Mariusz **KUDEŁKO**

# ARE EU ENVIRONMENTAL REGULATIONS CONSISTENT WITH THE CONCEPT OF INTERNALISATION OF EXTERNALITIES – THE CASE OF THE POLISH ELECTRICITY SECTOR

Mariusz **Kudełko** (ORCID: 0000-0002-4651-3165)
*AGH University of Science and Technology, Krakow*

Correspondence address:
Mickiewicza Street 30, 30-059 Krakow, Poland
e-mail: mkudelko@zarz.agh.edu.pl

ABSTRACT: The article's goal is to examine whether the existing EU environmental regulations implemented in the Polish electricity sector are consistent with the concept of internalisation of external costs. The tool used in the research is the partial equilibrium model of the mid-term development of the Polish power sector. There are two scenarios. The first 'base' scenario assumes gradual decarbonisation of the Polish energy sector. In the 'int' scenario, the structure of energy production results from the full internalisation of external costs. The structural changes in the 'base' scenario are a significant challenge. All coal-based technologies are being drastically phased out and will be replaced by RES and nuclear technologies. The climate policy leading to a gradual reduction of $CO_2$ emissions in Poland makes sense, assuming much higher external costs of $CO_2$ emissions (€65/Mg $CO_2$) than those assumed in this study.

KEYWORDS: electricity sector, externalities, energy mix, model

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## Introduction

Negative externalities provide a sufficient ground to justify government intervention to eliminate market distortions. The aim of this intervention should be to set a price for environmental use that allows getting the social optimum. The theoretical basis for this type of intervention was presented and developed by Pigou (1932). There are a number of classical works dealing with this issue (Baumol et al., 1988; Dales, 2002; Pearce et al., 1990). It has been proven there that the inclusion of external costs in the decision-making process is necessary to achieve a social optimum. This theoretical consequences of market failure are particularly evident in the case of energy sectors, where environmental impact is noticeable. The energy markets are typical examples of market failures in terms of negative externalities. Hence, the long-term development of energy sectors for increasingly stringent environmental constraints is intensively studied.

The aim of the article is to examine whether the existing EU environmental regulations implemented in the Polish electricity sector are consistent with the concept of internalisation of external costs, and whether their implementation is efficient. In the case of Poland, this applies in particular to coal-based technologies, which are a major source of environmental threats. In the case of PM, $SO_2$ or $NO_x$ emissions, the domestic power plants deals with them in a highly effective manner. Power plants are equipped with flue-gas desulfurization (FGD) and selective catalitical reduction (SCR) technologies. What is more, these methods are efficient as well, as their abatement costs are significantly lower than external costs due to the deposition of air pollutants (Dimitrijevic et al., 2012; Wu, 2001; Devitt et al., 2012; Marano et al., 2006). Here, the EU regulations such as emissions standards for individual power plants (for example the Industrial Emissions Directive (IED) or Best Available Technology (BAT) directive) are effective and efficient instruments of environmental policy. On the other hand, the current EU climate policy focuses on the complete reduction of $CO_2$ emissions. This raises the question of whether a full decarbonisation policy is sensible and economically justified? Are the costs of structural changes in electricity generation justified by the environmental benefits of $CO_2$ reduction. The author intends to analyse this issue based on his own mid-term development model of the Polish electricity sector.

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## An overview of the literature

Studies concerning the external costs of the energy sectors focuses on the methods of their valuation and potential internalisation through a set of economic instruments. The first group of studies tries to assess the negative impact arising from fossil fuel-fired power plant's air emissions and the damages related to global warming effects, human health, ecosystems, crops, materials and forests (Bickel et al., 2005; *New Energy…,* 2009; Jori et al., 2018; Hall, 2004). They also provide theoretical and methodological backgrounds of their assessment (Samadi, 2017; Kim, 2007). The results are used by policy makers to take measures to avoid additional costs and to apply newer and cleaner energy sources, which is directly linked to the issue of the internalisation of external costs.

There are numerous studies that examine the impact of internalisation of externalities on the structure of energy production, which can be found in (Rentizelas et al., 2014; Klaassen et al., 2007; Fahlén et al., 2010; Rafaj et al., 2007). All of them illustrate the same effect: faster retirement of fossil fuel-fired power plants and an increase of RES share. These studies are ongoing for the energy sectors of several countries, including Greece (Georgakellos, 2010), Croatia (Borozan et al., 2015), China (Chen et al., 2016) and Iran (Ghoddousi et al., 2021). They prove that if production costs reflect all the negative effects, the structure of energy production changes significantly. Other studies concern the effectiveness of environmental policy tools. They indicate that market-based instruments are not effective in internalizing of external costs (Maca et al., 2012). Research on the impact of internalization of external costs on the structure of electricity production in Poland can be found as well in Kudełko (2006) and Juroszek et al. (2016).

Mathematical modelling is a standard method used in the mid- and long-term development of energy sectors. Different types of energy models have been developed for various policy and planning concerns. The so-called "bottom-up" modelling approach is focused mainly on micro-level technological issues and does not capture important macroeconomic inter-links within the economy. These models are mainly concentrated on least-cost energy planning with reference to environmental constraints. They are limited to policy goals since they do not analyse the effects of price changes on other markets. Examples are PRIMES, LEAP, POLES, MARKAL/TIMES, MILP, MESSAGE, EFOM-ENV and other models. Description and specification of these models, including classification schemes used for bottom-up energy system modelling, their resolution in time, in space, in techno-economic detail and in sector-coupling are provided in (Prina et al., 2020).

A model-based approach is also commonly used for the long-term development of the Polish energy sector (Departament Analiz Strategicznych, 2015; Wierzbowski et al., 2017). The growing challenges related to decarbonisation impose a new perspective for new energy technologies. This issue is reflected in recent papers such as (*Risk associated…,* 2018; Gajowiecki, 2019; Engel et al., 2020; Wyrwa et al., 2022). Some of the works concerns the rationality and costs of full decarbonisation of energy sectors (Hübler et al., 2013; Capros et al., 2012), also in Poland (Kiuila, 2018). Part of them provide a strong support for the implementation of decarbonisation scenario (Sofia et al., 2020), however, there are other surveys as well (Tol, 2021). The author reviews the targets set by the European Union, discusses the costs and benefits of greenhouse gas emission reduction and concludes that the benefits of the European Union's climate policy do not outweigh its costs.

## Research methods

The concept of negative external effects and the economic consequences for an electricity market is presented on Figure 1. MPC (marginal private costs) represents individual electricity producers using different energy technologies with different generation costs. MSC (marginal social costs) is a function that includes the additional external cost of electricity production. The demand function represents energy consumers, i.e. economic sectors and households. If there are negative externalities, marginal social cost (MSC) is higher than the private cost of production (MPC) at the size of external costs (MEC). If producers do not include external costs in their cost calculations, the market supply function reflects only private costs (MPC). Market equilibrium is achieved at the price of $P_1$ and the production volume of $Q_1$. However, if a producer paid for the negative effects, the equilibrium point would be different – P* and Q*. Consequently, the negative externalities causes an overproduction of $Q_1$ – Q*.

The economic consequences for producers (producers surplus), consumers (consumers surplus), and the environment (external costs) of both cases are as follows. Net social welfare is the sum of consumer and producer surpluses minus external costs. If the volume of production is Q*, and the product is sold at a market price P*, net social welfare would increase by field M. Of course, it creates serious distribution effects. Consumers would suffer losses in the sum of fields B, G, K, whereas the situation of producers would improve by the total of fields B+G–N. Environmental costs would decrease by the sum of fields M+N+K. This type of price regulation limits the level of production to a socially optimal volume. Of course, energy producers can take other adaptation measures, such as using abatement technologies to reduce emissions. In this case, price intervention will reduce the negative impact to an optimal level without reducing energy production. Which strategy is chosen depends on which is more cost-effective for them.

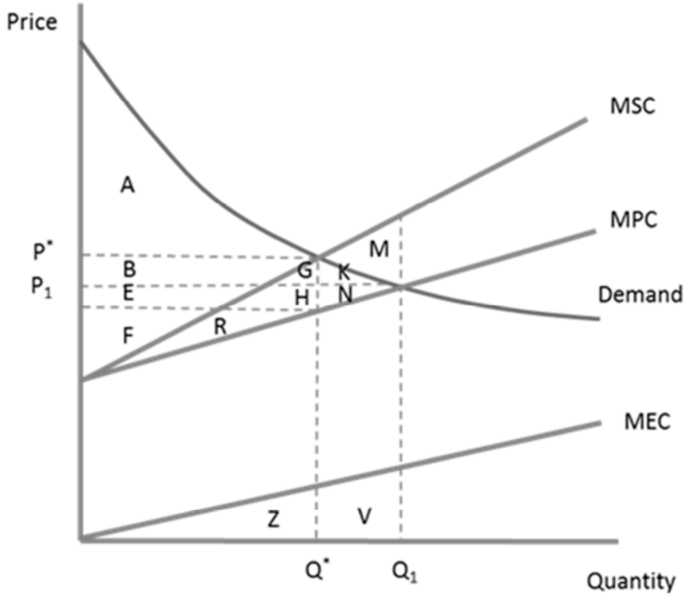

**Figure 1.** Negative externalities
Source: author's work.

The EU environmental policy, for various reasons, tends to avoid the use of price instruments (environmental taxation) in the energy sectors. It primarily uses direct tools (quotas – e.g. RES share; limits – $CO_2$ level; emissions standards – IED directive). However, the question is whether both types of regulation are coherent and whether they guarantee to meet the same environmental goals. This question is explored below.

The tool used is the partial equilibrium model of the mid-term development of the Polish electricity sector. It is a tool that allows analysing different scenarios of the electricity sector development. The model can apply both mentioned environmental adaptation strategies. The first one is reducing electricity production due to the increase in energy prices (demand reaction). The second one enables the use of abatement technologies or switching generation technologies. Both strategies allow compliance with imposed direct or indirect environmental regulations.

**Table 1.** Energy technologies characteristics

| Technology | net efficiency electr., effG [%] | load factor, lfG [h] | cogeneration factor, cogfG | capacity installed, cbM [MW] | investment costs, icG,t [€/kW] | fixed costs – electr., fcG,t [€/kW] | fixed costs –heat, fcG,t [€/kW] | variable costs – electr., vcG,t [€/GJ] | variable costs – heat, vcG,t [€/GJ] | emissions coefficient PM, efG [g/GJ] | emissions coefficient $SO_2$, efG [g/GJ] | emissions coefficient NOx, efG [g/GJ] | emissions coefficient $CO_2$, efG [kg/GJ] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| System power plants: | | | | | | | | | | | | | |
| Hard coal-fired power plants – life extension | 40 | 3565 | 0.92 | 10000 | 0 | 37 | 37 | 0.8 | 0.9 | 40 | 241 | 223 | 188 |
| Hard coal public power plants – simple modern. | 40 | 3565 | 0.92 | 0 | 160 | 37 | 37 | 0.8 | 0.9 | 40 | 241 | 223 | 188 |
| Hard coal public power plants – simple modern. + gas turbine | 40 | 3565 | 0.92 | 0 | 280 | 37 | 37 | 0.8 | 0.9 | 32 | 195 | 180 | 162 |
| Hard coal public power plants – FBC | 45 | 3565 | 0.92 | 0 | 950 | 37 | 37 | 0.8 | 0.9 | 40 | 24 | 76 | 188 |
| Hard coal-fired power plants – simple modern. with biomass co-firing | 38 | 3565 | 0.92 | 0 | 160 | 37 | 37 | 0.8 | 0.9 | 40 | 241 | 223 | 169 |
| Hard coal-fired power plants – biomass co-firing | 38 | 3565 | 0.92 | 8036 | 0 | 47 | 37 | 0.8 | 0.9 | 40 | 241 | 223 | 169 |
| Lignite-fired power plants – life extension | 38 | 5607 | 0.97 | 5500 | 0 | 47 | 37 | 0.9 | 0.9 | 43 | 256 | 224 | 197 |
| Lignite-fired power plants – simple modern. | 39 | 5607 | 0.97 | 0 | 160 | 47 | 37 | 0.9 | 0.9 | 43 | 256 | 224 | 197 |
| Lignite-fired power plants – simple modern. + gas turbine | 39 | 5607 | 0.97 | 0 | 280 | 47 | 37 | 0.9 | 0.9 | 35 | 207 | 180 | 169 |
| Lignite-fired power plants – FBC | 45 | 5607 | 0.97 | 0 | 950 | 47 | 37 | 0.9 | 0.9 | 43 | 26 | 76 | 197 |
| Lignite-fired power plants – simple modern. with biomass co-firing | 37 | 5607 | 0.97 | 0 | 160 | 47 | 37 | 0.9 | 0.9 | 43 | 256 | 224 | 177 |
| Lignite-fired power plants – biomass co-firing | 35 | 5607 | 0.97 | 3252 | 0 | 58 | 37 | 0.9 | 0.9 | 43 | 256 | 224 | 177 |
| Hydropower plants – life extension | 70 | 938 | 1 | 2341 | 0 | 65 | 0 | 0.5 | 0.0 | 0 | 0 | 0 | 0 |
| Wind turbines power plants – life extension | 40 | 1806 | 1 | 6621 | 0 | 30 | 0 | 0.1 | 0.0 | 0 | 0 | 0 | 0 |
| New coal-fired power plants | 46 | 6200 | 0.97 | 0 | 1400 | 37 | 37 | 0.9 | 0.9 | 40 | 40 | 74 | 188 |
| New lignite-fired power plants | 46 | 6200 | 0.97 | 0 | 1380 | 47 | 37 | 0.9 | 0.9 | 43 | 40 | 75 | 197 |
| New IGCC power plants | 47 | 6200 | 0.96 | 0 | 1860 | 37 | 37 | 0.4 | 0.4 | 36 | 2 | 74 | 169 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| New gas turbines power plants | 40 | 4100 | 0.96 | 0 | 470 | 19 | 19 | 0.2 | 0.2 | 39 | 3 | 75 | 58 |
| New CCGT power plants | 60 | 4100 | 0.96 | 0 | 770 | 19 | 19 | 0.2 | 0.2 | 0 | 10 | 6 | 58 |
| New biomass power plants | 36 | 6200 | 0.97 | 0 | 1440 | 70 | 37 | 0.5 | 0.5 | 0 | 10 | 6 | 100 |
| New biogas power plants | 40 | 4100 | 0.97 | 0 | 1440 | 93 | 0 | 0.5 | 0.0 | 20 | 80 | 80 | 58 |
| New PV power plants | 14 | 2000 | 1 | 0 | 1700 | 19 | 0 | 0.1 | 0.0 | 0 | 10 | 6 | 0 |
| New nuclear power plants | 36 | 6200 | 1 | 0 | 4400 | 93 | 0 | 0.5 | 0.0 | 0 | 0 | 0 | 0 |
| New hydropower power plants | 70 | 2000 | 1 | 0 | 2300 | 58 | 0 | 0.5 | 0.0 | 0 | 0 | 0 | 0 |
| New wind turbines power plants – offshore | 40 | 2100 | 1 | 0 | 1600 | 26 | 0 | 0.1 | 0.0 | 0 | 0 | 0 | 0 |
| New wind turbines power plants – onshore | 40 | 4000 | 1 | 0 | 3000 | 93 | 0 | 0.1 | 0.0 | 0 | 0 | 0 | 0 |
| District CHP plants: | | | | | | | | | | | | | |
| Hard coal-fired CHP plants – life extension | 55 | 3495 | 0.33 | 4000 | 0 | 37 | 37 | 0.8 | 0.9 | 40 | 241 | 223 | 188 |
| Hard coal-fired CHP plants – biomass co-firing | 55 | 3495 | 0.33 | 1179 | 0 | 58 | 37 | 0.8 | 0.9 | 40 | 241 | 223 | 169 |
| Gas turbine CHP plants – life extension | 62 | 4100 | 0.71 | 2330 | 0 | 65 | 19 | 0.2 | 0.2 | 0 | 10 | 6 | 58 |
| Hard coal-fired CHP plants – simple modern. | 57 | 3495 | 0.33 | 0 | 160 | 37 | 37 | 0.8 | 0.9 | 40 | 241 | 223 | 188 |
| Hard coal-fired CHP plants – simple modern. + gas turbine | 55 | 3495 | 0.33 | 0 | 280 | 37 | 37 | 0.8 | 0.9 | 32 | 195 | 180 | 162 |
| Hard coal-fired CHP plants – FBC | 61 | 3495 | 0.33 | 0 | 950 | 37 | 37 | 0.8 | 0.9 | 40 | 24 | 76 | 188 |
| Hard coal-fired CHP plants – simple modern. with biomass co-firing | 55 | 3495 | 0.33 | 0 | 160 | 37 | 37 | 0.8 | 0.9 | 40 | 241 | 223 | 169 |
| New coal-fired CHP plants | 56 | 4200 | 0.33 | 0 | 1400 | 37 | 37 | 0.8 | 0.9 | 40 | 40 | 74 | 188 |
| New gas turbines CHP plants | 40 | 4100 | 0.33 | 0 | 470 | 19 | 19 | 0.2 | 0.2 | 0 | 10 | 6 | 58 |
| New CCGT CHP plants | 60 | 4100 | 0.33 | 0 | 770 | 19 | 19 | 0.2 | 0.2 | 0 | 10 | 6 | 58 |
| New oil CHP plants | 60 | 4100 | 0.33 | 0 | 770 | 19 | 19 | 0.2 | 0.2 | 54 | 70 | 63 | 149 |

Note: Industry CHP plants and municipal heat plants are not presented here. The net efficiency, load factor, cogeneration factor, capacity installed, and emissions coefficients for the existing energy technologies were estimated based on public energy statistics (The Energy Market Agency, 2019; 2019a; 2019b; 2019c; Polish Statistics, 2019).

Source: author's work.

The demand side is represented by the leading electricity and heat consumers, i.e. industry and construction, transport, agriculture, trade and services, and individual consumers. The goal of the model is to find the structure of energy production that will be optimal from traditionally perceived production costs or in a broader social context. So, the first approach assumes to achieve the cost-efficiency condition, i.e., satisfying the exogenously final energy demand at a minimal cost. The second approach is based on maximising social welfare, which is defined as the sum of consumer and producer surplus, less negative externalities produced by energy technologies. The last one was applied here. Table 1 presents the most important technical, economic and emissions parameters of all energy technologies implemented in the model.

The equations and the structure of the model are described in (Kudełko, 2020). The model is being upgraded to cover new environmental policy targets (new regulations), economic conditions (e.g. electricity demand, fuel prices) or technological changes (new technologies, investment costs decrease, conversion efficiencies, etc.). This version of the model is recalibrated to the latest production, economic and environmental data of the Polish energy sector. The module for sensitivity analysis has been introduced to recalculate risk parameters, such as $CO_2$ reduction targets, the price of $CO_2$ allowances and the costs of nuclear and RES technologies. Furthermore, the rate of implementation of new investments in RES and nuclear sources were updated, which allowed for a more detailed calculation of the optimal structure of energy generation. This made it possible to look at the RES structure again and examine these technologies, which did not work in the previous version.

The external costs estimates of air pollutants are based on (Kudełko, 2009) and (*New Energy…*., 2009). The Polish statistics are very incomplete, and an extreme effort is needed to calibrate the model to actual economic and production parameters. Therefore, own estimations were required to calculate the production, cost and emission parameters for the existing energy technologies. Generally, the model assumptions (i.e. demand forecasts, fuel prices, investment and operating costs of energy technologies, energy fuel supply data, etc.) correspond to the deductions taken from the official Polish documents (Ministry of Energy, 2021), domestic and foreign literature (Mrowiec, 2019; European Commission, 2020; Agencja Rynku Energii, 2016) and data published in the Polish energy statistics (see the Table 1 references).

Very few countries have set clear targets for the use of in power generation. Hydrogen also plays a minor role in the Polish electricity sector. Hence, due to the insufficient potential and lack of commercial applications – so far – in Poland, hydrogen has not been considered a competitive source of energy.

The first ‘base’ scenario assumes that all environmental regulations are met (i.e., limits on production from RES – the target is 30% RES in the electricity-generation structure, the Industrial Emissions Directive (IED) standards for individual power plants, and the EU emissions trading system (EU ETS) for $CO_2$ emissions). This scenario is generally consistent with the assumptions of the Polish Energy Policy (Energy policy…, 2021). Furthermore, a $CO_2$ reduction target of 35% in 2035 is set. The intention was to illustrate a much deeper $CO_2$ reduction and thus a policy of gradual decarbonisation of the energy sector. It can be said that in this scenario, external costs are internalised by environmental regulation, which is not necessarily optimal in terms of efficiency.

In the ‘int’ scenario, the structure of energy production is a result of the internalisation of external costs suggested by economic theory (Pigou, 1932; Coase, 1960; Pearce et al., 1990). Using the ExternE methodology (Bickel et al., 2005) and own study for Poland (Kudełko, 2009), external costs were assigned to particular types of pollutants (€11,000/Mg for PM10, €6,000/Mg for NOX, €7,000/Mg for $SO_2$, and €25/Mg for $CO_2$). There are no environmental regulations here at all; the reduction of emissions and volume of energy production from RES technologies results from optimisation. In this way, the environmental rules implemented in the ‘base’ scenario are verified from the point of view of their efficiency. The model was run on the GAMS software package using the SIPLEX solver. Model statistics are presented in Table 2.

**Table 2.** Model statistics

| Specification | Number |
|---|---|
| Block of equations | 26 |
| Single equations | 66 457 |
| Block of variables | 17 |
| Single variables | 1 221 505 |
| Non zero elements | 2 941 101 |

Source: author’s work.

## Results of the research

Figure 2 presents the results of the computer simulations. In the ‘base’ scenario, existing hard coal-based and lignite-fired power plants are being drastically phased out. New coal-fired unitsare not built but are being replaced by new CCGT power plants. New biomass, biogas, and PV power plants (on a small scale), and mostly wind turbines (both offshore and onshore), fulfil the RES and $CO_2$ limits. The latter is to be the primary source of ‘green’ energy to meet the growing demand for electricity after 2030. Nuclear power is an efficient source of electricity after 2030, and it assures meet the required reduction of $CO_2$ emissions. Generally, the results correspond pretty well to the forecasts given in the official governmental documents (Energy policy…, 2021). The structure of electricity production from coal, RES and gas power plants is very similar in both studies. Nuclear power is being developed on a slightly larger scale due to a faster decarbonisation rate. These results are also comparable to (Departament Analiz Strategicznych, 2015) and (*Risk*…, 20018), which assumes a similar $CO_2$ reduction path.

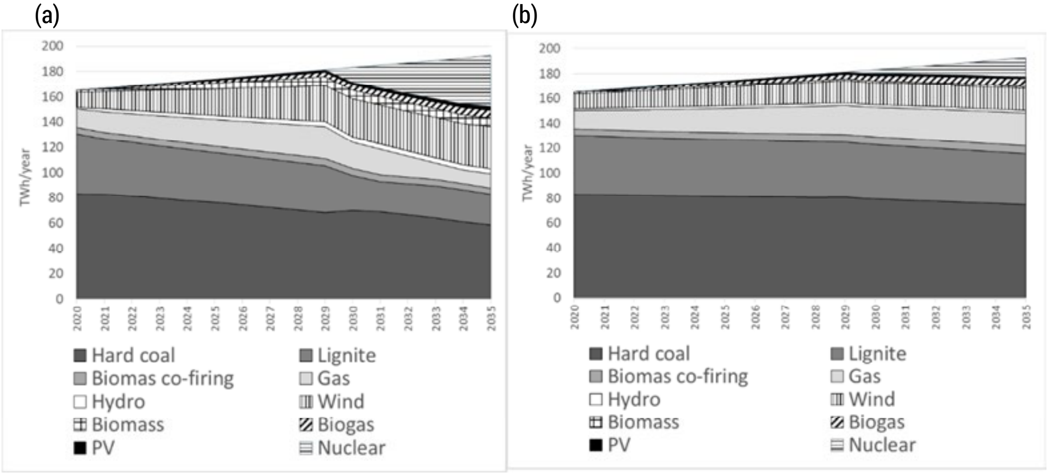

**Figure 2.** The structure of electricity production, TWh/year; (a) – ‘base’ scenario, (b) – ‘int’ scenario

Source: author’s work.

In the ‘int’ scenario, the share of coal-based technologies in electricity production is falling much more slowly than in the ‘base’ scenario (Figure 2b). Carbon technologies account for about 60% of the energy mix in 2035 (43% in the ‘base’ scenario). The share of electricity production from RES sources is about 19% in 2035 (30% in the ‘base’ scenario). Nuclear power is growing on a smaller scale (8% of the total share, compared to 21% in the ‘base’ scenario). Consequently, $CO_2$ emissions do not decrease between 2020 and 2035 and remain at the same level of 119 million Mg. This suggests that either the climate policy objectives are too ambitious, or the marginal external cost of $CO_2$ is underestimated in the ‘int’ scenario. It will be discussed below.

Table 3 shows the cost estimates of both scenarios. The social cost is the sum of generation costs (i.e., the sum of the investment, fuel, variable, fixed and abatement costs of energy technologies, excluding the costs of purchasing $CO_2$ allowances – as a financial transfer between power plants and the government) and external charges caused by the emission of air pollutants. The social costs in the 'int' scenario are 0.7% higher than in the 'base' (€187 billion compared to €185 billion) in discounted terms. This is the vast differences in the structure of electricity generation and significant different $CO_2$ emissions levels. Consequently, in the 'int' scenario, discounted generation costs are lower (€141 billion compared to €142 billion), while external costs are higher (€45 billion compared to €43 billion).

**Table 3.** The social costs of electricity production in system power plants, district and industry CHP plants (€ million)

| Cost | 2021-2025 | 2026-2030 | 2031-2035 | Total – not discounted | Total – discounted |
|---|---|---|---|---|---|
| 'base' scenario | | | | | |
| Generation costs | 63 636 | 70 328 | 74 881 | 208 845 | 142 381 |
| External costs | 22 675 | 20 570 | 18 560 | 61 804 | 43 539 |
| Total | 86 310 | 90 898 | 93 441 | 270 649 | 185 920 |
| 'int' scenario | | | | | |
| Generation costs | 63 706 | 68 874 | 74 863 | 207 442 | 141 469 |
| External costs | 22 207 | 22 009 | 21 674 | 65 890 | 45 694 |
| Total | 85 913 | 90 883 | 96 537 | 273 332 | 187 163 |

Source: author's work.

As noted, for the marginal external cost at a level of €25/Mg $CO_2$ in the 'int' scenario, $CO_2$ emissions remain virtually unchanged, and the structural changes in energy generation are relatively small compared to the 'base' scenario. This, in turn, suggests that either $CO_2$ emissions reduction targets and RES limits in the 'base' scenario seems to be too ambitious (which is somewhat questionable) or the marginal external cost assumed in this study is underestimated. A sensitivity analysis was made to verify this issue. It examined whether and to what extent the higher external cost of $CO_2$ would affect structural changes in the domestic electricity sector. The $CO_2$ allowance prices in the 'base' scenario were accordingly adjusted as well in order to maintain the assumptions comparable.

Table 4 presents the sensitivity analysis results for three levels of the marginal external cost of $CO_2$: €25, €50 and €65/Mg $CO_2$. An aggregate picture of these simulations is the electricity production structure in 2035 and the social costs in 2020-2035. The general conclusion is that the higher the marginal external cost of $CO_2$ emissions, the greater the structural changes. At a €65/Mg $CO_2$, the energy generation structure and $CO_2$ reductions are pretty similar to the 'base' scenario (except for coal and gas technologies). It means that the climate policy leading to a gradual reduction of $CO_2$ emissions in Poland makes sense, assuming much higher external costs of $CO_2$ emissions (€65/Mg $CO_2$) than adopted in this study. The same conclusion can be drawn by analysing the level of $CO_2$ abatement costs in the 'base' scenario. These costs result from the structural changes in the Polish electricity sector. The average abatement costs of $CO_2$ in 2020-2035 is around €70/Mg $CO_2$, which is pretty consistent with the results presented above. Thus, all measures aiming to meet climate policy goals in the Polish electricity sector are reasonable if the abatement costs of $CO_2$ are lower than the external costs of $CO_2$.

**Table 4**. Sensitivity analysis

| Parameters | RES,% | Coal,% | Nuclear,% | Gas,% | $CO_2$ reduction in 2035*, % | Generation costs increase, % | External costs increase, % | Total costs increase, % |
|---|---|---|---|---|---|---|---|---|
| 'base' scenario | 30 | 43 | 21 | 6 | 35 | - | - | - |
| 'int' scenario | €25/Mg $CO_2$ | | | | | | | |
| | 19 | 60 | 8 | 13 | 0 | -0.6 | 5.0 | 0.7 |
| | €50/Mg $CO_2$ | | | | | | | |
| | 26 | 43 | 19 | 12 | 23 | -1.5 | -2.4 | -1.9 |
| | €65/Mg $CO_2$ | | | | | | | |
| | 29 | 37 | 21 | 13 | 34 | -3.9 | -0.6 | -2.5 |

*Comparing to 2020

Source: author's work.

## Conclusions

The Polish electricity sector's scope and rate of structural changes strongly depend on the model assumptions, mainly the optimisation criteria. The optimisation procedure does not guarantee that such challenging changes will be implemented in the real economic policy. The decarbonisation of the Polish energy sector is a massive challenge for the entire economy, and there is no certainty that it will succeed.

The ‘base’ scenario assumes gradual decarbonisation of the Polish electricity sector. A $CO_2$ reduction rate of 2.3% per year has been taken in 2020-2035, ensuring a 35% reduction by 2035. But even for this relatively short period, the projected structural changes are a tremendous effort. The results show that investments in new electricity generation capacities – mostly RES – over 2020-2035 are within a range of 2,500-4,000 MW/year, and investment costs are estimated at around €2.3 billion/year on average. In addition, the cost of purchasing $CO_2$ allowances is approximately €2-3 billion/year. However, to achieve zero-carbon electricity production in 2050, the rate of $CO_2$ emissions reduction would have to increase even further – to more than 4% per year after 2035.

Consequently, the RES investment plan would have to accelerate, which seems to be a complicated process, both from a technical and financial point of view. It also means that the Polish coal mines will have to be phased out by 2050. The Polish Government has signed an agreement with the miners’ trade unions, which seems to guarantee the success of this process. However, it does not apply to the Polish coal-based power plants. Here, for several reasons, it is unclear whether and at what rate these plants will be closed. We know that investors do not plan to finance new coal capacities, and the government announced the early closure of the existing plants.

The decarbonisation pathway set out in the model assumes electricity generation from the nuclear power plant. The fundamental question is whether and when this investment will be made. This decision is up to the government, which must also consider a social resistance. Recent government declarations suggest that nuclear energy is gaining support among political decision-makers. It appears almost certain that a decarbonisation policy can not take place without nuclear energy, which also reflects this study’s results. The investment was initially planned in 2030, which was assumed in this study. However, this deadline is already out of date, and the investment has been delayed for several years. Shifting this investment beyond 2030 makes decarbonisation policy impossible to implement.

Interesting findings come from the analysis of effectiveness of both scenarios. In the case of system power plants, EU environmental instruments like IED standards and RES limits are both effective and efficient. This is evident for $SO_2$, $NO_X$, and PM emissions, where abatement technologies are cheaper than negative environmental effects. However, this is not the case for $CO_2$. The climate policy leading to a gradual reduction of $CO_2$ emissions makes sense assuming much higher external costs of $CO_2$ emissions than reported until recently as the most likely values (see Bickel et al., 2005 and *New Energy...,* 2009).

The high uncertainty concerning the energy sector and the EU environmental policy programmes stimulates further modelling experiments. Firstly, it is necessary to extend the research period to 2050. Only then will it be possible to fully assess the potential structural changes and economic costs of the Polish energy sector decarbonisation. Secondly, there is growing concern about new hydrogen technologies and energy storage issues. So far, there are no reliable technological and cost details to include these technologies in the model as an effective measure to mitigate $CO_2$ emissions. Moreover, if we assume an extensive expansion of hydrogen, the volume of electricity production must be strongly revised as well (*Neutralna emisyjnie Polska…*, 2020). Thirdly, the potential and costs of RES and nuclear energy need to be continuously updated, which can significantly improve their competitiveness.

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