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The Health Impact and External Cost of Electricity Production

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Abstract: The use of fossil fuels, which still dominate global primary energy consumption, results not only in emissions of greenhouse gas but also in emissions of pollutants such as SO_2, NO_x, and PM. Damage caused by air pollution can be expressed in monetary terms in the form of external costs to society. The goal of this paper is to answer the following questions: How much will the energy sector's emissions change as a result of decarbonization? What is the estimated level of external costs related to human health in future energy scenarios? How large are the estimated external costs compared to the planned investments in this sector? The study conducted for the period 2018–2050 used the impact pathway approach and covered the centralized power and heat generation sector in Poland. The reported values of the concentration–response functions that relate human exposure to air pollution with health impact were reviewed. The results show that external costs decrease from an estimated annual level in the range of EUR 782–1911 million in 2018 to EUR 36–876 million in 2050. The cumulative value of avoided external costs between 2018 and 2050 is significantly lower than the planned capital expenditures in the energy sector in Poland.

Keywords: power sector; health impact; emissions; models; energy scenarios

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1. Introduction

The scenarios presented in the recently published report of the Intergovernmental Panel on Climate Change (IPCC) show that only a reduction in carbon dioxide emissions to almost zero will keep the Earth's temperature at a level similar to today (scenario SSP1–1.9) [1]. Otherwise, there would be a significant increase in temperature by 2100, even above 5 °C, according to scenario SSP5–8.5. To address the challenges of global warming, the European Union (EU) has pledged to reduce its net greenhouse gas (GHG) emissions by at least 55% by 2030 compared to 1990 and to become climate neutral by 2050 [2]. In its National Energy and Climate Plan submitted to the European Commission, Poland sets the following climate and energy targets for 2030: (i) a 7% reduction in GHG emissions in non-ETS sectors compared to 2005 levels, (ii) a 21–23% share of renewable energy sources (RES) in gross final energy consumption, and (iii) a reduction in the share of coal in electricity production to 56–60% [3]. Ten years later, the share of RES in gross final energy consumption is planned at 28.5%, and the share of brown and hard coal in electricity production at 28% [4]. In 2018, the share of coal in electricity generation in Poland was 75.4% and the share of renewable energy sources was 12.7%. Having the highest share of coal in electricity and heat production of the EU means that Poland will have to incur substantial costs to achieve climate neutrality. According to a government document, the projected cost of investment in the entire energy sector between 2021 and 2040 is estimated at EUR 200 billion, of which EUR 117 billion is for the electricity sector [4]. One study showed that the capital expenditures (CAPEX) of the electricity sector to achieve carbon neutrality by 2050 is EUR 134 billion [5]. McKinsey & Company estimated the cost of decarbonizing the Polish power sector by 2050 at EUR 100 billion [6]. It is worth noting that Poland's gross domestic product at market prices in 2018 was EUR 497 billion.

The coal-based energy sector, in addition to CO_2 emissions, emits other pollutants that directly affect human health, such as SO_2, NO_x, and particulate matter (TSP: total suspended particles, PM10: particulate matter with a diameter of 10 µm and below, and PM2.5 with a diameter of up to 2.5 µm). These pollutants cause many diseases such as cancer, heart attack, neurological problems, pneumonia, chronic bronchitis, and asthma, leading to hospital admissions and a reduction in life expectancy [7–14]. The observed human effects of various kinds result in measurable economic costs and losses (external cost), e.g., hospitalization cost, absence at work due to illness, or premature death. An external cost (or externality) is the cost of an activity to those that are not directly participating in the activity itself [15]. In this paper, the term external cost refers to the cost to society caused by the negative health impact of direct emissions from the energy sector. To calculate the health effect, the concentration–response functions (CRFs) (also known as exposure–response functions, ERFs) were used. The slopes of concentration–response functions presented in several studies are listed in Table 1.

Table 1. The slopes of concentration–response functions (CRFs) associated with long-term exposure to pollutants. Based on [12,13,16–35].

Type of Health Impact	CRF (Per Person Per µg/m^3 Annually)	Units	References
	PM2.5		
Chronic mortality	6.51×10^{-4} 3.42×10^{-4}	years	[18,19] [12,20]
Restricted activity days	4.87×10^{-2} 4.20×10^{-2} 0.92×10^{-2} (adults aged 18–64) for Europe 0.57×10^{-2} (adults aged 18–64) for Poland	days	[18,19] [12,20] [13] [13]
Chronic bronchitis	4.90×10^{-5} 14×10^{-5}	cases	[12,20] [13]
Infant mortality	8.7×10^{-6} (children under 12 months)	cases	[13]
Cardiac hospital admissions	6.5×10^{-6}	cases	[13]
Respiratory hospital admissions	8.6×10^{-6}	cases	[13]
Lower respiratory symptoms	0.29 (children aged 5–14) 0.21 (adults with chronic respiratory symptoms-30% of the population)	days	[13] [13]
	PM10		
Restricted activity days	2.36379×10^{-2} (working adults aged 15–64) 2.67786×10^{-3} (nonworking adults aged 15–64) 9.02×10^{-2} (working adults aged 15–64)	days	[16] [16] [12]
Infant mortality	6.84×10^{-8} 1.7×10^{-7} (children under 12 months) 6.68×10^{-6} 4.0×10^{-4} 5.8×10^{-6}	cases years cases cases cases	[18,19] [16] [17,21] [12] [13]
Acute mortality	2.88×10^{-6} 3.0×10^{-6}	years	[16] [12]
Chronic mortality	4.0×10^{-4} 1.138×10^{-3} (adults aged over 30)	years years	[12,16] [17,22,23]

Table 1. *Cont.*

Type of Health Impact	CRF (Per Person Per μg/m^3 Annually)	Units	References
Chronic bronchitis	1.86×10^{-5} 1.81944×10^{-5} (adults aged 27+) 8.2×10^{-5} 2.65×10^{-6} 8.6×10^{-5} (adults aged 18+) 7.7×10^{-5}	cases	[18,19] [16] [17,24] [17,24] [13] [13]
Lung cancer	1.26×10^{-5}	cases	[17,22]
Congestive heart failure	3.09×10^{-5}	cases	[17,25]
Respiratory hospital admissions	7.03×10^{-6} 6.82×10^{-6} 3.46×10^{-6} 5.6×10^{-6}	cases	[12,18,19] [16] [17,26] [13]
Cardiac hospital admissions	4.34×10^{-6} 4.2×10^{-6}	cases	[18,19] [16]
Cerebrovascular hospital admissions	8.42×10^{-6} 4.3×10^{-6}	cases	[17,27] [13]
Medication use/bronchodilator use	4.03×10^{-4} (children) 3.27×10^{-3} (adults) 3.663×10^{-4} (children aged 5–14) 3.15×10^{-3} (adults aged 20+) 1.29×10^{-1} (children with asthma, 7.6% aged under 16) 2.72×10^{-1} (adults with asthma, 5.9% aged over 15) 1.8×10^{-2} (children aged 5–14 with asthma, 15% in Northern and Eastern Europe and 25% in Western Europe) 9.12×10^{-2} (adults with asthma, 4.5% aged over 20)	cases	[18,19] [18,19] [16] [16] [17,28] [17–19] [12] [12]
Lower respiratory symptoms	2.08×10^{-2} (children) 3.24×10^{-2} (adults) 2.057×10^{-2} (children aged 5–14) 3.076×10^{-2} (adults) 0.13 (adults with chronic respiratory symptoms-30% of the population) 0.186 (children aged 5–14) 1.72×10^{-1} (children with asthma, 7.6% aged under 16) 1.01×10^{-1} (adults with asthma, 5.9% aged over 15)	days	[18,19] [18,19] [16] [16] [12,13] [12,13] [17,28] [17,29]
Cough	4.46×10^{-1} (children with asthma, 7.6% aged under 16) 2.8×10^{-1} (adults with asthma, 5.9% aged over 15)	days	[17,30] [17,29]
Medical consultations for asthma	1.18×10^{-4} (children aged 0–14) 0.51×10^{-4} (adults aged 15–64) 0.95×10^{-4} (adults aged 65+)	cases	[12]
Medical consultations for upper respiratory diseases	4.0×10^{-4} (children aged 0–14) 3.2×10^{-4} (adults aged 15–64) 4.7×10^{-4} (adults aged 65+)	cases	[12]
Acute respiratory symptoms	0.465	days	[12]
	SO_2		
Acute mortality	7.85×10^{-6}	cases	[17,31,32]
Respiratory hospital admissions	2.04×10^{-6} 7.91×10^{-5}	cases	[17,26] [33,34]
Cardiovascular hospital admissions	7.94×10^{-4}	years	[33,34]

Table 1. *Cont.*

Type of Health Impact	CRF (Per Person Per μg/m^3 Annually)	Units	References
	NO_2		
Chronic mortality	3.91×10^{-4} (adults aged 15+)	years	[12,33]
Respiratory hospital admissions	7.03×10^{-6} (adults aged 15+)	cases	[33,35]

The external costs of pollutant emissions have been estimated in many studies. A recent report prepared by the European Commission showed that the national average external costs of electricity in the EU-27 were the highest in Estonia at 221 EUR/MWh, in Cyprus at 146 EUR/MWh, and in Poland at 139 EUR/MWh [15]. For heat production, the highest external costs were observed in Slovenia at 100 EUR/MWh and Estonia at 88 EUR/MWh. The European Commission's analysis considers the external costs of climate change, human health, eutrophication, acidification, and ozone depletion. The total external costs for electricity and heat production were estimated at EUR 23.7 billion and EUR 10.5 billion, respectively. Most of the external costs are due to the effects of climate change and particulate matter emissions. For example, in Poland, CO_2 emissions account for 70% and 46% of the total external costs of electricity and heat generation, respectively, while the respective shares for particulate matter are 32% and 16%. In Iran, based on the same approach but with different tools than those used in this paper, the annual health damages related to the emissions of 61 power plants were USD 723 million, averaging 2.85 USD/MWh [16]. A detailed analysis of external costs related to the energy sector in Turkey showed average external costs of 36 EUR/MWh for brown coal, 14 EUR/MWh for hard coal, and 5 EUR/MWh for natural gas. Most of the external costs were associated with CO_2 emissions. A study in China found that of external costs associated with the life cycle of coal, 96% arise from combustion, 3% from mining, and 1% from coal transport. Most of the costs (87.2%) are related to human health, and the rest to global warming and destruction of materials [36]. The low contribution of global warming to the cost of damages has also been reported in other works for many regions in the world [37]. Another work, based on the use of multiple models, estimates the average external costs (excluding CO_2) related to the health impacts of air pollution emitted by all sectors at EUR 334 billion and EUR 146 billion for Europe and the United States, respectively [17]. According to various estimates carried out around the world, the highest external costs are observed in coal combustion technology due to high emissions of CO_2 and particulate matter, while costs are very low (less than 2 EUR/MWh) for renewable and nuclear sources [15,37–42]. The results are influenced by the following factors: CO_2 emission costs (and also whether they are considered or not), emission values, concentration–response functions adopted, population, and monetary valuation of various health damages [43]. As a result, external cost estimates reported in the literature can fall into large ranges. Taking coal as an example, data from 36 estimates showed the external cost with a minimum value of 0.01, a maximum of 90.6, and a mean of 18.75 USD/kWh [42].

In this paper, we estimated the baseline (2018) and future (2030, 2035, 2040, 2045, 2050) external costs of emissions from the centralized power and heat generation sector (hereinafter referred to as the energy sector) in Poland. A full description and the results of the energy scenarios considered in this paper are given in [44]. The main question we addressed was: What is the proportion of the avoided external costs for the energy sector to the capital cost of transforming the sector into a climate-neutral one? The impact pathway approach (IPA) was used to estimate the external costs of emissions. This approach, developed as part of the ExternE projects, has been widely used to assess the environmental impact and calculate the external cost of the energy sector [12,16,41,42,45]. In this study, emissions in 2018 were estimated for all the stacks of the Polish energy sector, including public power plants (PP), public combined heat and power plants (CHP), district heating plants (DHP), and industrial combined heat and power plants (CHPI). Emissions in 2030, 2035, 2040, 2045, and 2050 were calculated based on energy sector development scenarios and EU emission standard regulations. Then, the atmospheric transport of pollutants emitted from the energy sector was modelled using the Polyphemus air quality modelling system. The obtained results of ambient concentration of PM10, PM2.5, NO_x, and SO_2 were then used to calculate the health impact and the associated external costs. In this study, only direct emissions from the energy sector were considered. Life-cycle emissions, e.g., those related to fossil fuel extraction or commissioning/decommissioning of power and heating plants, were not taken into account. According to a study in China, in the case of coal-fired power plants, only 4% of life-cycle emissions are related to the extraction and transport of coal [36].

2. Methodology

The impact pathway approach used in this study is based on four main steps: (i) identification of emission sources, (ii) modelling the atmospheric transport of pollutants, (iii) estimation of the impact of air pollution on human health, and (iv) estimation of the external cost. In this article, the impact of direct emission from fuel combustion on human health and related external cost were calculated. The external cost of climate change, eutrophication, acidification, and ozone depletion were not taken into consideration.

2.1. Emission Estimation

In this paper, two emission scenarios were developed for four groups of units: public power plants (PP), public combined heat and power plants (CHP), district heating plants (DHP), and industrial combined heat and power plants (CHPI). The scenarios provide estimates of fuel consumption in each group. Fuels such as biomass (BM), hard coal (HC), brown coal (BC), natural gas (GS), biogas (BG), heavy fuel oil (HFO), and light fuel oil (LFO) were considered. Heavy fuel oil (HFO) and light fuel oil (LFO) are used during combustion start-up in units that burn solid fuels such as coal and biomass. The emission scenarios were developed on the basis of the scenarios for the development of the Polish energy sector described by the authors in the previous work [44]. The first one, referred to in this article as the non-nuclear scenario (NN) and in [44] as the RES scenario, assumes that no nuclear power plant will be built in Poland in the future. In this scenario, electricity generation takes place mainly through renewable energy sources supported by gas peaking units. The power sector annual emissions of CO_2 are less than 10 Mt in 2050. The second one, referred to in this article as the nuclear scenario (YN) and in [44] as NUC, assumes that the first nuclear power plant will be built in Poland between 2030 and 2035. The total electrical capacity installed in nuclear power plants reaches 10.4 GW by 2050. The results of the energy scenarios include fuel consumption of existing and new power plants. The levels of emissions of pollutant released into the air from the energy sector in Poland were estimated for 2030, 2035, 2040, 2045, and 2050 based on fuel activity provided in each group of generation units and fuel-specific emission limit values (ELVs) for pollutants. Emission limit values for pollutants from the power sector are defined by European Union regulation in the so-called best available techniques (BAT) conclusions [46]. These regulations are the same for all Member States and apply from January 2021. The average annual emission limit values applied to the power sector for existing and new plants are shown in Table 2. It is the first attempt to estimate future emissions using the ELVs presented in the BAT conclusions. The volume of flue gas resulting from combustion of GJ of a given fuel was determined for different fuels on the basis of previous research [47–49].

Table 2. The average annual emission limits of pollutants according to BAT conclusions (mg/Nm) [46].

Fuel	Thermal Input [MW]	TSP		SO_2		NO_x	
		Existing	New	Existing	New	Existing	New
Hard coal (HC), Brown coal (BC),	<100	18	5	360	200	270	150
	100–300	14	5	200	150	180	100
	>300 PC			130	75	150	85
	>300 FBC			190	75	150	85
	300–1000	12	5				
	>1000	8	5				
Biomass (BM)	50–100	15	5	100	70	225	150
	100–300	12	5	70	50	180	140
	≥300	10	5	50	35	150	140
Heavy fuel oil (HFO), Light fuel oil (LFO)	<100					270	200
	≥100					110	75
	<300	20	10	175	175		
	≥300	10	5	100	50		
Natural gas (NG), Biogas (BG)	50–600					45	30
	≥600					40	30

Emissions of SO_2, NO_x, TSP, PM2.5, and PM10 in 2018 were individually estimated for 18 public power plants (PP), 60 public combined heat and power plants (CHP), 439 district heating plants (DHP), and 63 industrial combined heat and power plants (CHPI). These emissions were estimated based on the Enviro database, which has been developed since 2006 at AGH UST [50]. This database is continuously updated based on publicly available information. The Enviro database contains detailed information on boilers (1965 boilers), stacks (580), SO_X, NO_x, and TSP emission control systems, fuel consumption (natural gas, coal, biomass, biogas, heavy fuel oil, light fuel oil), and emissions. Based on these data, the emissions for the period 2030–2050 were disaggregated over Poland. Future emissions have been distributed proportionally according to the fuel consumption of the individual boilers in 2018.

2.2. Modelling of Air Transport of Pollutants

The Polyphemus air quality system was applied to model the atmospheric transport of pollutants emitted from the considered point sources from the energy sector [51]. Polyphemus includes the Eulerian-type model Polair3D, which enables modelling of dispersion of gaseous and dust pollutants. The model considers reactions and transformations in gaseous, aqueous, and solid phases. Polyphemus has been used extensively by many research groups, and the results obtained over Europe and Poland have been thoroughly evaluated. The results of the evaluation of concentrations and deposition of particulate matter (PM2.5, PM10), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), ozone (O_3), mercury (Hg), lead (Pb), and cadmium (Cd) against measurements from different types of stations (background, urban, industrial, and transport) can be found in [20,52–54]. In Poland, the Polyphemus air quality system has previously been used from local to continental scale to assess air quality and the impact of different sectors and emission sources [45,54–56].

The modelling domain applied in this study covers Poland and consists of 67 × 112 cells (along latitude and longitude respectively), starting at 48.40°N latitude and 13.50°E longitude with a horizontal resolution of 0.1°. Five vertical levels were used with the following limits (in meters above surface level): 0, 50, 600, 1200, 2000, and 3000. The simulation was run with a time step of 10 min, and results were saved for each hour as the average value of the six steps. In total, 12 one-year simulations of pollutant dispersion were run. The simulations were run based on emissions for the years 2018 (base year), 2030, 2035, 2040, 2045, and 2050. For the period 2030–2050, simulations were run for two scenarios:

non-nuclear (NN) and nuclear (NY). Additionally, one simulation without emissions from the energy sector was run to assess the background level. The difference between the concentration results of the simulations with and without emissions from the energy sector makes it possible to calculate the impact of this sector on air quality in each of the years and scenarios considered.

Emissions from the power sector were determined for each stack based on detailed location [57]. This process was performed by Polyphemus using land-use coverage (LUC) data with a horizontal resolution of 1 km by 1 km [58]. Emissions from other sectors and natural emissions remained at 2018 levels. In this article, in order to examine the impact of the energy sector alone, changes in emissions in other sectors by 2050 have been omitted, although we are fully aware that these emissions affect the physical and chemical changes of pollutants in the atmosphere. Meteorological conditions were calculated based on the data of the European Centre for Medium-Range Weather Forecasts for 2008 [59]. These data were provided every 3 h with a horizontal resolution of 0.25° at 54 vertical levels. The boundary condition was estimated from a simulation run over Europe with emissions for 2018. The domain for this simulation consisted of 50 × 72 cells starting from 40.0° latitude and −3.0° longitude with a horizontal resolution of 0.5°. The vertical levels were similar to those in the simulation over Poland.

Particulate matter is distributed among 10 different size sections (between 0.01 to 10 μm) with the following threshold limits (in μm) of diameter: 0.01–0.02–0.0398–0.0794–0.1585–0.3162–0.6310–1.2589–2.5119–5.0119–10. The following particulate matter components were included in the model: black carbon, aromatics, mineral dust, primary and secondary organic aerosols, SO_4, NO_3, and NH_4 ions and hydrochloric acid aerosols.

2.3. Estimation of Health Impact and External Cost

In this study, health impact was estimated based on the concentration–response functions (CRFs), population statistics (population density and pyramids, life expectancy), and pollutant concentrations. A similar approach is used by the World Health Organization and the European Environment Agency, among others [7,17,60].

The health impact was calculated using Equation (1).

$$HI = \sum_j \Delta C_j P_j CRF \tag{1}$$

where *HI* is the health impact of a given type (cases); ΔC is the change in annual average concentration of SO_2, NO_x, and PM10 at ground level due to emissions from the energy sector calculated using the Polyphemus air quality system ($\mu g/m^3$); *P* is population exposed (number), *CRF* is the concentration–response function for a given impact type (<cases, days, years>/$\mu g/m^3$); and j is the index of the cell in the domain (7504 cells). We assumed a linear CRF without a threshold.

Average annual concentration (C) of pollutants is calculated using the Polyphemus air quality system. Data on the Polish population in the modelled years, by gender and age group, were obtained from [61,62]. These sources give population distributions at a spatial resolution of 0.00833°. According to these estimates, Poland's population was 37.921 million in 2018 and is projected to fall to 36.944 million in 2030, 35.282 million in 2040, and 33.294 in 2050. The age structure of the Polish population will also change. In Poland, as in other developed countries, a significant ageing of the society will be observed. The share of children under 16 in the total population will decrease from 17% in 2018 to 14.6% in 2050. During this period, the proportion of people aged over 65 will change from 17.5% to 31.1%.

The external costs are calculated based on the literature review and gross domestic product (GDP) per capita in Poland for all modelled years. In 2018, this was EUR 12,420 PPP (gross domestic product based on purchasing power parity) [16,17,33,63–65]. For the future unit damage costs, the GDP growth paths published by the Ministry of Finance were adopted. An average annual growth rate of 1.4–4.7% was assumed over the 30-year period [66]. Cumulative GDP growth to 2050 will be 115%, compared to 2018. Services and industry will be mainly responsible for creating added value.

Based on the data and sources presented in Table 1, the health impact was calculated for two cases. In the first case ("low estimation"), a low value of CRFs was considered, and in the second one ("high estimation"), a high value of CRFs was considered (Table 3). Table 3 also shows the unit damage costs for health effects in Poland in 2018.

Table 3. The concentration–response function (CRF) used in the two cases (low and high estimation). Costs given for Poland in 2018 in EUR 2018. Based on the data presented in Table 1.

Type of Health Impact	Low Estimation (Per Person Per μg/m^3 Annually)	High Estimation (Per Person Per μg/m^3 Annually)	Units	Unit Cost EUR 2018
	PM10			
Acute mortality	2.88×10^{-6}	3.0×10^{-6}	case	768,380
Restricted activity days (only working adults aged 15–64)	2.36379×10^{-2}	9.02×10^{-2}	days	49
Infant mortality	6.84×10^{-8}	4.0×10^{-4}	cases	1,152,570
Chronic mortality	4.0×10^{-4}	1.138×10^{-3}	years	28,842
Chronic bronchitis	2.65×10^{-6}	8.2×10^{-5}	cases	19,347
Lung cancer	1.26×10^{-5}		cases	8065
Congestive heart failure	3.09×10^{-5}		cases	5515
Respiratory hospital admissions	3.46×10^{-6}	7.03×10^{-6}	cases	2666
Cardiac hospital admissions	4.2×10^{-6}	4.34×10^{-6}	cases	2666
Cerebrovascular hospital admissions	4.3×10^{-6}	8.42×10^{-6}	cases	3377
Medication use/bronchodilator use	4.03×10^{-4} (children)	1.29×10^{-1} (children with asthma, 7.6% aged under 16)	cases	8
	3.27×10^{-3} (adults)	2.72×10^{-1} (adults with asthma, 5.9% aged over 15)		
Lower respiratory symptoms	2.057×10^{-2} (children aged 5–14)	0.186 (children aged 5–14)	days	4
	3.076×10^{-2} (adults)	0.13 (adults with chronic respiratory symptoms–30% of population)		
Medical consultations for asthma	1.18×10^{-4} (children aged 0–14) 0.51×10^{-4} (adults aged 15–64) 0.95×10^{-4} (adults aged 65+)		cases	48
Medical consultations for upper respiratory diseases	4.0×10^{-4} (children aged 0–14) 3.2×10^{-4} (adults aged 15–64) 4.7×10^{-4} (adults aged 65+)		cases	48
	SO_2			
Respiratory hospital admissions	2.04×10^{-6}	7.91×10^{-5}	cases	2666
Acute mortality	7.85×10^{-6}		cases	768,380
Cardiovascular hospital admissions	7.94×10^{-4}		cases	3377
	NO_2			
Chronic mortality	3.91×10^{-4} (adults aged 15+)		years	28,842
Respiratory hospital admissions	7.03×10^{-6}		cases	2666

The CRF coefficients presented in Table 3 make it possible to indicate the upper and lower values for the number of cases of human health damage. Some slopes of CRFs reported in the literature differ significantly. For example, the lowest and highest values of CRF for infant mortality differ by nearly 6000-fold.

3. Results and Discussion

3.1. Emission Results

In Poland, 15.51 kt of TSP, 168.22 kt of NO_x, and 261.21 kt o of SO_2 were emitted in 2018 (Table 4). The majority of NO_x and SO_2 emissions originated from power plants (PP). Due to the application of BAT emission standards, as well as reduced fuel consumption at selected plants, emissions in 2030 compared to 2018 will be reduced by 63% for SO_2, 53% for TSP, and 32% for NO_x in both scenarios. In 2050, when all planned nuclear power plants are operational, the differences in emissions between the two scenarios becomes more evident. In 2050, under the non-nuclear scenario, 10.97 kt of SO_2, 15.73 kt of NO_x, and 9.48 kt of TSP will be emitted, whereas under the nuclear scenario, 6.36 kt of SO_2 and 9.12 kt of NO_x will be emitted (Tables 5 and 6).

Table 4. Annual emissions of the main pollutants in Poland in 2018 from public power plants (PP), public combined heat and power plants (CHP), district heating plants (DHP), and industrial combined heat and power plants (CHPI) (kt).

Type of Units	TSP	NO_X	SO_2
PP	5.48	107.47	144.18
CHP	3.10	32.07	53.81
DHP	5.07	14.23	41.48
CHPI	1.86	14.56	21.74

Table 5. Emission of SO_2 in 2030–2050 from various fuels (BM: biomass, HC: hard coal, HFO: heavy fuel oil, BC: brown coal, LFO: light fuel oil) from public power plants (PP), public combined heat and power plants (CHP), district heating plants (DHP), and industrial combined heat and power plants (CHPI) for non-nuclear (NN) and nuclear (YN) scenarios (kt). A blank field in the table means that a respective fuel is not used in a given model year.

	2030		2035		2040		2045		2050	
	NN	YN	NN	YN	NN	YN	NN	YN	NN	YN
PP										
BM	0.36	0.36	0.36	0.36						
HC	22.87	22.87	20.94	20.94	15.45	15.45	6.16	6.16		
HFO	0.22	0.19	0.17	0.13	0.12	0.09	0.05	0.06		
BC	37.34	37.34	16.32	16.32	11.47	11.47	8.66	8.76		
SUM	60.78	60.76	37.78	37.74	27.03	27.00	14.87	14.98		
CHP										
BM	2.29	2.39	3.16	3.16	4.75	3.81	6.98	5.23	9.37	6.10
HC	21.83	21.83	18.90	18.97	9.50	9.46	3.25	4.83		
HFO	0.09	0.09	0.08	0.08	0.04	0.04	0.01	0.02		
SUM	24.21	24.32	22.14	22.21	14.29	13.31	10.24	10.08	9.37	6.10
DHP										
BM	0.11	0.11	0.05	0.06	0.58	0.13	1.09	0.19	1.60	0.26
HC	8.87	8.87	5.07	5.07						
BC	0.07	0.07	0.03	0.03						
SUM	9.05	9.05	5.16	5.16	0.58	0.13	1.09	0.19	1.60	0.26
CHPI										
BM	0.37	0.37	0.03	0.18	0.01	0.03				
HC	2.01	2.01	0.63	0.12	0.39	0.92				
LFO	0.02	0.02	0.01	0.01	0.01	0.01				
SUM	2.39	2.39	0.67	0.31	0.41	0.96				

Table 6. Emission of NO_x between 2030 and 2050 from various fuels (BM: biomass, HC: hard coal, HFO: heavy fuel oil, BC: brown coal, LFO: light fuel oil, NG: natural gas, BG: biogas) from public power plants (PP), public combined heat and power plants (CHP), district heating plants (DHP), and industrial combined heat and power plants (CHPI), for non-nuclear (NN) and nuclear (YN) scenarios (kt). A blank field in the table means that a respective fuel is not used in a given model year.

	2030		2035		2040		2045		2050	
	NN	YN	NN	YN	NN	YN	NN	YN	NN	YN
PP										
BM	1.08	1.08	1.08	1.08						
HC	30.79	30.79	28.19	28.19	20.80	20.80	8.29	8.29		
HFO	0.33	0.30	0.26	0.20	0.18	0.14	0.08	0.09		
BC	36.30	36.30	15.86	15.86	11.15	11.15	8.42	8.52		
SUM	68.50	68.46	45.38	45.33	32.12	32.08	16.79	16.90		
CHP										
BM	6.28	6.57	8.72	8.72	13.17	10.53	6.98	5.23	9.37	6.10
NG	0.07	0.07	1.60	0.61	3.12	2.04	2.65	1.29	1.46	0.87
HC	29.39	29.39	25.44	25.54	12.79	12.73	4.37	6.50		
HFO	0.14	0.14	0.12	0.12	0.06	0.06	0.02	0.03		
BG	0.48	0.48	0.03	0.44	0.04	0.07	0.25	0.30	1.47	1.01
SUM	36.36	36.65	35.92	35.44	29.18	25.44	14.28	13.35	12.30	7.98
DHP										
BM	0.21	0.21	0.11	0.12	1.23	0.27	2.33	0.41	3.43	0.55
NG	0.08	0.08	0.00	0.04	0.24	0.32	0.15	0.45		0.60
HC	6.66	6.66	3.80	3.80						
BC	0.05	0.05	0.03	0.03						
SUM	7.00	7.00	3.93	3.99	1.48	0.59	2.48	0.86	3.43	1.14
CHPI										
BM	0.81	0.81	0.06	0.41	0.02	0.06				
NG	0.01	0.01	0.01	0.01	0.00	0.00				
HC	1.54	1.54	0.48	0.09	0.30	0.70				
LFO	0.03	0.03	0.02	0.02	0.02	0.02				
SUM	1.50	1.50	0.33	0.37	0.19	0.45				

Power plants emit relatively low amounts of particulate matter compared to combined heat and power plants (CHP) and district heating plants (DHP), as these units are equipped with the best dust abatement equipment. Between 2030 and 2045, however, power plants will be the main emitter of SO_2 and NO_x (Tables 5 and 6), although the emission will fall faster than in the case of cogeneration plants. Emissions of SO_2 from power plants are approximately 60 kt in 2030 and 15 kt in 2045 in both scenarios. In CHP plants, a reduction from 24 kt in 2030 to around 10 kt in 2045 is observed. In 2050, the SO_2 will be emitted from biomass burning in DHP and CHP.

Between 2030 and 2050, a sharp reduction in NO_x emissions from power plants is observed (Table 6). In the case of DHP, the lowest emissions are observed in 2040. In 2050, biomass will be the main source of NO_x emissions from the Polish power sector. An increase of NO_x emissions from the power sector is not observed, despite the growth in consumption of this transient fuel.

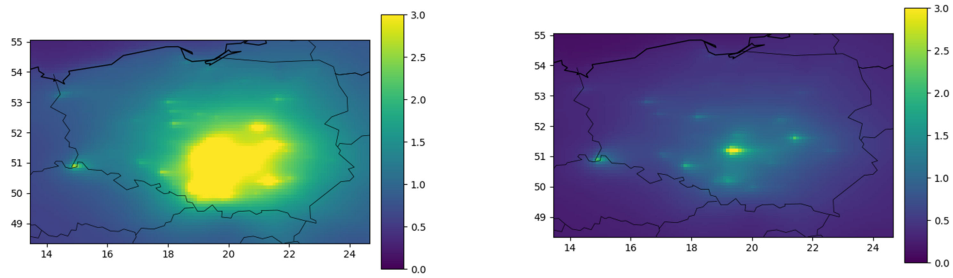
A significant reduction in TSP emissions from power plants is observed during the modelled period (Table 7). TSP emissions from CHP will grow rapidly due to increasing biomass consumption. In 2045, biomass will become the main source of TSP emissions from the power sector. Therefore, a further tightening of emission limits for this fuel is to be expected, particularly as CHP plants are located in large cities, so the particulate matter emitted from them would affect a relatively large number of people. In order to model the atmospheric dispersion of particulate matter, emissions of PM2.5 and PMcoarse (i.e., PM10–PM2.5) had to be provided to Polyphemus. Emissions of these particles were calculated individually for each stack based on TSP emissions, fuel, boiler, emission control device, and reported values for 2018.

Table 7. Emissions of TSP between 2030 and 2050 from various fuels (BM: biomass, HC: hard coal, HFO: heavy fuel oil, BC: brown coal, LFO: light fuel oil) from public power plants (PP), public combined heat and power plants (CHP), district heating plants (DHP), and industrial combined heat and power plants (ICHP) for non-nuclear (NN) and nuclear (YN) scenarios (t). A blank field in the table means that a respective fuel is not used in a given model year.

	2030		2035		2040		2045		2050	
	NN	YN	NN	YN	NN	YN	NN	YN	NN	YN
					PP					
BM	108	108	108	108						
HC	2111	2111	1933	1933	1426	1426	569	569		
HFO	25	22	19	15	13	10	6	6		
BC	1660	1660	725	725	510	510	385	389		
SUM	3903	3900	2785	2781	1949	1946	960	964		
					CHP					
BM	268	278	355	355	514	419	6977	5232	9375	6105
HC	2351	2351	2035	2043	1023	1019	350	520		
HFO	11	11	9	9	5	5	2	2		
SUM	2629	2640	2399	2407	1541	1443	7328	5755	9375	6105
					DHP					
BM	16	16	8	9	41	9	78	14	114	18
HC	444	444	254	254						
BC	3	3	2	2						
SUM	463	463	263	264	41	9	78	14	114	18
					CHPI					
BM	58	58	4	29	1	4				
HC	105	105	33	6	20	48				
LFO	2	2	1	1	1	1				
SUM	165	165	38	36	23	54				

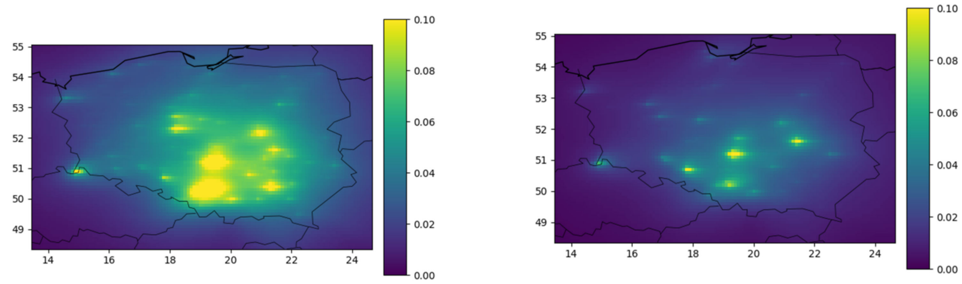
3.2. Concentration of Air Pollutants Results

Simulations of the dispersion of pollutants emitted from the power sector using the Polyphemus air quality system make it possible to obtain results of the concentration and depositions of (i) NO_x as the sum of NO_2, NO, and N_2O, (ii) SO_2, and (iii) PM2.5 as the sum of different types (black carbon, mineral dust, and others) and particle sizes of particulate matter. An example of an impact of the emissions from the energy sector on SO_2, NO_x, and PM10 concentrations is shown in Figures 1–3. The highest SO_2 and PM10 concentrations related to the energy sector are observed in central and southern Poland, where the biggest brown-coal-fired power plant and many hard-coal-fired power plants are located. The impact of emissions from the energy sector on concentration is significantly lower in 2030 compared to 2018 (Figures 1–3). SO_2 emissions from the power sector over this period are reduced from 261.21 kt in 2018 to 96.43 kt in 2030 (Tables 4 and 5). NO_x emissions are reduced from 168.33 kt in 2018 to 133.36 kt in 2030 (Tables 4 and 6). TSP emissions are reduced in this period from 15.51 kt to 7.16 kt (Tables 4 and 7). Although Poland has serious problems with exceedance of the air quality threshold values for PM10, this can only marginally be attributed to emissions from the power sector [67]. PM10 emissions from the energy sector represent about 6.5% of total emissions. In addition, unlike the residential sector, they are released at high altitudes (stacks above 70 m), which facilitates dilution of pollutants.



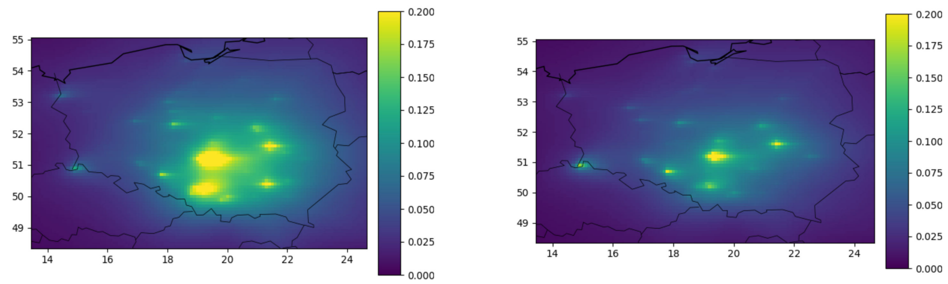
(**a**) (**b**)

Figure 1. The ambient SO_2 concentration at surface level resulting from the emissions of the power sector in (**a**) 2018 and (**b**) 2030, according to the non-nuclear scenario (µg/m^3).



(**a**) (**b**)

Figure 2. The ambient PM10 concentration at surface level resulting from the emissions of the power sector in (**a**) 2018 and (**b**) 2030, according to the non-nuclear scenario (µg/m^3).



(**a**) (**b**)

Figure 3. The ambient NO_x (sum of NO_2, NO, and N_2O) concentration at surface level resulting from the emissions of the power sector in (**a**) 2018 and (**b**) 2030, according to the non-nuclear scenario (µg/m^3).

The IPA methodology requires annual average pollutant concentrations as input data. Therefore, the model was validated against the 2018 annual mean measurements. Validation of the model against observations conducted over Poland is presented in Table 8. The model was validated against the observations of background rural stations. The results were not compared with the observations from traffic, industrial, urban, and suburban stations. These stations are highly influenced by local sources (cars, households, local factories). The simulation was carried out at a resolution that does not allow for accurate modelling of pollution inside cities.

Table 8. Evaluation of the modelled result against measurements of the annual average concentration. Source of observation data [68]. Statistical performance measures: RMSE: root mean square error, FB: faction bias, FAC2: the fraction of predictions within a factor of two of the observations. Based on measurement data provided for 2018 [69].

Pollutant	Number of Stations	Average from Observation [μg/m^3]	Average from Model [μg/m^3]	RMSE [μg/m^3]	FB	FAC2
SO_2	22	12.5	17.06	8.33	−0.30	0.70
NO_2	19	7.42	3.78	4.39	0.64	0.52
PM10	13	23.15	19.90	4.55	0.15	1
PM2.5	4	15.75	18.10	2.69	−0.13	1

The results of the simulations are overestimated for SO_2 and PM2.5 and underestimated for PM10 and NO_2 (Table 8). Generally, better results are obtained for particulate matter (PM10 and PM2.5) and worse results are obtained for NO_2. To improve the results, the emissions from other sectors (especially transport) should be provided in better resolution. In this paper, the EMEP data with a resolution of 50 × 50 km were used for all sectors apart from the power sector.

3.3. Health Impact and External Costs Results

Health impacts and external costs were calculated using Equation (1) based on the results of pollutant concentration modelling, information on the number of people exposed to air pollution, concentration–response functions (CRFs), and the unit costs of health impacts presented in Table 3. According to the results, 280 cases of lung cancer, from 6 to 189 new cases of chronic bronchitis, 710 cases of congestive heart failure, and 7 cases of acute mortality occurred in Poland in 2018 due to PM10 emissions from the energy sector. These negative cases will be reduced in 2050 to 21 and 13 cases of lung cancer; 4–138 and 3–89 new cases of chronic bronchitis; and 52 and 38 cases of congestive heart failure under the non-nuclear and nuclear scenarios, respectively. The number of restricted activity days was estimated to be between 99 and 150 thousand in 2018. Years of life lost (YLL) attributable to PM10 emissions equals 920–2590.

The number of acute mortalities attributable to SO_2 emissions from the power sector was estimated at 636 cases in 2018 and 230 in 2030. In 2040, these numbers were 100 for the NN scenario and 102 for the YN scenario, and in 2050 the numbers were 27 and 16, respectively. An equally pronounced decrease was observed in the number of years of life lost due to emissions of NO_x. The estimated number of YLL was 1200 in 2018, whereas in 2050 it was 109 for the nuclear scenario and 68 for the non-nuclear scenario. The total number of hospital admissions for respiratory diseases related to PM10, SO_2, and NO_x emissions from the power sector in 2018 was estimated in the range from 228 to 6490. Likewise, in 2050, a significant reduction in their number was observed; total admissions ranged from 36 to 305 under the non-nuclear scenario and from 23 to 187 under the nuclear scenario.

The greatest differences in external costs occurred for infant mortality. For the lower estimate, the cost is only EUR 0.18 million, and for the high estimate, it is EUR 1060 million (Table 9). The high value of external costs in the case of the high estimate is particularly visible in the period from 2040 to 2050, in which there is a significant rise in infant mortality due to rising PM emissions and thus concentrations (Table 7 and Figure 2). Such a high value of the CRF slope coefficient makes the result very sensitive to changes in PM concentrations, and it may be overestimated. When lower estimates of CRFs are used, the external costs decrease constantly from 2018 to 2050. In this case, external costs are mainly generated by chronic mortality attributable to SO_2 emissions. The external costs of SO_2 in 2018 were estimated in the range of EUR 776.4–1910.75 million. These values accounted for 0.1–0.4% of Polish GDP in that year. Relatively low external costs are attributable to NO_2 emissions.

Table 9. External costs associated with the Polish power sector in 2018 (million EUR 2018).

Type of Health Impact	Low Estimation	High Estimation
PM10		
Acute mortality	5.09	5.30
Restricted activity days	1.92	7.35
Infant mortality	0.18	1059.92
Chronic mortality	26.52	74.80
Chronic bronchitis	0.12	3.65
Lung cancer	0.23	0.23
Congestive heart failure	0.39	0.39
Respiratory hospital admissions	0.02	0.04
Cardiac hospital admissions	0.03	0.03
Cerebrovascular hospital admissions	0.07	0.07
Medication use/bronchodilator use	0.06	0.42
Lower respiratory symptoms	0.32	0.56
Medical consultations for asthma	0.01	0.01
Medical consultations for upper respiratory diseases	0.04	0.04
Total for PM10	35.00	1152.68
SO_2		
Respiratory hospital admissions	0.44	17.11
Acute mortality	488.84	488.84
Cardiovascular hospital admissions	217.58	217.58
Total for SO_2	706.86	723.53
NO_2		
Chronic mortality	34.47	34.47
Respiratory hospital admissions	0.07	0.07
Total for NO_x	34.54	34.54
Total for all pollutants	776.40	1910.75

The values presented above are lower than those presented in the European Commission's (EC) report on the external costs [15]. Disregarding CO_2-related external costs, which were not calculated in this paper, external costs related to the power sector amounted to EUR 12 billion for Poland in 2018 in the EC report. For the same year, the external cost estimates of this study are in the range of EUR 0.8 to EUR 1.9 billion (Figure 4).

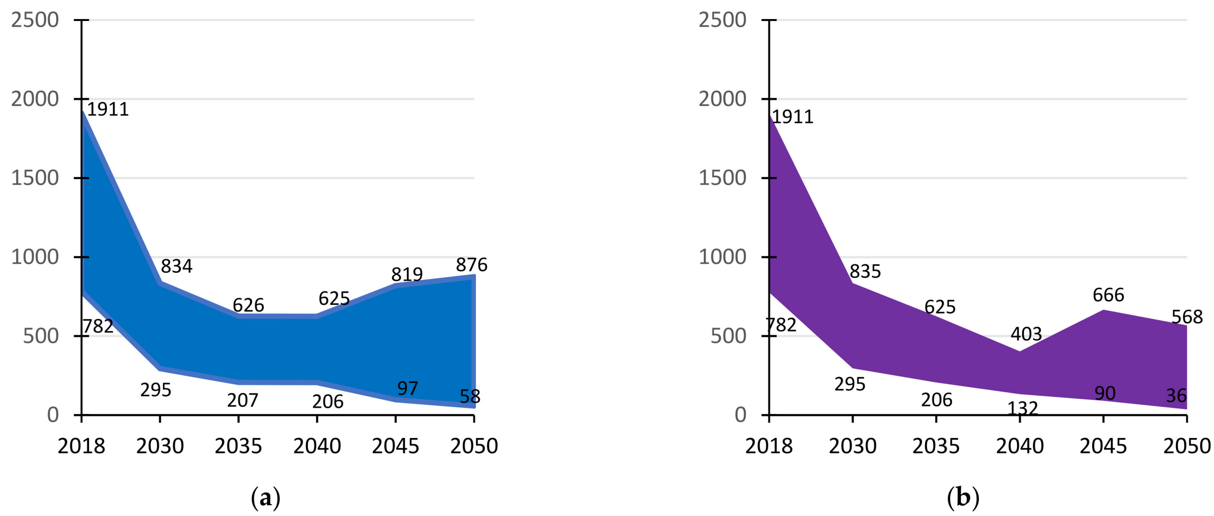


Figure 4. The range of external costs associated with the power sector in Poland from 2018 to 2050 according to (**a**) the non-nuclear scenario, and (**b**) the nuclear scenario (million EUR 2018).

Considering that 152 TWh of electricity and 109 TWh of district heat were produced in Poland in 2018, the associated external costs are in the range of 2.9–7.3 EUR/MWh. This value corresponds to the results presented for the G20 countries [70]. External costs of 3 USD/MWh and 1.5 USD/MWh were reported in the US [11]. A relatively old study estimated the external costs of fossil fuel-based power plants at 11.795 EUR/MWh [37]. Our values are higher than the results presented for Iran [16].

The maximum annual value of avoided external costs occurs in 2040 and amounts to EUR 1286 and EUR 1507 million in the case of the non-nuclear and nuclear scenarios, respectively (Figure 5). With regard to the reduction of SO_2, NO_x, and PM10 emissions in the Polish power sector, the avoided external costs are estimated at EUR 15.5–30.6 billion under the non-nuclear scenario and at EUR 15.8–33.4 billion under the nuclear scenario (Table 10). This is about 1/3 of the cost needed to transform the Polish energy sector towards climate neutrality [4–6].

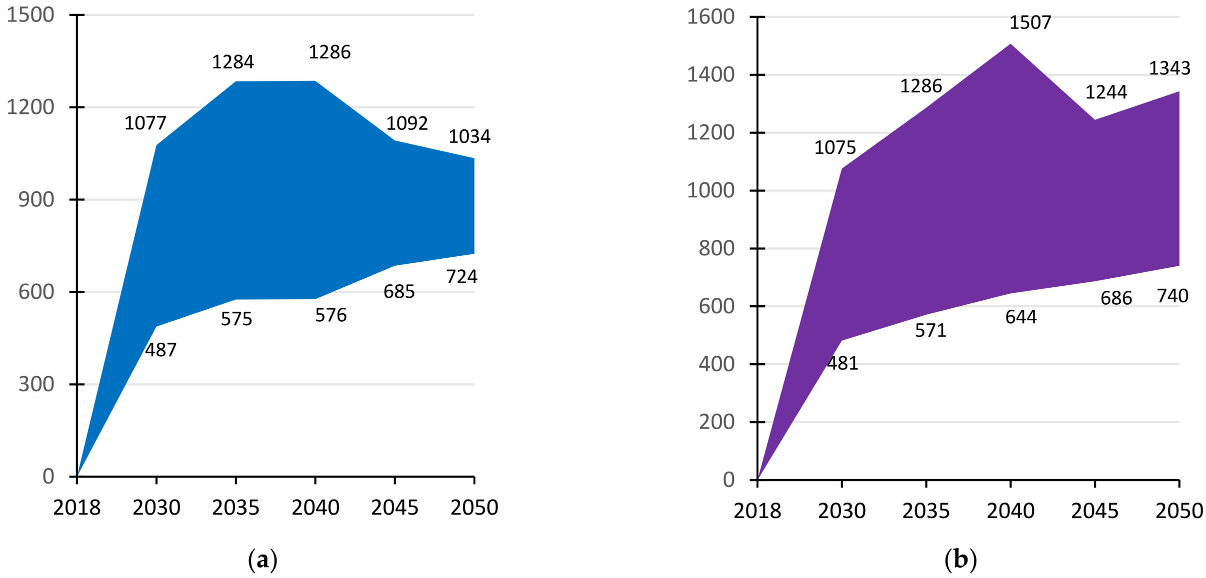


Figure 5. The range of avoided external costs associated with the power sector in Poland from 2018 to 2050 according to (**a**) the non-nuclear scenario, and (**b**) the nuclear scenario (million EUR 2018).

Table 10. Cumulative and avoided external costs associated with the Polish power sector in 2018–2050 (billion EUR 2018).

Scenario	Cumulative External Costs	Avoided External Costs
Non-nuclear scenario	10.3–32.5	15.5–30.6
Nuclear scenario	9.8–29.7	15.8–33.4

4. Conclusions

The impact pathway approach (IPA), developed as part of the ExternE projects, was used in this study to estimate the external costs attributable to NO_x, PM, and SO_2 emissions from the Polish energy sector. Emissions reported in 2018 for 580 stacks belonging to power plants (PP), combined heat and power plants (CHP), district heating plants (DHP), and industrial combined heat and power plants (CHPI) were used as input. Future emissions for 2030–2050 were calculated for two energy scenarios: non-nuclear and nuclear, described in detail in the article [44]. External costs were calculated based on the results of pollutant concentration modelling, information on the number of people exposed to air pollution, concentration–response functions, and the unit costs assigned to given health impacts.

The results show that the external costs in Poland related to emissions from the energy sector in 2018 were in the range of EUR 0.78–1.91 billion (Table 9). These results are significantly lower compared to the EUR 12 billion presented in the last European Commission report [15]. The EC report does not use the impact pathway approach (IPA) but instead uses a direct external cost factor at the technology level. In general, the estimated external cost per unit of energy produced in the range of 2.9–7.3 EUR/MWh is in agreement with the results of other studies [15,37–42].

The external cost in Poland decreases sharply until 2040 and may then increase due to the increase in PM10 emissions (Figure 4). Higher PM10 emissions after 2040 can be explained by the increase in the use of biomass in power generation (Table 7). It is therefore important to adequately set the future emission standards for biomass-fired units to minimize their impact.

The avoided external costs between 2018 and 2050 are in the range of EUR 15.5–30.6 and 15.8–33.4 billion (EUR 2018) for the non-nuclear and nuclear scenarios, respectively (Table 10). The first conclusion from these results is that the development of nuclear energy will not have a significant impact on external costs. The results from the non-nuclear and nuclear scenarios are relatively close. The second most important conclusion of this paper is that the external costs avoided are lower than the costs of transforming the Polish energy sector towards carbon neutrality by 2050. The avoided external costs constitute only about 15–30% of the estimated investment cost of decarbonizing the Polish power sector.

It should be noted that this paper did not take into account the costs of climate change related to CO_2 emissions. The climate costs borne by society in Poland may be much higher than the costs of the energy transition. However, the effects related to CO_2 are difficult to estimate as they appear globally and depend on all sources (total emissions). The separation of one sector in one relatively small country (responsible for about 1% of global emissions) is subject to a large error.

When estimating the external costs related to the health impacts of air pollution, one should be aware of possible inaccuracies appearing at all steps of the impact pathway approach: emission estimation, dispersion modelling, and slopes of concentration–response functions [71]. Therefore, it is difficult to estimate the uncertainties in each step. Considering the discussion and results of estimating uncertainty of pollution damage costs using the uniform world model (UMW), the cumulative external costs for the non-nuclear scenario and nuclear scenario can be in the range of (68% CI) 2.1–51.3 and 1.9–47.2 billion EUR 2018, respectively.

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