies of domestic hard coal. This approach relies on a precise assessment of the expected energy deficit resulting from coal supply reductions. A unit conversion analysis was carried out, applying coefficients that translate the mass of hard coal into energy units (GJ), in order to determine the anticipated reduction in available energy for each activity.

The calculation was performed according to the following formula:

$$EIU_{wke,i} = is_{wke,i} \cdot wo_{wke} \qquad (1)$$

$EIU_{wke,i}$ – energy value of the fuel that must be imported (hard coal energy deficit), GJ/year,
$is_{wke,i}$ – amount of hard coal in sector i, Mg/year,
wo_{wke} – calorific value of hard coal, GJ/Mg.

The total amount of energy to be imported for substitution across all substitutes (fuels – energy carriers – such as imported hard coal, imported natural gas, and imported electricity) was determined for each individual sector i $\left(\sum_s EI_{s,i}\right)$. In summary, the total value of energy to be imported is equal to the hard coal energy deficit ($EIU_{wke,i}$), according to the following equation:

$$\sum_s EI_{s,i} = EIU_{wke,i} \tag{2}$$

$\sum_s EI_{s,i}$ – total amount of energy that must be imported for substitution across all substitutes in sector i, GJ/ year,
s – substitute (energy carrier), i.e., imported hard coal ($wkeI$), imported natural gas (gzI), imported electricity (eeI),
$EIU_{wke,i}$ – energy value of the missing fuel (hard coal energy deficit) that must be imported, GJ/year.

In the following part of this subsection, the methods for calculating the amount of energy for each resource are presented.

For the purposes of this article, it is assumed that the shortages generated by the reduction of hard coal on the domestic market will be fully covered by imported fuels, so as not to disrupt the structure of inter-industry flows across the economy. It should be noted, however, that imported fuels will affect the flows from the following sectors: *Hard coal*, *Crude oil and natural gas, metal ores, other mining products*, as well as *Electricity, gas, steam, and hot water*. In these cases, changes in supply occur due to the necessity of replacing coal-based energy with imported resources.

At this stage of the study, the substitution model assumes that the level of production in the branches – excluding *Hard coal*, *Crude oil and natural gas, metal ores, other mining products*, and *Electricity, gas, steam, and hot water* – remains unchanged. Therefore, in order to preserve the structure of the economy within the input–output framework, it is assumed that the entire coal deficit to be substituted will be covered by imports.

The variable element, however, is the flow from the *Hard coal* sector to other branches of the economy, and the magnitude of this change, as already noted, depends on the extent of the reduction in domestic hard coal production.

An additional important aspect is the reduction in coking coal, which results from the reduction of thermal coal. Since this shortage is relatively small, it is assumed that the missing quantity of coking coal in the flows from the *Coking coal* sector will be substituted with imported coking coal at the same prices as domestic coal. Consequently, in this respect, the flows remain unchanged.

1.2. Costs of technology change concerning part I of the input–output tables

The first step in developing the substitution model focused on analyzing the costs of switching to another technology resulting from the replacement of domestic hard coal with another fuel (energy carrier). To thoroughly understand the costs associated with such a transition, a two-stage analysis was carried out.

The first stage was to identify the purposes for which coal fuel is used within each sector. The analysis concentrated on identifying the key applications and functions of coal in a given industry. This included aspects such as energy supply, heat generation, and other sector-specific needs.

The second stage was to define the costs associated with the transition from coal fuel to another energy source. In this context, a wide range of factors was considered, such as investment costs related to switching to new technologies and infrastructure adjustments. Among the investment costs, additional expenses may also arise, such as employee training and the adaptation of production processes.

This analysis was intended to create a comprehensive financial picture of the relationship between the current use of hard coal and the potential costs of switching to a more sustainable energy source (fuel).

Accordingly, the necessary investment outlay for a 1 MW power capacity was determined for technologies based on hard coal, natural gas, and electricity, applied in heat generation, electricity production, and as input for chemical processes.

In summary, the results of this analysis enable an assessment of the costs associated with a company’s transition to another energy source (fuel), while considering the energy demand of a given sector. The calculation was based on the assumption of an average annual operating time for a specific technology, which allowed for the precise determination of the required substitution capacity. This parameter constitutes a key measure for the proper configuration of supply capacity. By identifying the scale of energy demand and the unit investment costs related to technological change, it was possible to calculate the necessary investment outlays.

In this context, variable costs – mainly related to the price of the fuel needed to operate the new technology – were also taken into account. Annual depreciation values for each technology were calculated as well, since the model considers one year as the unit of analysis.

The reference parameters adopted for the substitution model calculations are presented in Table 1.

Table 1. Reference parameters adopted for substitution model calculations, 2020 and 2022

Tabela 1. Parametry odniesienia przyjęte do obliczeń modelu substytucyjnego w latach 2020 i 2022

Parameter	Symbol	Value	Unit
Calorific value of hard coal (thermal)	wo_{wke}	21	GJ/Mg
Calorific value of coking coal	wo_{wkk}	29.40	GJ/Mg
Calorific value of natural gas	wo_{gz}	0.0376	GJ/ m^3
Efficiency of hard coal use for heat production (for electricity generation in the *Electricity, gas, steam, and hot water* sector)	η_{wke}	0.70 (0.40)	–
Efficiency of natural gas use for heat production (for electricity generation in the *Electricity, gas, steam, and hot water* sector)	η_{gz}	0.85 (0.50)	–
Efficiency of electricity use	η_{ee}	3.00	–
Unit investment cost of transition to natural gas technology	IN_{gz}	528.40	thousand PLN/W
Unit investment cost of transition to electricity-based technology	IN_{ee}	1,656.10	thousand PLN
Lifetime of natural gas technology	LT_{gz}	25.00	years
Lifetime of electricity-based technology	LT_{ee}	25.00	years
Average annual operating time of gas technology	t_{gz}	4,500.00	h/year
Average annual operating time of electricity-based technology	t_{ee}	4,500.00	h/year
Average annual operating time of hard coal technology	t_{wk}	7,008.00	h/year

Source: own elaboration based on IEA (2020), URE (2023), ARE (2023), GUS (2023d), Ogrzewamy (2023).

In summary, the substitution model within the inter-industry flows in Part I of the input–output tables is constructed in such a way that the objective function is the minimization of technology costs related to the substitution of hard coal. The decision variable ($u_{s,i}$) represents the share of energy carrier *s* (fuel) consumed in sector *j*:

$$\min \rightarrow \sum_{s} \sum_{i} u_{s,i} \left(KE_{s,i} + KN_{s,i} \right) \tag{3}$$

$$\sum_{s} u_{s,i} = 1 \tag{4}$$

↳ *s* – substitute (energy carrier), i.e. imported hard coal (*wkeI*), imported natural gas (*gzI*), imported electricity (*eel*),

i – product/supplier of the product/sector of the economy from which the product originates,

$KE_{s,i}$ – variable operating costs, including the cost of switching to energy carrier s in sector i, thousand PLN,

$KN_{s,i}$ – annual investment cost of the technology powered by energy carrier s in sector i, thousand PLN,

$u_{s,i}$ – share of energy carrier s in sector i, the decision variable of the optimization model, determined as the solution (generated as an outcome of the model).

The values of $KN_{s,i}$ and $KE_{s,i}$ depend on the level of demand for a given energy carrier (fuel), and this demand influences the share of the fuel in the overall structure. Calculations of the costs of technology change (transition from hard coal-based technology to another energy source) in the Substitution Model were carried out according to the algorithm, with parameter values adopted from Table 1:

- For the transition to coal technology:

$$KE_{wke,i} = \frac{EI_{wkeI,i}}{wo_{wke}} \cdot CI_{wke} \tag{5}$$

and

$$KN_{wke,i} = 0 \tag{6}$$

↳ $KE_{wke,i}$ – variable operating costs, including the cost of switching to energy carrier (fuel) hard coal for sector i, thousand PLN/year,

$KN_{wke,i}$ – annual investment cost of the technology powered by hard coal in sector i, thousand PLN/year,

wo_{wke} – calorific value of hard coal, GJ/Mg,

CI_{wke} – price of imported hard coal, thousand PLN/Mg,

$EI_{wkeI,i}$ – total amount of energy that must be imported for substitution by imported hard coal for sector i, GJ/year, calculated as:

$$EI_{wkeI,i} = \sum_{s} EI_{s,i} \cdot uI_{wke,i} \tag{7}$$

↳ $\sum_{s} EI_{s,i}$ – total amount of energy that must be imported for substitution across all substitutes, GJ,

s – substitute (energy carrier), i.e. imported hard coal (*wkeI*), imported natural gas (*gzI*), imported electricity (*eeI*),

$uI_{wke,i}$ – share of imported hard coal consumption in sector i, decision variable of the model.

- For the transition to natural gas:

$$KE_{gz,i} = \frac{EI_{gzI,i}}{wo_{gz}} \cdot CI_{gz} \tag{8}$$

$KE_{gz,i}$ – variable operating costs, including the cost of switching to natural gas in sector *i*, thousand PLN,
CL_{gz} – price of imported natural gas, thousand PLN/1000 m^3,
wo_{gz} – calorific value of natural gas, GJ/1000 m^3,
$EI_{gzI,i}$ – total amount of energy that must be imported for substitution by imported natural gas for sector *i*, GJ/year, calculated as:

$$EI_{gzI,i} = \frac{\sum_{s} EI_{s,i}}{\frac{\eta_{gz}}{\eta_{wke}}} \cdot uI_{gz,i} \tag{9}$$

$uI_{gz,i}$ – share of imported natural gas consumption in sector *i*, decision variable of the model,
η_{wke} – efficiency of coal use for heat (and for electricity in the *Electricity, gas, steam, and hot water* sector),
η_{gz} – efficiency of natural gas use for heat (and for electricity in the *Electricity, gas, steam, and hot water* sector),
other markings as in formula (7).

The annual investment cost of gas technology is calculated as:

$$KN_{gz,i} = \frac{\frac{EI_{gzI,i}}{3.6}}{t_{gz}} \cdot \frac{IN_{gz}}{LT_{gz}} \tag{10}$$

$KN_{gz,i}$ – annual investment cost of gas technology in sector *i*, thousand PLN/year,
$EI_{gzI,i}$ – the total amount of energy that must be imported for substitution by natural gas, for sector *i*, GJ/year,
3.6 – conversion factor from GJ to MWh,
IN_{gz} – unit investment cost of gas technology, thousand PLN/MW,
LT_{gz} – lifetime of gas technology, years,
t_{gz} – average annual operating time of gas technology, h/year.

- For the transition to electricity:

$$KE_{ee,i} = \frac{EI_{eeI,i}}{3.6} \cdot CI_{ee} \tag{11}$$

↳ CI_{ee} – price of imported electricity, thousand PLN/MWh,
$EI_{eeI,i}$ – the total amount of energy that must be imported for substitution by electricity, for sector i, MWh, calculated as;

$$EI_{eeI,i} = \frac{\sum_{s} EI_{s,i}}{\frac{\eta_{ee}}{\eta_{wke}}} \cdot uI_{eei} \tag{12}$$

↳ $\sum_{s} EI_{s,i}$ – total amount of energy to be imported for substitution across all substitutes, GJ,
η_{ee} – efficiency of electricity use,
η_{wke} – efficiency of hard coal use for heat production (for electricity generation in the *Electricity, gas, steam, and hot water sector*),
$uI_{ee,i}$ – share of imported electricity consumption in sector i, decision variable of the model;

and

$$KN_{ee,i} = \frac{\frac{EI_{eeI,i}}{3.6}}{t_{ee}} \cdot \frac{IN_{ee}}{LT_{ee}} \tag{13}$$

↳ $KN_{ee,i}$ – the annual investment outlay cost for technology supplied with the energy carrier (fuel) s – electricity, for sector j, thousand PLN/year
3.6 – conversion factor from GJ to MWh,
$EI_{eeI,i}$ – the total amount of energy that must be imported for substitution by electricity, for sector i, GJ/year,
IN_{ee} – unit investment outlay for transition to electricity-based technology, thousand PLN/MW,
LT_{ee} – lifetime of electricity-based technology, years,
t_{ee} – average annual operating time of electricity-based technology, h/year.

In line with the procedure adopted in this article, the model also incorporates constraints, which are described in the following sections.

1.3. Substitution variants

In order to compensate for the loss of energy resulting from the introduction of the Reduction Variants, it was necessary to identify potential substitution options for these deficits. Therefore, the Substitution Variant WS2 was introduced:

The substitution of hard coal for power generation, the reduction of which occurs under the Reduction Variants WR25%, WR50%, WR75% and WR100%, is carried out for each Reduction Variant through three imported energy carriers (fuels), namely: imported hard coal in five price variants, imported natural gas in five price variants, and imported electricity. The prices adopted for each of the Reduction Variants are as follows:

- the price of imported hard coal equal to the reference price of domestic hard coal, the price of imported hard coal 20% and 40% higher than the domestic price, and the price of imported hard coal 20% and 40% lower than the domestic price,
- the price of imported natural gas equal to the reference price of domestic natural gas, the price of imported natural gas 20% and 40% higher than the domestic price, and the price of imported natural gas 20% and 40% lower than the domestic price.

The diversity of import price scenarios considered in this article results from several factors, such as demand elasticity, production costs, market competition, and import capabilities. Historical data analysis demonstrates significant volatility in raw material prices, which can have a considerable impact on the economy. Therefore, in order to capture this complexity, it was decided to adopt a broad price range in this study, covering possible price changes from –40% to +40%.

In the model, it was assumed that under the Substitution Variant WS2, limits to import capacity would apply, reflecting the actual import possibilities currently present in the Polish market, as presented in the subsequent parts of this article.

Substitution possibilities were considered separately for the supply side and the demand side, given their specific nature. Thus, substitution of flows in enterprises (Part I of the input–output tables) and substitution of flows on the demand side of the input–output tables (Part II of the input–output tables) were analyzed.

Determining substitution directions for both the supply and demand sides – each of which constitutes an important aspect as a recipient of domestic production – required a multifaceted analysis of the domestic market.

Following these analyses, substitution directions for the demand side were determined based on historical data regarding shifts to alternative fuels, drawing on the Central Statistical Office's publication *Energy consumption in households* (GUS 2022a). For enterprises, on the other hand, substitution directions were determined using cost-based criteria, assuming that enterprises would, in the first instance, adopt the cheapest available technology. The estimates for enterprises account for both the costs of switching technologies and the operating costs of the respective technology, as described in detail in the following sections of this article.

1.4. Import of energy carriers

1.4.1. Import of hard coal

In the context of substituting domestic hard coal with other energy carriers (for substitution in Part I of the input–output tables), the maximum import capacity for each substitute was determined. Establishing this parameter is crucial in order to define constraints on the feasibility of importing a given energy carrier, while accounting for current national energy needs and resource availability. This procedure allows for a more precise delineation of the scope of substitution, as well as for a better understanding of potential scenarios associated with the introduction of alternative energy sources and the effective management of the national energy balance.

The maximum import capacity for hard coal, taking into account all seaports and border crossings through which coal imports are possible, is presented in Table 2. It was determined

Table 2. Maximum import capacity for hard coal in 2021, thousand Mg

Tabela 2. Maksymalna zdolność importowa węgla kamiennego w 2021 r. tys. Mg

Seaport / border crossing	Location	Maximum import capacity for hard coal, thousand Mg
Gdańsk (seaport)	Gdańsk	6,000
Gdynia (seaport)	Gdynia	3,000
Szczecin (seaport)	Szczecin	350
Świnoujście (seaport)	Świnoujście	2,000
Braniewo (border crossing)	Braniewo–Mamonowo	2,500
Kuźnica (border crossing)	Kuźnica–Grodno	2,500
Siemianówka (border crossing)	Siemianówka–Swisłocz	2,500
Terespol (border crossing)	Terespol–Brześć z terminalem Małaszewicze	3,000
Dorohusk (border crossing)	Dorohusk–Jagodzin	300
Medyka (border crossing)	Przemyśl–Medyka	300
Sławków (border crossing)	Hrubieszów–Sławków (LHS)	2,000
Seaborne imports (total)		11,350
Land-based imports (rail)		13,100
Total		24,450

Source: own elaboration based on ARP (2023b), GUS (2022g).

that the maximum import capacity for hard coal is 24.5 million Mg, which is a key value for Substitution Variant WS2. In the model, this maximum import capacity was assumed, given that developments in 2023 demonstrated that it is possible to further expand this capacity, particularly through seaports.

When analyzing the prices of imported hard coal and determining import capacities, historical data were used. Price analysis is illustrated in Figure 1, where the average prices of domestic hard coal were calculated on the basis of three groups of consumers (professional power plants, non-professional and professional heating plants, and other domestic consumers through authorized suppliers).

The results of the analysis indicate that over time, the price of imported hard coal was generally higher than that of domestic coal. Nevertheless, there were also periods when the price of imported coal was equal to or slightly lower than that of domestic coal. This suggests that international price volatility has a significant impact on the price relationship between imported and domestic hard coal. Consequently, decisions regarding imports may vary depending on specific market and economic conditions.

For this reason, it was considered essential to analyze substitution options across the full range of possible price scenarios. Therefore, it was assumed that substitution could be explored in relation to differentials in import prices relative to domestic prices: equal to, 20% and 40% higher, as well as 20% and 40% lower. This approach allows for a more comprehensive understanding of the effects of price volatility on substitution decisions and provides for the consideration of multiple price scenarios in the analysis.

A reduction in the availability of hard coal for energy purposes also implies a reduction in the coking coal supply to the market. For this reason, it was assumed that the resulting

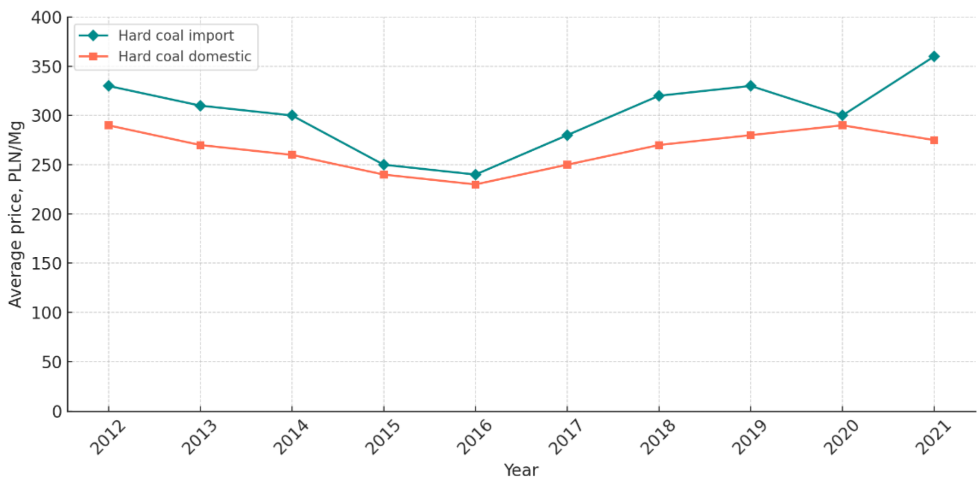

Fig. 1. Average prices of imported and domestic hard coal for energy purposes, PLN/Mg
Source: own elaboration based on ARP (2023b)

Rys. 1. Średnie ceny importowanego i krajowego węgla kamiennego energetycznego, zł/Mg deficit would be entirely covered by imports, with imported coking coal priced at the same level as domestic coal.

In the case of Substitution Variant WS2, additional constraints arise in the model. Particularly important are generating units powered by hard coal. Based on information on the generating resources of the National Power System (PSE 2022), the total available capacity of coal-fired power plants is 15,902 MW. However, many of these units are outdated, and therefore, it is assumed that units built before 2000 will be modernized and may be converted to gas-fired units. At the same time, coal-fired generating units built after 2000 or modernized after 2000 are assumed to remain coal-based. The available capacity of these coal-fired units amounts to 11,651 MW, which was adopted in the substitution model.

1.4.2. Import of natural gas

As part of the research, the import capacity for natural gas was analyzed, taking into account several aspects:
- resource availability,
- trade agreements,
- infrastructure and technology.

In this context, one may assume that the availability of natural gas resources on international markets is sufficient to meet import demand. If the importing country has access to many different sources of natural gas, it can be assumed that capacity may be practically unlimited. A country may hold long-term contracts for natural gas imports with various supplier countries, which guarantee stable deliveries under specified conditions. In such cases, capacity may be considered de facto unlimited. If import infrastructure – such as LNG terminals – is well developed and natural gas transportation technology is advanced, it can be assumed that import capacity is practically unlimited, since effective means of transportation and distribution exist.

However, despite these assumptions, in reality, there are certain limitations, such as political factors, infrastructural constraints, global price volatility, or even technological challenges, which may affect the availability and capacity of imported natural gas. Therefore, even if capacity is assumed to be unlimited, potential risks and factors affecting its stability and availability must be considered.

In the case of the Polish economy, the role of natural gas has clearly increased in recent years, and in light of PEP2040, it may be concluded that this resource will become one of the main factors supporting decarbonization (Szurlej i in. 2015; Hebda 2022). In 2022, Poland had recoverable natural gas reserves of 153.52 billion m^3 (including balance and off-balance reserves), an increase of 8.25 billion m^3 compared to the previous year (PIG-PIB 2022).

Therefore, although the import capacity of natural gas for Poland may generally be considered sufficient, certain constraints exist that may affect its stability and availability in the longer term.

In the substitution model, it was assumed that natural gas import capacity is sufficient to cover current energy needs. This is justified by the following premises:

1. Forecast increase in production – Orlen is conducting intensive operations on the Norwegian Continental Shelf (99 licenses, 17 fields) and plans to increase production to 12 billion m^3 annually by 2030 (PGNiG 2022; Sobczyk-Grygiel 2022; Businessinsider 2022).
2. Expansion of LNG terminals – the second stage of the Świnoujście investment (third LNG tank) will increase regasification capacity; in 2022, LNG accounted for 43% of imports, mainly from the United States (Orlen Group 2023a).
3. Orlen's LNG carrier fleet – introduction of the first vessel *Lech Kaczyński*, and a planned fleet of eight ships will improve supply security and reduce transport costs (Vinet and Zhedanov 2011).
4. Expansion of storage facilities – by 2025, the capacity of domestic storage will increase by 25% (PMG Wierzchowice), with additional projects including Mogilno caverns (Orlen Group 2023b).
5. Poland's role as a transit country – central location and growing transmission infrastructure strengthen Poland's potential as a regional gas hub (Chmielarz 2023).

All the above premises support the assumption of unlimited natural gas import capacity in the model.

When determining the price of imported natural gas for calculations in the substitution model, historical data from the Polish Power Exchange (TGE) were used (Figure 2). Establishing the price of imported natural gas based on historical TGE data makes it

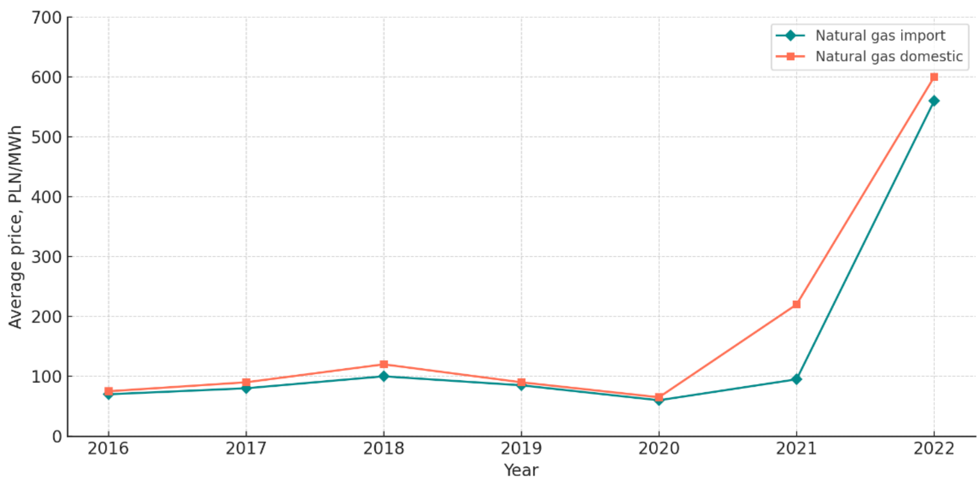

Fig. 2. Average price of natural gas with next-day delivery (RDNg), PLN/MWh
Source: Author's elaboration based on (TGE 2023)

Rys. 2. Średnia cena gazu ziemnego z dostawą w kolejnej dobie (RDNg), zł/MWh possible to create more realistic forecasts and analyses regarding the import costs of this resource. Several reasons justify the use of TGE data, including reliability. As the main trading platform for energy commodities in Poland, TGE provides a representative picture of trading activity and price formation on the natural gas market.

An analysis of data from 2016 to 2022 shows that the domestic natural gas price fluctuated both upward and downward. As a reference for these fluctuations, the average domestic natural gas price was calculated at 0.7 PLN/m^3. Similarly to the price variants for imported hard coal, the price of imported natural gas was also subject to fluctuations, both increases and decreases relative to the domestic natural gas price. Consequently, five different price variants for imported natural gas were adopted in the substitution model: equal to the domestic gas price, 20% and 40% higher, and 20% and 40% lower.

In the calculations, the possibility of importing natural gas from Russia was excluded due to the current blockade of this route. Therefore, import prices were assumed to reflect the average purchase prices of natural gas imported from EU Member States or from member states of the European Free Trade Association (EFTA) – parties to the Agreement on the European Economic Area.

As mentioned in the assumptions of the substitution model, coal-fired generating units constructed before the year 2000 will, if required by market needs, be modernized or converted into natural gas-fired units. Additionally, in this study, a limitation was introduced on the maximum capacity that can be generated by gas-fired units, set at 11.8 GW. This value is consistent with national documents, in accordance with PEP2040, as the maximum possible capacity of natural gas power plants expected to be achieved by 2030.

1.4.3. Import of electricity

Based on data from Polskie Sieci Elektroenergetyczne SA (PSE SA 2022), the annual electricity import capacity was estimated at 32.76 TWh. For the purposes of the model, it was assumed that a safe level would correspond to 25% of the total import capacity. This value appears relatively high compared to the current annual consumption level of around 13.3 TWh (Energia RP 2023). For imported electricity, the price was assumed to remain constant at 852.39 PLN/MWh (2022) (TGE 2023).

1.5. Final assumptions: substitution

In the substitution model of energy carriers, it is assumed that any quantity of a resource can be imported at a given price, with the main limitation being import capacity as well as the existing infrastructure and its planned expansion up to 2030 (including coal and gas capacities). Imports are assumed to originate from the global market, and thus the volume of imports does not affect price, given the scale of the global market. The quantity of a resource that can replace hard coal is determined by both import capacity and price, with the substitution model always selecting the imported resource (fuel–energy carrier) that is cheaper, taking into account both the unit energy costs and the costs of switching to a new technology.

In the case of imported hard coal, no technology-switching costs are incurred, since the technology remains the same and costs are determined solely by coal price. For natural gas and electricity, however, the above principle applies.

The substitution model functions in such a way that the dominant resource (fuel – energy carrier) is the one for which the total substitution costs (including purchase and potential technology change) are the lowest. The limitation is import capacity, which means that if imported hard coal is cheaper than imported natural gas (i.e., the total costs of one resource are lower than the other), substitution will be implemented through imported hard coal up to the maximum transmission capacity. The remaining energy deficit may then be substituted by natural gas, the total costs of which are higher than imported coal but lower than imported electricity.

The model also introduces a constraint on technology-switching options – for the power sector, this limitation is linked to the number of domestic coal and gas units, taking into account the generating capacity of the National Power System (KSE).

For each technology change, so-called sunk costs were also considered as part of the investment costs (Tarnawska 2014). Sunk costs are expenditures that cannot be recovered and whose incurrence cannot be avoided once the service requiring them is discontinued (Śliwa 2012).

Decisions regarding the choice of substitution technology are based on total costs. A comparison of these costs was performed using Macros implemented in the MS Excel programming environment. This approach makes it possible to select optimal substitution pathways for energy resources (in line with the assumptions of the substitution model), taking into account both economic aspects and the capacities of import and generation infrastructure.

Substitution in part II of the input–output tables

An important element of this part of the input–output tables is the inclusion of exports of domestic resources. Consequently, the substitution model in this part of the tables was constructed in such a way that reductions in hard coal supply occur first by decreasing exports of domestic coal. Only once exports reach zero (i.e., when no exports occur) does the substitution process begin.

Substitution of final consumption

Substitution within the "Final consumption" categories – *households, non-profit institutions serving households, and government and self-government institutions* – was based on the observed long-term tendency to shift towards alternative energy sources. Data were drawn from the publication Energy consumption in households in 2021 (GUS 2022a) (Table 3).

Table 3. Structure of fuels and energy carriers used in households for heating, 2012–2021, %

Tabela 3. Struktura paliw i nośników energii zużywanych w gospodarstwach domowych do ogrzewania w latach 2012–2021 (%)

Specification	2012	2015	2018	2021
Electricity	5.4	4.5	5.1	5.5
District heating	41.5	41.7	40.4	52.2
Natural gas	8.8	10.1	14	14.6
Liquefied petroleum gas (propane–butane)	0.3	0.3	0.5	0.8
Heating oil	0.4	0.4	0.5	0.3
Hard coal	40.8	40.4	36.5	20.9
Lignite	1.4	1.1	0.5	0.4
Coke	0.7	0.8	0.6	0.2
Firewood	40	41.7	28.8	20.7
Other types of biomass	4.3	3	1.3	2.3
Solar energy	0.07	0.15	0.13	0.4
Heatpump	0.05	0.07	0.28	0.69

Sources: GUS 2022a.

Substitution in part III of the input–output tables

All tax parameters in this section were calculated on the basis of the modified inter-industry flows under the Reduction and Substitution Variants. Individual tax values were determined analogously to those in section 3 Results.

2. Results

Below is an example of calculations taking into account the assumptions described in the preceding subsections for inter-industry flows in the Decomposed Input–Output Table (TPMD). In this respect, the focus was on changes in flows in the TPMD resulting from the introduction of Reduction Variants and Substitution Variants (substitution model).

Part I of the input–output tables

Flows from any branch of the economy to all other branches (excluding flows to coal branches: *Thermal hard coal*, *Coking coal*, and *Lignite*) remain in the fixed flow structure as specified in the TPMD. A different situation occurs for flows to the coal branches, i.e. flows to *Hard coal* ($x2_{i,wke}$), *Coking coal* ($x2_{i,wkk}$), and *Lignite* ($x2_{i,wb}$).

Flows from branches of the economy to the coal branches in the TPMD (excluding flows originating from the branches *Thermal hard coal*, *Crude oil and natural gas, metal ores, other mining products*, and *Electricity, gas, steam, and hot water*) are calculated using the algorithms below. For example, the flow:

- From *Agricultural and hunting products* to *Hard coal* ($x2_{pril,wke}$):

$$x2_{pril,wke} = \frac{Z^*_{wke}}{Z_{wke}} \cdot x1_{pril,wke} \tag{14}$$

↳ $x1_{pril,wke}$ – flow from *Agricultural and hunting products* to *Thermal hard coal* in the TPMD, thousand PLN;
Z_{wke} – number of persons employed in *Hard coal*, persons;
Z^*_{wke} – number of persons employed in *Hard coal*, the introduction of the Reduction Variant (WR25%, WR50%, WR75%, WR100%), persons.

- From *Agricultural and hunting products* to *Coking coal* ($x2_{pril,wkk}$):

$$x2_{pril,wkk} = \frac{Z^*_{wkk}}{Z_{wkk}} \cdot x1_{pril,wkk} \tag{15}$$

↳ $x1_{pril,wkk}$ – flow from *Agricultural and hunting products* to *Coking coal* in the TPMD, thousand PLN;
Z^*_{wkk} – number of persons employed in *Coking coal* after the Reduction Variant, persons;
Z_{wkk} – number of persons employed in *Coking coal*, persons.

- From *Agricultural and hunting products* to *Lignite* ($x2_{pril,wb}$):

$$x2_{pril,wb} = x1_{pril,wb} \tag{16}$$

↳ $x1_{pril,wb}$ – flow from *Agricultural and hunting products* to *Lignite* in the TPMD, thousand PLN.

Flows originating from *Hard coal*, *Crude oil and natural gas, metal ores, other mining products* and *Electricity, gas, steam, and hot water* are calculated as follows (excluding the coal-direction recipients):

- From *Hard coal* to *Agricultural and hunting products* ($x2_{wke,pril}$):

$$x2_{wke,pril} = \frac{W^*_{wke}}{\left(W^*_{wke} + W^*_{wkk} + W^*_{wb}\right)} \cdot x1_{wke,pril} + SEI_{wkeI,wke} \tag{17}$$

↳ W^*_{wke}, W^*_{wkk}, W^*_{wb} – quantities of *Hard coal*, *Coking coal*, and *Lignite* after reduction (WR25%, WR50%, WR75%, WR100%), Mg;

$x1_{wke,pril}$ – flow from *Thermal hard coal* to *Agricultural and hunting products* in the TPMD, thousand PLN;

$SEI_{wkeI,wke}$ – the monetary value of the total energy that must be imported for substitution for sector (sum over substitutes) $\left(\sum_s EI_{s,i}\right)$, in *Hard coal* sector thousand PLN, calculated as:

$$SEI_{s,i} = \sum_s \left(EI_{s,i} \cdot CI_s\right) \tag{18}$$

↳ $\sum_s EI_{s,i}$ – total amount of energy to be imported for substitution for sector *i*, GJ;

CI_s – price of the imported substitute *s*, thousand PLN/GJ.

- From *Crude oil and natural gas, metal ores, other mining products* to any branch ($x2_{rigz,j}$) as:

$$x2_{rigz,j} = \frac{W^*_{wke}}{\left(W^*_{wke} + W^*_{wkk} + W^*_{wb}\right)} \cdot x1_{rigz,j} + SEI_{gzI,j} \tag{19}$$

↳ $SEI_{gzI,j}$ – the monetary value of the total amount of energy that must be imported for substitution for all substitutes $\left(\sum_s EI_{s,j}\right)$ (in this case substitution by imported natural gas, in the branch *Crude oil and natural gas, metal ores, other mining products*), thousand PLN,

$x1_{rigz,j}$ – flow from *Crude oil and natural gas, metal ores, other mining products* from *TPMD*, tys. zł,

other symbols as in the formula (19).

- Flows from *Electricity, gas, steam, and hot water* are calculated for each branch ($x2_{eegipw,j}$) (as a sum):

$$x2_{eegipw,j} = \frac{W^*_{wke}}{\left(W^*_{wke} + W^*_{wkk} + W^*_{wb}\right)} \cdot x1_{eegipw,j} + SEI_{eeI,j} \tag{20}$$

↳ $SEI_{eeI,j}$ – monetary value of the total amount of energy that must be imported for substitution for all substitutes $\left(\sum_s EI_{s,i}\right)$ (in this case substitution by imported electricity) in the branch *Electricity, gas, steam, and hot water*, thousand PLN,

$x1_{eegipw,j}$ – flow from *Electricity, gas, steam, and hot water* from TPMD, thousand PLN,

other symbols as in the formula (17).

Flows from the branches: *Hard coal*, *Crude oil and natural gas, metal ores, other mining products,* and *Electricity, gas, steam, and hot water* to the coal directions are as follows:

- Flow from *Crude oil and natural gas, metal ores, other mining products* to the branch *Hard coal* ($x2_{rigz,wke}$):

$$x2_{rigz,wke} = \frac{W^*_{wke} \cdot e_{wke}}{\left(W^*_{wke} \cdot e_{wke} + W^*_{wkk} \cdot e_{wkk} + W^*_{wb} \cdot e_{wb}\right)} \cdot x1_{rigz,wke} \tag{21}$$

↳ W^*_{wke}, W^*_{wkk}, W^*_{wb} – quantities of *Hard coal*, *Coking coal*, and *Lignite* after reduction (WR25%, WR50%, WR75%, WR100%), Mg,

e_{wke} – energy intensity of hard coal, kWh/Mg,

e_{wkk} – energy intensity of coking coal, kWh/Mg,

e_{wb} energy intensity of lignite, kWh/Mg,

$x1_{rigz,wke}$ – flow from *Crude oil and natural gas, metal ores, other mining products* to the *Hard coal* branch in the TPMD, thousand PLN.

- Flow from *Crude oil and natural gas, metal ores, other mining products* to the branch *Coking coal* ($x2_{rigz,wkk}$):

$$x2_{rigz,wkk} = \frac{W^*_{wkk} \cdot e_{wkk}}{\left(W^*_{wke} \cdot e_{wke} + W^*_{wkk} \cdot e_{wkk} + W^*_{wb} \cdot e_{wb}\right)} \cdot x1_{rigz,wkk} \tag{22}$$

↳ $x1_{rigz,wkk}$ – flow from *Crude oil and natural gas, metal ores, other mining products* to the *Coking coal* branch in the TPMD, thousand PLN,
other symbols as in the formula (21).

- Flow from *Crude oil and natural gas, metal ores, other mining products* to the branch *Lignite* ($x2_{rigz,wb}$):

$$x2_{rigz,wb} = \frac{W^*_{wb} \cdot e_{wb}}{\left(W^*_{wke} \cdot e_{wke} + W^*_{wkk} \cdot e_{wkk} + W^*_{wb} \cdot e_{wb}\right)} \cdot x1_{rigz,wb} \tag{23}$$

↳ $x1_{rigz,wb}$ – flow from *Crude oil and natural gas, metal ores, other mining products* to the branch *Lignite* in the TPMD, thousand PLN,

other symbols as in the formula (21).

Flows from *Electricity, gas, steam, and hot water*:

- *Electricity, gas, steam, and hot water* to all branches except the coal branches:

$$x2_{eegipw,j} = x1_{eegipw,j} + SEI_{s,j} \tag{24}$$

↳ $x1_{eegipw,j}$ – flows from *Electricity, gas, steam, and hot water* in the *TPMD*, thousand PLN,

$SEI_{s,j}$ – the monetary value of the total amount of energy that must be imported for substitution for all substitutes $\left(\sum_s EI_{s,j}\right)$ (branch *Electricity, gas, steam, and hot water*), thousand PLN.

- *Electricity, gas, steam, and hot water* to the branch *Hard coal* ($x2_{eegipw,wke}$):

$$x2_{eegipw,wke} = \frac{W^*_{wke} \cdot e_{wke}}{\left(W^*_{wke} \cdot e_{wke} + W^*_{wkk} \cdot e_{wkk} + W^*_{wb} \cdot e_{wb}\right)} \cdot x1_{eegipw,wke} \tag{25}$$

↳ $x1_{eegipw,wke}$ – flow from *Electricity, gas, steam, and hot water* to the branch *Hard coal* branch in the TPMD, thousand PLN,

other symbols as in the formula (21).

- *Electricity, gas, steam, and hot water* to the branch *Coking coal* ($x2_{eegipw,wkk}$):

$$x2_{eegipw,wkk} = \frac{W^*_{wkk} \cdot e_{wkk}}{\left(W^*_{wke} \cdot e_{wke} + W^*_{wkk} \cdot e_{wkk} + W^*_{wb} \cdot e_{wb}\right)} \cdot x1_{eegipw,wkk} \tag{26}$$

↳ $x1_{eegipw,wkk}$ – flow from *Electricity, gas, steam, and hot water* to the branch *Coking coal* in the TPMD, thousand PLN,
other symbols as in the formula (21).

- *Electricity, gas, steam, and hot water* to the branch *Lignite* ($x2_{eegipw,wb}$):

$$x2_{eegipw,wb} = \frac{W^*_{wb} \cdot e_{wb}}{\left(W^*_{wke} \cdot e_{wke} + W^*_{wkk} \cdot e_{wkk} + W^*_{wb} \cdot e_{wb}\right)} \cdot x1_{eegipw,wb} \tag{27}$$

↳ $x1_{eegipw,wb}$ – flow from *Electricity, gas, steam, and hot water* to the branch *Lignite* in the TPMD, thousand PLN,

other symbols as in the formula (21).

Part III of the input–output tables

Taking into account the reference part of the table related to the amount of taxes paid, the following assumptions were made for particular payments (excluding *Coal branches*):

- Taxes on products less subsidies on products – *PPdp*2 – remain unchanged, because the volume of production in the branch does not change; it remains at a constant level (although the cost of production changes). Therefore, the value of product-related taxes will remain at the same level, equal to the value in the Decomposed Input–Output Table (TPMD).
- Employment-related costs – *KZ*2 – remain unchanged, because it is assumed that when the production technology shifts from coal-based to substitution-based, employment remains constant, and therefore, employment-related costs also remain constant. Their value corresponds to the value in the TPMD.
- Other taxes less subsidies on production – *POPdp*2 – are assumed to remain unchanged, similarly to taxes on products less subsidies on products. They depend on the volume of production, which remains constant. The value corresponds to the value in the TPMD.
- Depreciation of fixed assets – *AM*2 – this value changes compared to the TPMD. Depreciation is calculated on the basis of investment outlays. However, the depreciation amount also depends on the lifetime of the installation – the longer the lifetime, the lower the annual depreciation. All this was taken into account when calculating the depreciation value. The explanation of how *Depreciation* (AM) was calculated in the Input–Output Table after applying the substitution model is presented below. Thus, *Depreciation* after applying the substitution model is calculated as follows:

$$AM2_i = AM1_i + KN_{gz,i} + KN_{ee,i} \tag{28}$$

and

$$KN_{gz,i} = \frac{\frac{EI_{gzI,i}}{3.6}}{t_{gz}} \cdot \frac{IN_{gz}}{LT_{gz}} \tag{29}$$

$$KN_{ee,i} = \frac{\frac{EI_{eeI,i}}{3.6}}{t_{ee}} \cdot \frac{IN_{ee}}{LT_{ee}} \tag{30}$$

↳ $AM1_i$ – value of *Depreciation* from the TPMD, thousand PLN,
$KN_{gz,i}$ – annual investment cost for technology supplied with the energy carrier (fuel) *s* – natural gas for branch *i*, thousand PLN,
IN_{gz} – unit investment outlay for transition to natural gas technology, thousand PLN/MW,

LT_{gz} – lifetime of gas technology, years,
$KN_{ee,i}$ – annual investment cost for technology supplied with the energy carrier (fuel) s – electricity for branch i, thousand PLN,
IN_{ee} – unit investment outlay for transition to electricity-based technology, thousand PLN/MW,
LT_{ee} – lifetime of electricity-based technology, years,
other symbols as in formulas (10, 12).

- *Net operating surplus* (*NOn*2) – this value changes compared to the Decomposed Input–Output Table. It is calculated as:

$$NOn2_j = \left(NOn1_j - \left(\sum_s KoEI_{s,j} + x2_{wke,j} - x1_{wke,j} \right) \right) \cdot \frac{RP1_j + \Delta RP_j}{RP1_j} \tag{31}$$

and

$$\Delta RP_j = RP2_j - RP1_j \tag{32}$$

$\sum_s KoEI_{s,j}$ – cost of the total amount of energy that must be imported for substitution for all substitutes (s), for branch j, thousand PLN/year,
$x1_{wke,j}$ – flow from the *Hard coal* branch to branch j from the TPMD, thousand PLN,
$x2_{wke,j}$ – flow from the *Hard coal* branch to branch j after applying the Reduction Variant and the Substitution Variant, thousand PLN,
$NOn1_j$ – *Net operating surplus* in the *TPMD*, thousand PLN,
$RP2_j$ – *Total products* after applying the Reduction Variant and the Substitution Variant, thousand PLN,
$RP1_j$ – *Total products* in the *TPMD*, thousand PLN.

The results of import structures for the substitution variant WS2 are presented in the following Figure 3.

Conclusions

The conducted analysis confirmed that the proposed substitution model, based on input–output tables, is an effective tool for examining the consequences of the energy transition in Poland. The model consistently integrates the techno-energetic perspective with macroeconomic accounting. This made it possible to capture both the direct effects of the reduction in the supply of domestic hard coal and the economic consequences of applying different substitution pathways.

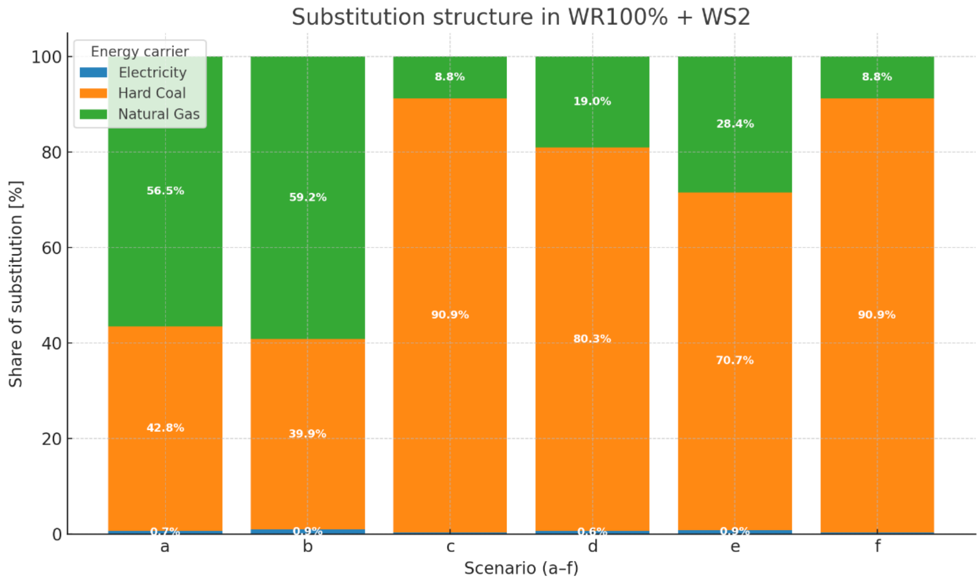

Fig. 3. Percentage share of substitution of energy from hard coal for Reduction Variant (WR100%), Migration Variant (WM), and Substitution Variant (WS2)
a) reduction of natural gas price by 40%, price of imported coal equal to the reference price (cwr),
b) reduction of natural gas price by 40%, price of imported coal higher by 40% than the reference price,
c) reduction of natural gas price by 40%, price of imported coal lower by 40% than the reference price,
d) increase of natural gas price by 40%, price of imported coal equal to the reference price,
e) increase of natural gas price by 40%, price of imported coal higher by 40% than the reference price,
f) increase of natural gas price by 40%, price of imported coal lower by 40% than the reference price
Source: author's own elaboration

Rys. 3. Procentowy udział zastąpienia energii z węgla kamiennego energetycznego dla Wariantu Redukcji WR100%, Wariantu Migracji i Wariantu Substytucji WS2
a) zmniejszenie ceny gazu ziemnego o 40%, cena węgla z importu równa referencyjnej (cwr),
b) zmniejszenie ceny gazu ziemnego o 40%, cena węgla z importu wyższej o 40% od referencyjnej,
c) zmniejszenie ceny gazu ziemnego o 40%, cena węgla z importu niższej o 40% od referencyjnej,
d) zwiększenie ceny gazu ziemnego o 40%, cena węgla z importu jest równa cenie referencyjnej,
e) zwiększenie ceny gazu ziemnego o 40%, cena węgla z importu wyższej o 40% od referencyjnej,
f) zwiększenie ceny gazu ziemnego o 40%, cena węgla z importu niższej o 40% od referencyjnej

The results of the calculations clearly indicate that the substitution structure is strongly dependent on the price relationship between imported coal and natural gas. In a situation of low natural gas prices, it is gas that assumes the dominant role in balancing the deficit, whereas in the case of cheaper imported coal, coal retains the advantage. Electricity imports, due to high unit costs and infrastructural constraints, remain a marginal factor. The final fuel mix is shaped not only by prices but also by the limitations of import capacity and the technological possibilities of power units.

From the perspective of energy policy, these conclusions confirm the importance of flexibility in import infrastructure – both for coal and gas – as well as the necessity of designing solutions that can reduce the risks associated with price volatility on global markets. At the same time, the analysis reveals that the current cost and technological parameters are not conducive to deeper electrification of industrial and heating processes. If such a transformation pathway is desired, additional investment incentives and support for innovative technologies are required.

An important direction for further research is the expansion of the substitution model to include additional energy carriers – in particular biomass, waste, and hydrogen – which in the longer term may play a stabilizing role in the energy balance and enhance supply security. Including these carriers would allow for better representation of realistic energy transition scenarios, especially in the context of the growing role of renewable sources and local energy resources.

In conclusion, the modelling of hard coal substitution within the framework of input–output tables not only provides a quantitative assessment of potential substitution pathways but also highlights their implications for the stability of the Polish energy market. By linking reductions in hard coal supply with realistic options for replacement, the model demonstrates how the Polish economy may respond to structural changes in energy availability. This approach offers a robust analytical basis for policymakers and industry stakeholders to anticipate the consequences of coal phase-out and to design strategies that ensure both energy security and economic resilience.

The Author has no conflicts of interest to declare.

This work was carried out as part of the statutory activity of the Mineral and Energy Economy Research Institute of the Polish Academy of Sciences.

REFERENCES

ARE 2023 – *Electricity statistics* (*Statystyka elektroenergetyki*). Warszawa (*in Polish*).

ARP 2023b – *Basic information about the hard coal market and sector in Poland in 2010–2022* (*Podstawowe informacje o rynku oraz sektorze węgla kamiennego w Polsce w latach 2010–2022*). Katowice (*in Polish*).

Businessinsider 2022 – *PGNiG will invest PLN 700 million in two oil and gas mines and extend production* (*PGNiG zainwestuje 700 mln zł w dwie kopalnie ropy i gazu i przedłuży wydobycie*). [Online:] https://businessinsider.com.pl/ [Accessed: 2022-06-07] (*in Polish*).

Chmielarz, P. 2023. *Natural gas supply security policy in Poland in 2017–2021 against the background of the European Union energy security strategy* (Doctoral dissertation) (*Polityka bezpieczeństwa dostaw gazu ziemnego w Polsce w latach 2017–2021 na tle strategii bezpieczeństwa energetycznego Unii Europejskiej (Rozprawa doktorska)*) (*in Polish*).

Grupa Orlen 2023a – *Orlen Group 2023* (*Grupa Orlen 2023*). [Online:] https://www.orlen.pl/ [Accessed: 2024-01-01].

Grupa Orlen 2023b – ORLEN focuses on safety – the largest investment in domestic gas storage facilities begins (*ORLEN stawia na bezpieczeństwo – rusza największa inwestycja w krajowe magazyny gazu*) [Online:] https://tiny.pl/d738z [Accessed: 2023-08-31] (*in Polish*).

GUS 2019 – *Input-output balance at current basic prices in 2015* (*Bilans przepływów międzygałęziowych w bieżących cenach bazowych w 2015 r.*). Warszawa (*in Polish*).

GUS 2022a – *Household Energy Consumption in 2021. Signal Information* (*Zużycie energii w gospodarstwach domowych w 2021 r. Informacje sygnalne*). Warszawa (*in Polish*).

GUS 2023b – *Energy efficiency 2011–2021* (*Efektywność wykorzystania energii w latach 2011–2021*). Warszawa–Rzeszów (*in Polish*).

Hebda, W. 2022. *Natural gas in the process of decarbonizing the Polish energy sector* (*Gaz ziemny w procesie dekarbonizacji polskiej energetyki*). Analiza KBN Nr 2(97), 2(2), pp. 1–5 (*in Polish*).

IEA 2020 – International Energy Agency and Nuclear Energy Agency (2020). Projected Costs of Generating Electricity.

Ogrzewamy 2023 – *Calorific value* (*Wartość opałowa*). [Online:] https://tiny.pl/dr727 [Accessed: 2023-10-25] (*in Polish*).

Olczak, P. and Matuszewska D. 2023. Energy Storage Potential Needed at the National Grid Scale (Poland) in Order to Stabilize Daily Electricity Production from Fossil Fuels and Nuclear Power. *Energies* 16(16), DOI: 10.3390/en16166054.

Pepłowska, M. 2024. The effect of coal mine closures on worker migration in Poland: an input-output analysis. *Gospodarka Surowcami Mineralnymi – Mineral Resources Management* 40(4), DOI: 10.24425/gsm.2024.152721.

PGNiG 2022 – *PGNiG Annual Report 2022* (*PGNiG Raport roczny 2022*). [Online:] https://pgnig2021.pl/ [Accessed: 2023-02-02] (*in Polish*).

PIG-PIB 2022 – *Natural gas* (*Gaz ziemny*). [Online:] https://www.pgi.gov.pl/surowce/energetyczne/gaz-ziemny.html 05.05.2023) (*in Polish*).

PSE 2022 – *Production resources 2022* (*Zasoby wytwórcze 2022*). [Online:] https://www.pse.pl/kariera/-/asset_publisher/jDMkkGMtSFLd/document/id/3075175474/exclusive [Accessed: 2023-03-13] (*in Polish*).

Sobczyk-Grygiel, S. 2022. *We can extract more gas* (*Możemy wydobywać więcej gazu*). [Online:] https://serwisy.gazetaprawna.pl/edukacja/artykuly/8528962,wydobycie-gazu-2023.html [Accessed: 2023-10-25] (*in Polish*).

Szurlej i in. 2015 – Szurlej, A., Ruszel, M. and Olkuski. T. 2015. Will natural gas be competitive fuel? (*Czy gaz ziemny będzie paliwem konkurencyjnym?*). *Rynek Energii* 5 (*in Polish*).

Śliwa, R. 2012. Sunk costs in telecommunications (*Koszty utopione w działalności telekomunikacyjnej*). *Telekomunikacja i Techniki Informacyjne*, pp. 10–17 (*in Polish*).

Tarnawska, K. 2014. Theoretical Analysis of Regional Development Determinants in the Light of Evolutionary Economic Geography (*Analiza determinant rozwoju regionalnego w świetle ewolucyjnej geografii ekonomicznej*). *Prace Naukowe Uniwersytetu Ekonomicznego we Wrocławiu* 367, DOI: 10.15611/pn.2014.367.38.

TGE 2023 – *Polish Power Exchange. Market data* (*Towarowa Giełda Energii. Dane rynkowe*). [Online:] https://tge.pl/ [Accessed: 2023-02-01] (*in Polish*).

URE 2023 – *Thermal energy in numbers – 2022* (*Energetyka cieplna w liczbach – 2022*). Warszawa (*in Polish*).

Vinet, L. and Zhedanov, A. 2011. A “missing” family of classical orthogonal polynomials. *Journal of Physics A: Mathematical and Theoretical* 44(8), DOI: 10.1088/1751-8113/44/8/085201.

MODELLING THE SUBSTITUTION OF HARD COAL IN INPUT–OUTPUT TABLES: IMPLICATIONS FOR THE POLISH ENERGY MARKET

Keywords

hard coal, decarbonization, energy transition, substitution model, input–output tables

Abstract

The article presents a model for substituting hard coal in the Polish energy market based on input–output tables. The study addresses the crucial issue of how the gradual reduction in domestic hard coal supply can be compensated for through alternative energy carriers. The proposed model combines techno-economic parameters with inter-industry flows, allowing the simultaneous assessment of technical feasibility, cost structures, and macroeconomic consequences of substitution.

Several Reduction Variants (25%, 50%, 75% and 100%) were analyzed together with Substitution Variants, covering imported coal, natural gas, and electricity under diverse price scenarios. Import capacity limits, conversion efficiencies, and investment and operating costs were explicitly included, which makes the results not only technically possible but also economically meaningful.

The results show that substitution structures are highly sensitive to price relations between imported coal and natural gas. When gas prices are low, natural gas dominates as the main substitute. Conversely, when imported coal is cheaper, coal retains its advantage. Electricity imports, due to high unit costs and limited infrastructure, play only a marginal role. Beyond the energy balance, the model also reflects changes in depreciation, net operating surplus, and tax flows, thereby capturing the broader economic impact. The findings underline the importance of flexible import infrastructure and reducing exposure to international price volatility.

MODELOWANIE SUBSTYTUCJI WĘGLA KAMIENNEGO Z WYKORZYSTANIEM TABLIC PRZEPŁYWÓW MIĘDZYGAŁĘZIOWYCH: IMPLIKACJE DLA POLSKIEGO RYNKU ENERGII

Słowa kluczowe

węgiel kamienny, dekarbonizacja, transformacja energetyczna, model substytucji, tablice przepływów międzygałęziowych

Streszczenie

W artykule przedstawiony jest model substytucji węgla kamiennego energetycznego na rynku energii w Polsce, oparty na tablicach przepływów międzygałęziowych. Badanie podejmuje kluczowy problem kompensacji stopniowego ograniczania krajowej podaży węgla poprzez alternatywne nośniki energii. Proponowany model łączy parametry techniczno-ekonomiczne z powiązaniami międzygałęziowymi, co umożliwia jednoczesną ocenę wykonalności technicznej, struktur kosztowych oraz konsekwencji makroekonomicznych procesów substytucji.

Analizie poddano kilka Wariantów Redukcji (25%, 50%, 75% i 100%) w połączeniu z Wariantami Substytucji obejmującymi importowany węgiel, gaz ziemny i energię elektryczną w różnych scenariuszach cenowych. W modelu uwzględniono ograniczenia przepustowości importowej, sprawności konwersji oraz nakłady inwestycyjne i koszty operacyjne, dzięki czemu uzyskane wyniki są nie tylko technicznie możliwe, lecz także ekonomicznie uzasadnione.

Wyniki wskazują, że struktury substytucji są silnie zależne od relacji cenowych między importowanym węglem a gazem ziemnym. Przy niższych cenach gazu to on dominuje jako główny substytut, natomiast w sytuacji tańszego węgla przewagę utrzymuje węgiel. Import energii elektrycznej, ze względu na wysokie koszty jednostkowe i ograniczoną infrastrukturę, odgrywa jedynie marginalną rolę. Poza bilansem energetycznym model odzwierciedla także zmiany w amortyzacji, nadwyżce operacyjnej i przepływach podatkowych, ujmując szerszy wymiar gospodarczy.

Wyniki podkreślają znaczenie elastycznej infrastruktury importowej oraz konieczność ograniczania ryzyk związanych ze zmiennością cen światowych.