The International Journal of Life Cycle Assessment (2018) 23:2165–2177
https://doi.org/10.1007/s11367-018-1450-z

Comparative life cycle assessment of current and future electricity generation systems in the Czech Republic and Poland

Dorota Burchart-Korol[1] · Pavlina Pustejovska[2] · Agata Blaut[3] · Simona Jursova[2] · Jerzy Korol[3]

Received: 12 October 2017 / Revised: 8 February 2018 / Accepted: 12 February 2018 / Published online: 19 February 2018

Abstract

Purpose The purpose of the study was to perform a comparative life cycle assessment of current and future electricity generation systems in the Czech Republic and Poland. The paper also outlines the main sources of environmental impact for the different impact categories for the electricity generation technologies analyzed. The analyses covered the years 2000–2050, and were conducted within the framework of the international programme Interreg V-A Czech Republic-Poland, Microprojects Fund 2014–2020 in the Euroregion Silesia.

Methods Environmental assessment was done using the life cycle assessment (LCA) and ReCiPe Midpoint and Endpoint methods, which allowed the presentation of different categories of environmental impact and damage. The LCA was based on ISO 14040 and ISO 14044, using SimaPro 8.2.3 software with the Ecoinvent 3.2 database. The analyses cover both the current electricity production structures in the Czech Republic and Poland, and the projected energy production.

Results and discussion The LCA analyses performed for the energy systems under consideration in the Czech Republic and Poland enabled a comparative analysis of current and forecast energy systems in these countries, as well as identification of the main sources of environmental impact. Comparative analysis of the LCA results showed that current and future electricity generation systems in Poland caused higher environmental impact there, than in the Czech Republic.

Conclusions The assessment of the life cycle of electricity sources showed that the main determinant of the negative impact on the environment of energy systems in both Poland and the Czech Republic was the consumption of solid fuels, and in particular, the consumption of lignite. It is important to highlight that this is the first attempt of a comparative LCA of electricity production in the Czech Republic and Poland. This is also the first approach that contains analyses of the life cycle assessment of both present and future energy systems. The economic assessment and eco-efficiency of current and future electricity generation systems in European Union countries will be addressed in future research.

Keywords Current and future electricity generation systems · Czech Republic · Poland · Environmental impact categories · Life cycle assessment

Abbreviations

1,4-DB	1,4-Dichlorobenzene
E/A	Egalitarian/average
FU	Functional unit
GHG	Greenhouse gas
GWh	Gigawatt-hour
GWP	Global Warming Potential
H/A	Hierarchist/average
I/A	Individualist/average
IEA	International Energy Agency
LCA	Life cycle assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MWh	Megawatt Hour
PM10	PM10 particulate matter 10 μm or less in diameter
PMF	Particulate matter formation
Pt	Ecopoints
TPES	Total primary energy supply

Responsible editor: Shabbir Gheewala

✉ Jerzy Korol
jkorol@gig.eu

[1] Silesian University of Technology, ul. Akademicka 2A, 44-100 Gliwice, Poland

[2] Technical University of Ostrava, 17. listopadu 15, Ostrava-Poruba, Czech Republic

[3] Central Mining Institute, Plac Gwarków 1, 40-166 Katowice, Poland

1 Introduction

Energy technology is an important factor in global development. With the economic growth now occurring in many countries, the consumption of electricity is growing. Between 1974 and 2014, global gross electricity production increased from 6287 to 23,815 TWh; the average annual growth rate was 3.4%. In 2014, 66.7% of the world's gross electricity production came from fossil fuels, including coal (40.8%), natural gas (21.6%), and oil (4.3%). Hydro power plants supplied 16.4%, nuclear power plants 10.6%, biofuels and waste 2.1%, and geothermal, solar, wind, and other sources accounted for the remaining 4.2% (World Energy Resources Report 2016; Electricity Information Overview 2017).

The World Energy Scenarios Report (2016) presents three exploratory world energy scenarios—Modern Jazz, Unfinished Symphony and Hard Rock. These scenarios were quantified with a global multi-regional energy system model. Each scenario describes the development of a possible future energy system at the global and regional level. Modern Jazz is a competitive world shaped by market mechanisms and a highly complex and fast-paced economic and energy landscape that is constantly changing and evolving due to rapid technology innovation. Emerging technologies are exceptionally disruptive to energy systems and lead to substantial diversification of primary energy. Table 1 shows electricity generation based on Modern Jazz scenario. According to Modern Jazz scenario, a push for efficiency drives rapid electrification of energy systems. New power generation is dominated by natural gas, which accounts for 43% of generation growth to 2030. Wind and solar encompass 31% of new electricity production. Electricity generation has grown 2.0 times since 2014 and the electrification of final energy consumption has reached 28%. Wind and solar generation reflect 30% of total electricity production (World Energy Scenarios Report 2016).

In Unfinished Symphony, national governments unite and take effective policy action on climate change, supported by the values of civil society and an effective system of international governance. Economic growth is moderated, but also more environmentally and socially sustainable and more evenly distributed, with high levels of infrastructure investment.

Table 2 shows electricity generation based on Unfinished Symphony scenario. An emphasis on energy efficiency, moderated economic growth and higher electricity prices dampen electricity demand early in the period. The push for efficiency also accelerates the electrification of energy systems. The electrification of the final consumption of energy grows from 18% in 2014 to 20% in 2030. Natural gas accounts for 20% of growth in generation. By 2060, electricity generation has grown 1.9 times since 2014, and the electrification of final energy consumption has reached 29%. More than 39% of electricity generation comes from wind and solar power plants (World Energy Scenarios Report 2016).

Hard Rock explores a world where the geopolitical tensions in East Asia, Europe, the US and the Middle East weaken international governance systems. Governments establish policies that balance security, social welfare and environmental concerns based on the local context and without much consideration for global impacts. Table 3 shows electricity generation based on Hard Rock scenario. According to Hard Rock scenario, slower economic growth, coupled with restricted funding capacity for infrastructure build-out, reduce electricity demand early in the period. Electrification of final energy use rises from 18% in 2014 to 19% in 2030. Growth in

Table 1 Electricity generation based on Modern Jazz scenario, share by fuel type

Electricity generation, %	2014	2020	2030	2040	2050	2060
Coal	41	35	28	20	10	5
Coal with CCS	0	0	0	0	1	1
Oil	4	3	2	1	1	1
Gas	22	25	29	32	33	22
Gas with CCS	0	0	0	0	2	10
Nuclear	11	12	10	10	10	10
Hydro	16	16	15	14	14	14
Biomass	2	3	3	4	4	5
Biomass with CCS	0	0	0	0	0	0
Wind	3	5	8	11	15	18
Solar	1	2	4	7	9	12
Geothermal	0	0	1	1	1	1
Other	0	0	0	0	0	0
Total	100	100	100	100	100	100

Source: The World Energy Council report (2016)

Table 2 Electricity generation based on Unfinished Symphony scenario, share by fuel type

Electricity generation, %	2014	2020	2030	2040	2050	2060
Coal	41	34	25	13	1	0
Coal with CCS	0	0	0	1	2	2
Oil	4	2	1	1	0	0
Gas	22	24	23	20	11	2
Gas with CCS	0	0	0	3	11	15
Nuclear	11	13	14	16	16	17
Hydro	16	17	17	16	16	16
Biomass	2	3	4	5	5	5
Biomass with CCS	0	0	0	0	0	0
Wind	3	5	9	14	19	21
Solar	1	2	5	11	15	18
Geothermal	0	1	1	1	2	2
Other	0	0	0	0	0	0
Total	100	100	100	100	100	100

Source: The World Energy Council report (2016)

natural gas and coal generation account for 36 and 4% of added generation in the period, respectively. Renewable energy sources reflect 26% of growth. By 2060, the electrification of final energy consumption has reached 25%, with 20% of electricity generation coming from wind and solar plants (World Energy Scenarios Report 2016).

According to European Commission "Energy Roadmap 2050" (2011a), the European Union is committed to reducing greenhouse gas (GHG) emissions to 80–95% below 1990 levels by 2050 in the context of necessary reductions by developed countries. The European Commission analyzed the implications of this in its "Roadmap for moving to a competitive low-carbon economy in 2050" (European Commission 2011b). In the Energy Roadmap 2050, the Commission explores the challenges posed by delivering the decarbonization objective while at the same time ensuring security of energy supply and competitiveness. The Roadmap shows that the biggest share of energy supply technologies in 2050 comes from renewable energy sources. The second major prerequisite for a more sustainable and secure energy system is a higher share of renewable energy beyond 2020. Coal in the European Union (EU) adds to a diversified energy portfolio and contributes to security of supply. With the development of carbon capture and storage (CCS) and other emerging clean technologies, coal could continue to play an important role in a sustainable and secure supply in the future. Improving energy efficiency is a priority in all decarbonization scenarios. Nuclear energy is a decarbonization

Table 3 Electricity generation based on Hard Rock scenario, share by fuel type

Electricity generation %	2014	2020	2030	2040	2050	2060
Coal	41	34	32	31	24	18
Coal with CCS	0	0	0	0	0	0
Oil	4	4	2	2	1	1
Gas	22	24	25	24	27	26
Gas with CCS	0	0	0	0	0	0
Nuclear	11	12	13	13	13	15
Hydro	16	16	16	15	15	15
Biomass	2	2	3	3	3	4
Biomass with CCS	0	0	0	0	0	0
Wind	3	5	6	8	10	12
Solar	1	2	3	4	5	7
Geothermal	0	0	0	1	1	1
Other	0	0	0	0	0	0
Total	100	100	100	100	100	100

Source: The World Energy Council report (2016) option providing today most of the low-carbon electricity consumed in the EU. It remains a key source of low carbon electricity generation. CCS, if commercialized, will contribute significantly in most scenarios with a particularly strong role of up to 32% in power generation in the case of constrained nuclear production and shares between 19 and 24% in other scenarios. The future of CCS crucially depends on public acceptance and adequate carbon prices.

CO_2 emissions from power generation significant decline between 2010 and 2050, while electricity demand still increases. In 2050, 18% of electricity is generated through power plants with CCS (solids and gas). CCS prevents CO_2 emissions, but is comparatively resource inefficient in relation to unabated fossil fuel combustion (European Commission 2011c).

The EU countries remain fully committed to the Paris Agreement and to climate action. The EU has deposited its instrument of ratification and will meet commitment to reduce its domestic emissions by at least 40% between 1990 and 2030 (European Commission 2011d).

In the European Union in 2015, the main sources of electricity included nuclear energy 867,402 GWhe (26.68%), solid fuels 846,834 GWhe (26.04%), and natural gas 566,075 GWhe (17.41%). All other sources of energy accounted for 29.87%. Figure 1 shows current and future electricity generation systems in the European Union. There has been a projected increase in gross electricity generation from 2000 to 2050 of 3,005,548 to 4,063,737 GWhe. With respect to nuclear energy, the highest consumption was recorded in 2005 (997,699 GWhe). By 2050, nuclear energy consumption is projected to be 736,532 GWhe. In the case of electricity from solids, a significant reduction in consumption is anticipated, up to 251,549 GWhe in 2050. Similarly, for oil, the largest consumption was 181,296 GWhe in 2000, while the lowest is expected in 2050 (4844 GWhe). With respect to electricity from natural gas, consumption is expected to continue to increase (Honus et al. 2016a, b). Also in the case of electricity from biomass, wind, and solar sources, a constant increase in the consumption of these energy sources is anticipated. In the European Union, the gross electricity generation from biomass in 2000 was 46,401 GWhe, and in 2050, generation is forecast to reach 391,380 GWhe. Gross electricity generation from wind in 2000 was 22,254 GWhe, while in 2050, it is projected to be 979,998 GWhe. From solar, in 2000, generation was 117 GWhe, while in 2050, it is expected to be 428,535 GWhe (EU Reference Scenario 2016).

In some European countries, vast coal and lignite resources are still being used to produce electricity. Because this practice generates high greenhouse gas emissions, it is desirable to reduce the consumption of fossil fuels in energy systems. According to the European Commission's recommendations, this trend should change towards a steady reduction of hard coal use in the structure of electricity production. Information on the energy market in EU countries (including energy profiles that include facts on energy mix, energy security, competitiveness, sustainability, and EU state infrastructure) is included in the European Commission's reports (European Commission 2017).

Economic and environmental aspects of the development of new energy technologies are both important. The environmental impact of individual energy systems varies depending on the sources used, including coal, nuclear power, renewable energy, and other sources. The reference literature shows the environmental impact of individual energy sources; however, there are no results of environmental analyses that take into account the LCA of the projected energy sources. One of the methods used to assess the environmental impact of energy systems is Life Cycle Assessment (LCA). In the literature, there are only a few papers on the LCA for energy systems, including electricity and heat production in Poland

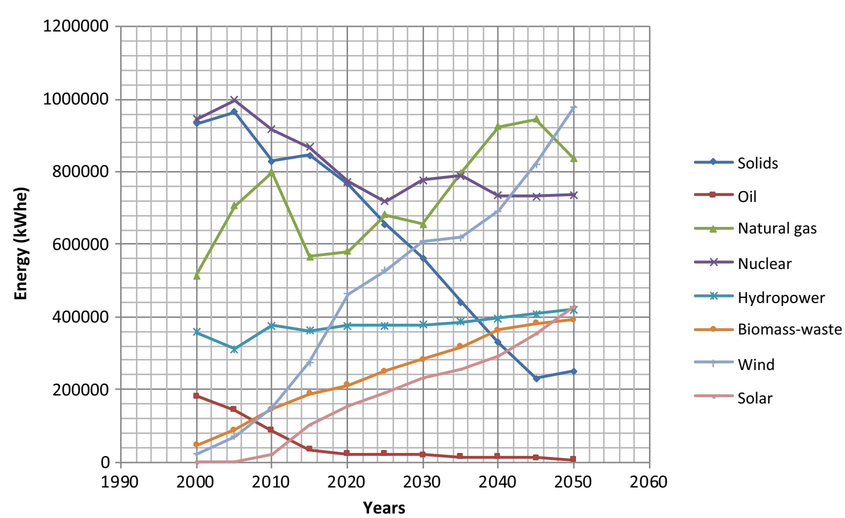

Fig. 1 Life cycle inventory of electricity generation by source in the European Union (EU Reference Scenario 2016)

(Kulczycka and Pietrzyk-Sokulska 2012; Bieda 2011; Lelek et al. 2016; Adamczyk and Dzikuć 2014; Lewandowska et al. 2015; Dzikuć and Adamczyk 2015). The literature also contains the results of the LCA analyses for innovative clean coal technologies (Burchart-Korol et al. 2016; Czaplicka-Kolarz et al. 2014). Previous papers on LCA for Poland focused on analysis of current energy systems. In the case of the Czech Republic, there is a lack of papers concerning LCA in the literature on energy systems, both current and projected. Only the results of LCA analyses for municipal waste management in the Czech Republic are present in the literature (Koci and Trecakova 2011).

The purpose of this paper was to assess the potential environmental impact of the life cycle of present and future energy systems in the Czech Republic and Poland, in connection with the implementation of the project: Programme Interreg V-A Czech Republic-Poland, Microprojects Fund 2014–2020 in the Euroregion Silesia.

2 Materials and methods

2.1 Goal and scope of analysis

The aim of this paper is the life cycle assessment of current and future electricity generation systems in the Czech Republic and Poland, taking into account the trend from 2000 to 2050. The most important environmental impact categories have been presented and the main sources of the environmental impact of electricity generation in Poland and the Czech Republic were identified. For comparative purposes, all analyses were referred to the same functional unit. The function of the system was the production of electricity; therefore, the functional unit (FU) was 1 MWhe of obtained electricity. The boundary of the system covered all the technologies included in the individual electricity mix in the countries covered in the analysis. The approach used was "from cradle to gate" (i.e., from cradle to the factory gate).

2.2 Data inventory—electricity generation in the Czech Republic and Poland

The Czech Republic is located in central Europe. The population is 10.5 million, and the country surface area is 78,866 km^2. The Czech Republic is one of the most developed and industrialized economies in Central and Eastern Europe. The dominant source of energy in the Czech Republic is coal, which constitutes 39.2% of the total primary energy supply (TPES). Poland is a Central European state located by the Baltic Sea, and the ninth largest country in Europe with an area of 312, 679 km^2. The population is estimated at 38 million inhabitants. The main source of energy in Poland is coal, which generates 51% of the total primary energy supply (TPES).

For the purpose of environmental life cycle assessment, data for the current and future electricity generation in the Czech Republic and Poland were identified and documented. The data from European and global energy bases were used for the purpose of the LCA analyses of energy systems. Tables 4 and 5 show the inventory data required to perform the LCA analyses. Detailed description of the energy policy in the Czech Republic was presented in the paper (Energy Policies of IEA Countries—Czech Republic 2016 Review), while the description of energy policy in Poland was presented in the paper (Energy Policies of IEA Countries—Poland 2016 Review).

In the Czech Republic, in comparison to the remaining International Energy Agency (IEA) member countries in 2015, the share of fossil fuels in electricity generation was thirteenth-highest. In contrast, the share of coal was fourth-highest for Estonia, Poland, and Australia; natural gas the fifth-lowest and oil the fourth-lowest. The nuclear share was eighth-highest among the IEA member states producing nuclear power. A life cycle inventory of electricity generation by source in the Czech Republic is presented in Table 4. In the Czech Republic, in recent years, the main sources of energy include nuclear energy and solids. The trend in the years 2000–2050 shows a significant increase in nuclear energy (from 13,590 to 54,467 GWhe) and a significant drop in solids consumption (from 52,752 to 17,948 GWhe). In the case of electricity obtained from oil, there has been a decline, and after 2020, this source is not expected to be used in the Czech Republic for the production of electricity. With regard to gas, biomass, wind and solar, increase in consumption in the years until 2050 is expected.

For Poland, the life cycle inventory of electricity generation by source is presented in Table 5. Electricity production in Poland is dominated by coal. Hard coal constitutes more than 60% of the coal used for energy production, the remaining part is lignite. Poland has the highest share of coal in electricity production among all the IEA countries and the second largest share of fossil fuel consumption in electricity generation after Australia. Despite the rapid growth of renewable sources, Poland is still among the IEA member countries with the lowest shares of renewable energy sources. Coal will continue to be the main source of energy for years to come. In 2035, it is planned to reduce this source to 105,487 GWhe, yet by 2050 it is likely to remain 63,563 GWhe. No nuclear power is currently produced in Poland, but two reactors with a combined capacity of 6 GWe of nuclear energy are planned after 2035.

2.3 LCA method

The Life Cycle Assessment (LCA) technique was used to evaluate the potential environmental impact of the analyzed

Table 4 Life cycle inventory (LCI) of gross electricity generation by source in the Czech Republic (GWhe)

	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Nuclear energy	13,590	24,728	27,998	27,596	27,596	27,596	27,594	37,668	47,742	54,556	54,467
Solids	52,752	49,522	47,113	41,095	41,990	40,672	38,739	28,716	14,514	6972	17,948
Oil	372	326	159	231	0	0	0	0	0	0	0
Gas	3907	4215	4121	5853	3591	6677	10,047	12,143	15,189	16,583	11,840
Biomass-waste	531	739	2188	2214	1097	2781	3669	4533	6602	8251	7608
Hydro	1758	2380	2789	2421	2541	2471	2561	2716	2941	3453	3877
Wind	1	21	335	508	759	824	878	912	991	1664	1782
Solar	0	0	615	2149	2214	2254	2276	2352	2395	2422	2967
Total	72,911	81,931	85,319	82,069	79,790	83,278	85,766	89,041	90,376	93,905	100,491

Source: Energy Policies of IEA Countries—Czech Republic 2016 Review

energy systems. The LCA method was chosen for environmental assessment because it allows performance of environmental analysis taking into account the life cycle of electricity production systems, and makes it possible to show many different environmental aspects. Life cycle analysis was conducted in accordance with the ISO 14040: 2006 and ISO 14044: 2006 standards. The LCA was made using the SimaPro v.8.2.3 package with the Ecoinvent 3.2 database. Several ReCiPe Midpoint and ReCiPe Endpoint methods were selected to present various impact categories and damage categories. The main goal of the (Goedkoop et al. 2013) is to convert the long list of input and output data for the entire ReCiPe method life cycle into a limited number of indicators that express the relative intensity of the environmental impact category (ReciPe 2012). The life cycle assessment consisted of four stages (PN EN ISO 14040: 2009):

1. Defining the purpose and scope—at this stage, the functional unit, the boundaries of the system, and the basic assumptions of the analysis were established.
2. Life Cycle Inventory (LCI)—included inventory of all the data necessary for the LCA analysis.
3. The Life Cycle Impact Assessment (LCIA)—consisted of the calculation of the environmental impact category.
4. Interpretation of the results.

The choice of the ReCiPe method was justified by its ability to assess, in a holistic and complementary manner, the environmental impact. Moreover, the possibility of including the weighting stage in this method allows obtaining a result in the form of a single indicator. The ReCiPe method takes into account the environmental impact from the use of lignite and hard coal, which is an important issue for energy technology. The main advantages of the ReCiPe method include its versatility—it encompasses many environmental impact categories—and that the model was developed for Europe. The impact category and damage categories in the ReCiPe method are described in detail in Goedkoop et al. (2013).

Life cycle assessment according to the ReCiPe method adopted for this analysis is based on the following stages:

– Classification: The collected input and output data are assigned to the impact categories.

Table 5 Life cycle inventory (LCI) of gross electricity generation by source in Poland (GWhe)

	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Nuclear energy	0	0	0	0	0	0	0	27,703	41,555	55,407	69,258
Solids	135,888	142,161	136,592	137,628	141,228	131,372	132,075	105,487	76,601	69,230	63,563
Oil	1916	2757	2892	9	0	471	471	447	283	279	292
Gas	2961	6573	6689	2968	9649	20,733	30,214	35,886	43,646	45,154	41,710
Biomass-waste	298	1532	6332	9667	11,436	13,082	15,892	17,444	21,299	20,772	20,850
Hydro	2106	2201	2920	2397	2427	2553	2765	2766	3243	4019	4403
Wind	5	135	1664	9669	11,437	20,135	21,665	21,687	32,411	37,073	44,968
Solar	0	0	0	29	67	67	84	132	190	241	303
Total	143,174	155,359	157,089	162,367	176,244	188,413	203,166	211,552	219,228	232,175	245,347

Source: Energy Policies of IEA Countries—Poland 2016 Review

- Characterization: The value of the indicator category is calculated using the characterization parameter. As a result of this stage, the value of the category indicators for the different impact categories is obtained.
- Standardization: This is the stage during which the values of the impact category indicators are referred to the reference information (in the ReCiPe 2008 method), to the value of indicators obtained annually across Europe per capita. As a consequence of standardization, the contribution of the particular effect to the total effect is determined and the information about the relative importance of an indicator is obtained.
- Grouping: This consists of assigning impact categories to sets; ReCiPe 2008 gives the ability to group impact categories (intermediate points) into three categories of damage (end points). These are:

• Human health—the following categories of impacts were added to this category of impacts: greenhouse gas emissions, depletion of the ozone layer, toxicity to humans, photochemical smog formation, dust formation, and ionizing radiation.
• Ecosystems—this includes greenhouse gas emissions, land acidification, eutrophication of fresh and marine waters, ecotoxicity of land, ecotoxicity of freshwater and marine waters, occupation of agricultural and urban areas, and conversion of natural areas.
• Resources—this includes the consumption of fossil fuels and metals.

- Weighting: This involves converting the standardized values using the selected weighting factors and aggregating these values within the impact category and damage category. The result of damage after weighting is expressed in ecopoints (Pt). One ecopoint (1 Pt) represents one thousandth of the annual environmental damage caused by one resident of Europe.

3 Results and discussion

Based on the LCA analysis using the ReCiPe Midpoint method for energy systems, environmental indicators were obtained in terms of impact categories (Pang et al. 2015). On the basis of standardization, the relative importance of the environmental impact categories derived was compared to the effects of this type occurring in other parts of Europe. It was found that the most important categories of impact include climate change, human toxicity, particulate matter formation, and fossil depletion. The climate change impact category refers to greenhouse gas emissions and expresses the radiative forcing of greenhouse gas emissions over a 100-year horizon, expressed in kilograms of CO_2 equivalent. The GHG emission factor is calculated based on the Global Warming Potential (GWP). The impact category of human toxicity includes exposure to toxic substances by inhalation of air and ingestion of food. The reference substance selected was 1,4-dichlorobenzene, expressed in kg 1,4-DB eq. The impact category particulate matter formation considers air pollution as a result of dust emissions < 10 μm in diameter (PM10), as well as the formation of aerosols of sulfur oxides, nitrogen, and ammonia. The presence of such particles in the air increases the probability of respiratory diseases. The impact category, fossil fuel consumption, includes consumption of methane, oil, and coal. The impact of fuel consumption is assessed on the basis of an increase in the cost of acquiring energy resources in the future as a result of their reduced quality. The conversion of fuels to the equivalent of oil (kg-oil eq) was based on a net calorific value of 42 MJ/kg (Goedkoop et al. 2013).

Results from the comparative analysis of environmental impact categories of electricity production in Poland and the Czech Republic are presented in Fig. 2. For all impact categories, higher environmental indicators for electricity generation in Poland have been demonstrated. The greenhouse gas emission factor for the electricity generation system in the Czech Republic was 984.90 kg-CO_2 eq/FU in 2000, while in 2050 the potential impact on greenhouse gas emissions was projected to be 331.40 kg-CO_2 eq/FU. The starting value of greenhouse gas emissions from 2000 through the next 50 years is projected to decrease by 66.1%. In the case of the electricity generation system in Poland in the year 2000, it amounted to 1135.57 kg-CO_2 eq/FU, and in the year 2050 is expected to amount to 460.37 kg-CO_2 eq/FU, which for Poland, is 59.45% lower than the starting value.

Human toxicity for the electricity generation system in the Czech Republic in 2000 amounted to 249.12 kg-1,4-DB eq/FU, while in 2050 it is projected to be 245.58 kg-1,4-DB eq/FU. Human toxicity for electricity generation in Poland in 2000 was 850.36 kg-1,4-DB eq/FU, but in 2050 is projected to be 248.60 kg-1,4-DB eq/FU. The projected change in the Czech Republic for human toxicity for the electricity generation system was negligible and amounted to just over 1%, while in Poland it was 70.77%.

Particular matter formation (PMF) for the electricity generation system in the Czech Republic in 2000 was 0.59 kg-PM10 eq/FU, but in 2050 is projected to be 0.44 kg-PM10 eq/FU. The particulate matter formation for the electricity generation system in Poland in 2000 was 1.72 kg-PM10 eq/FU and in 2050 is projected to be 0.76 kg-PM10 eq/FU. In the case of PMF, the values in both the Czech Republic and Poland are expected to decrease, in the Czech Republic by 25.44% and in Poland by 55.81%. While analyzing the results of the PMF emission, it was found that the emissions during the years from 2020 to 2050 in Poland

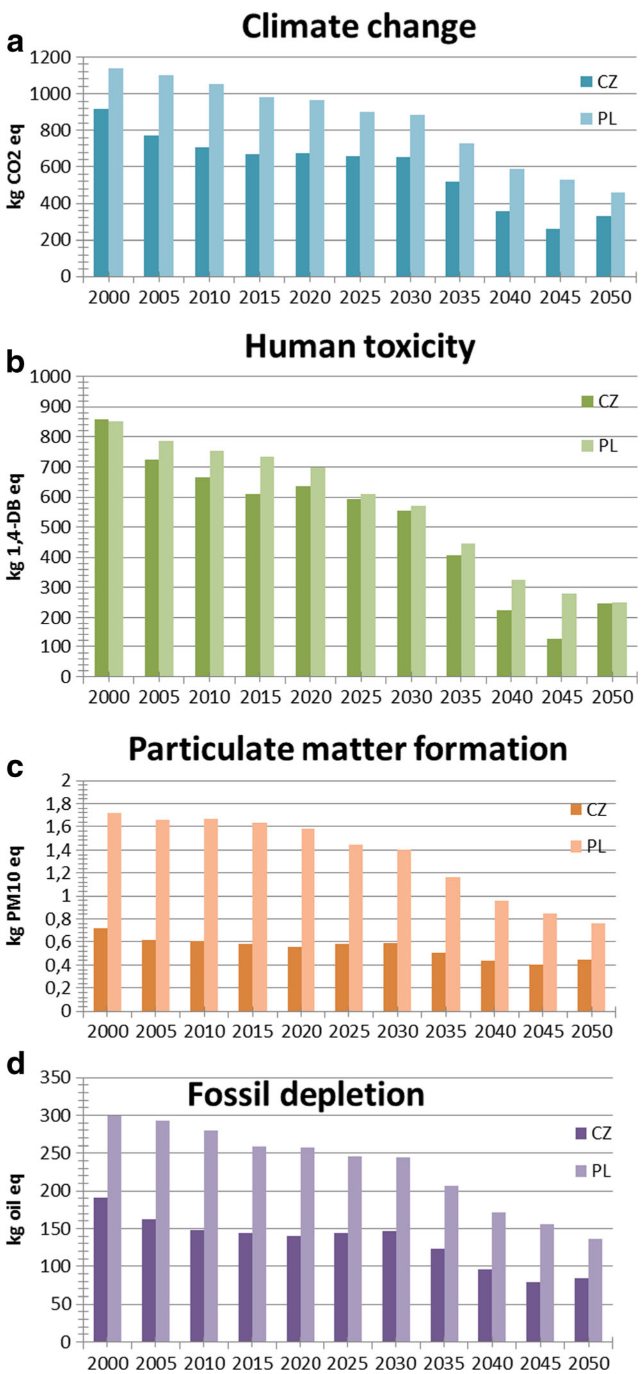

Fig. 2 Comparative analysis of environmental impact of electricity production in Poland and the Czech Republic

are expected to decrease much faster than in the Czech Republic.

Fossil depletion for the electricity generation system in the Czech Republic in 2000 amounted to 258.39 kg-oil eq/FU, but in 2050 is expected to amount to 84.00 kg-oil eq/FU. Fossil depletion for electricity generation in Poland in 2000 amounted to 299.40 kg-oil eq/FU, while in 2050 it is expected to amount to 135.74 kg-oil eq/FU. In the case of the Czech Republic fossil depletion for electricity generation is expected to decrease by 67.49%, and in Poland in 2050, fossil depletion for electricity generation could be lower by 54.66%.

It has been shown that despite the decreasing tendency of environmental impact in the Czech Republic, a slight increase in the impact related to all the impact categories analyzed was indicated between 2045 and 2050, including human toxicity, where the increase is the highest. This is primarily due to a slight increase in the share of solid fuels in the electricity generation structure in 2050 compared to 2045, as shown in Table 4.

A detailed analysis of the impact categories for individual sources of electricity in the Czech Republic and Poland was made in order to determine the environmental determinants of the life cycle assessment. The determinants of the environmental life-cycle assessment of current and future electricity generation systems in the Czech Republic are presented in Fig. 3. The environmental assessment of Czech electricity sources shows that the greenhouse gas emission factor is determined by the amount of solids used, and in particular lignite. Life cycle analysis showed that lignite consumption is the factor most affecting human toxicity. Likewise, the effects on the impact categories, particulate matter formation and fossil depletion, have indicated similar outcomes. The solids in the electricity generation system in the Czech Republic were mostly lignite over the period analyzed. It was shown that lignite consumption is associated with high impact in all categories. In the case of the impact category particulate matter formation, the increase in biomass-waste consumption for electricity production from 2025 also results in an increase in the environmental index in this impact category. It has been shown that a significant increase in the consumption of natural gas for the production of electricity affects the increase of greenhouse gas emissions and the PMF. Increasing the consumption of natural gas to produce electricity after 2025 also increases the value of the fossil depletion index. Based on the analyses performed, it was shown that, despite the fact that the share of nuclear energy increases in electrical energy production in the Czech Republic, it is not associated with an increase in environmental impact in any of the impact categories, and the same was demonstrated in the case of solar, wind, and hydropower energy.

The determinants of the environmental life-cycle assessment of current and future electricity generation systems in Poland are presented in Fig. 4. The environmental assessment of electricity sources in Poland showed that the greenhouse gas emission factor is determined by the amount of consumed solids, both hard coal and lignite. The life cycle analysis showed that factors affecting human toxicity are primarily influenced by lignite consumption. It was shown that, despite the fact that lignite consumption in Poland is smaller than hard coal consumption (only about 40%), it significantly influences the human toxicity index. This is mainly related to lignite

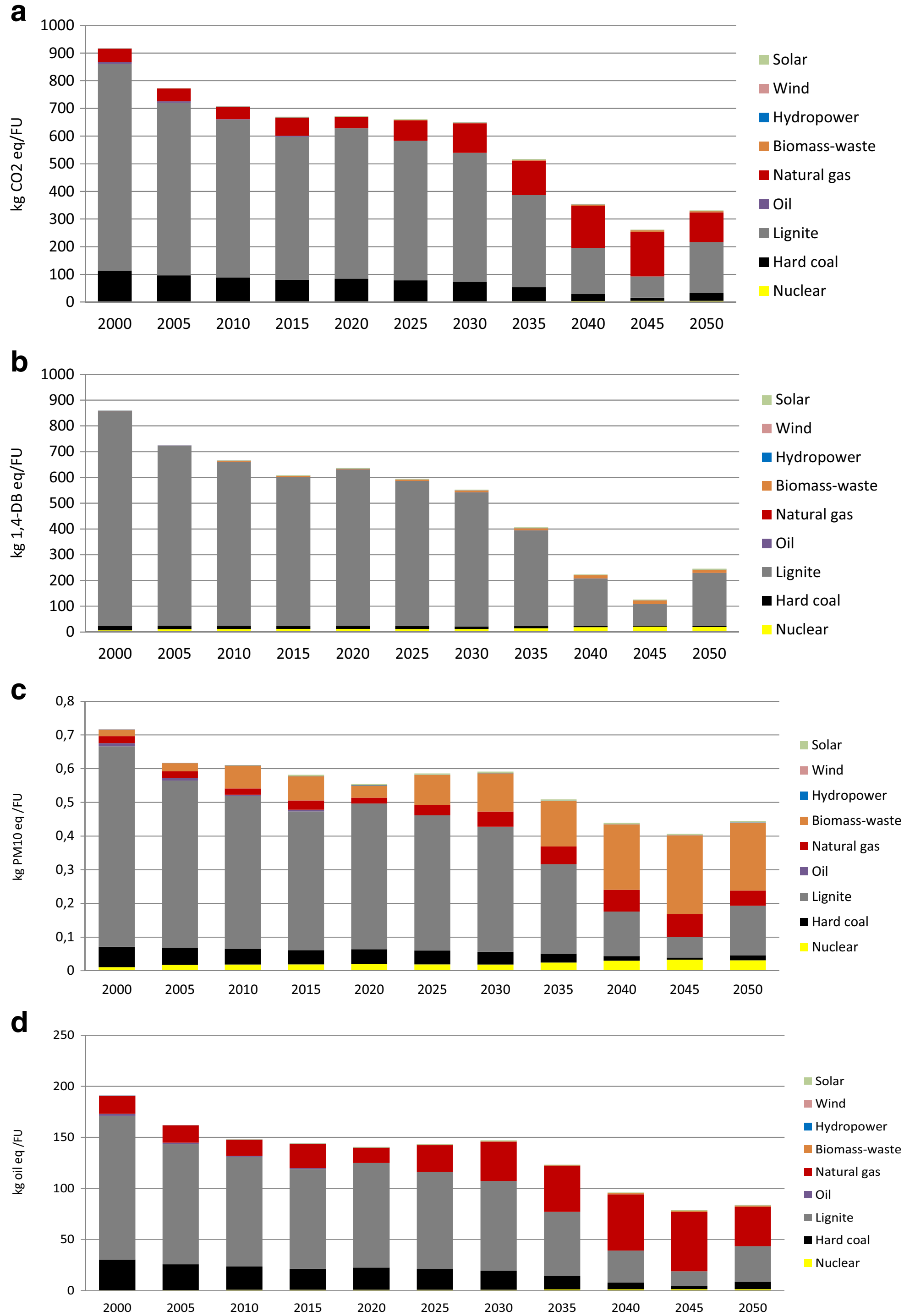

Fig. 3 Determinants of the environmental life cycle assessment of current and future electricity generation systems in the Czech Republic. **a** Climate change. **b** Human toxicity. **c** Particulate matter formation. **d** Fossil fuel depletion

mining, where fly ash still continues to be a significant environmental concern. Particularly high exposure occurs in underground mines in the areas directly related to the extraction and transportation of raw materials and the servicing of mechanical equipment in the mines. Most of the personnel employed in these positions exceed the applicable hygiene exposure standards for dust (Mikołajczyk et al. 2010).

In the case of the impact categories, particulate matter formation and fossil depletion, the consumption of solids was shown to be most influential. The increase in biomass-waste consumption for electricity production from 2025 also resulted in an increase in the environmental index in the case of particulate matter formation. Increasing the use of natural gas for electricity production from 2015 resulted in increased

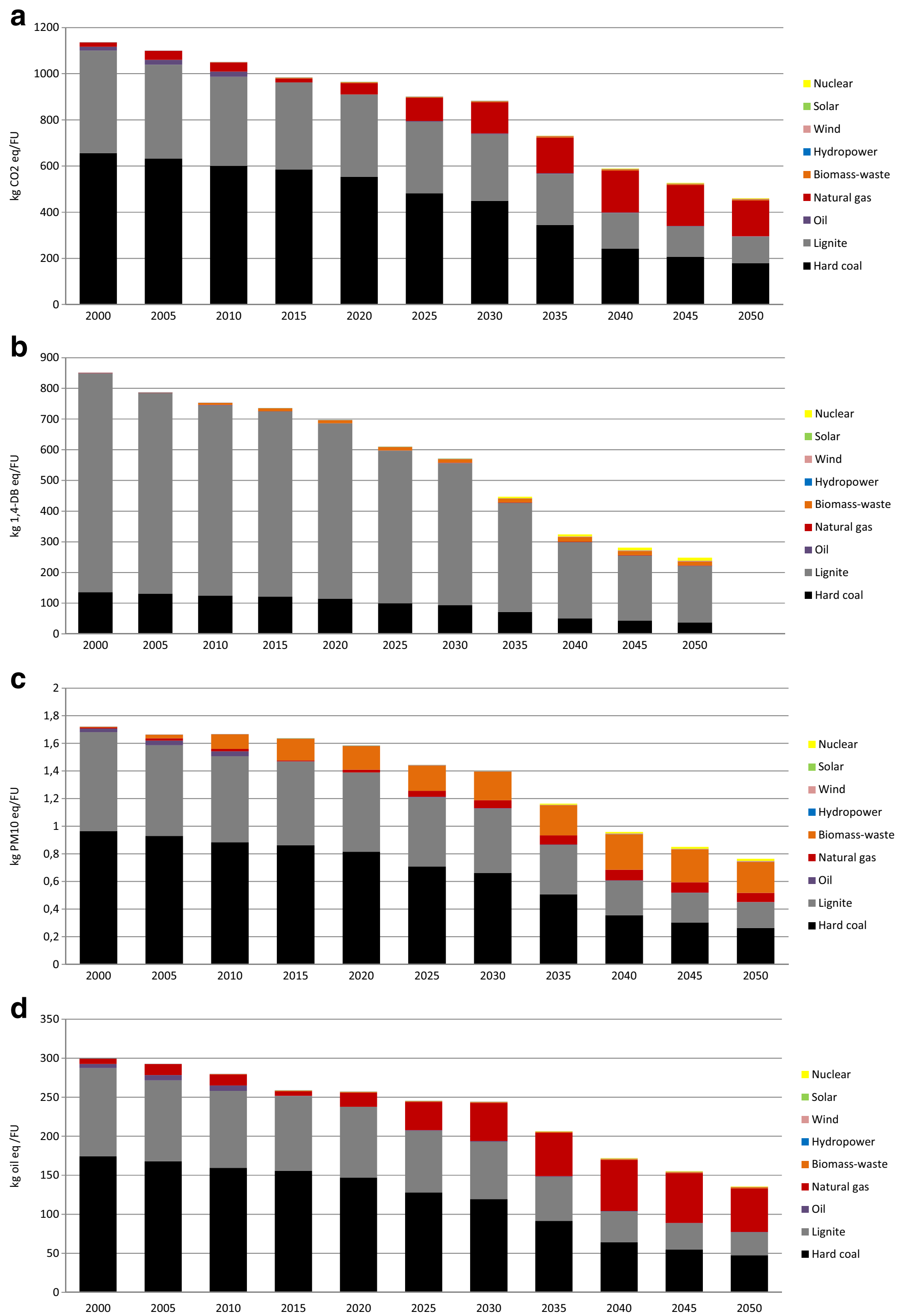

Fig. 4 Determinants of the environmental life cycle assessment of current and future electricity generation systems in Poland. **a** Climate change. **b** Human toxicity. **c** Particulate matter formation. **d** Fossil fuel depletion

fossil depletion and greenhouse gas emissions. It was also found that the planned (projected) introduction of nuclear energy after 2035 would not adversely affect the analyzed impact categories.

Based on the characterization results, it is not possible to determine in which categories the impact is to be considered significant or to compare indicators for different impact categories. This is why standardization and weighting of the results based on standardization indicators and weightings developed for the ReCiPe Endpoint 2008 method were performed. The set of indicators presented in Table 6 was used.

Regarding the analyses carried out, the weighting stage was necessary in view of the comparative analysis of the impact of the individual energy systems of the analyzed

Table 6 Indicators used in the standardization and weighting stage in the ReCiPe 2008 (H/A) method for Europe

Damage category	Standardization	Weighting
Human health	49.5	400
Ecosystems	5530	400
Resources	0.00324	200

Source: ecoinvent 3.2, ReCiPe 2008 method

countries for each year. Tables 7 and 8 outline the results of the life cycle assessment, taking into account the stages of standardization and weighting divided into particular damage categories: human health, ecosystem, and resource consumption calculated according to the ReCiPe Endpoint H/A method.

On the basis of the analyses of the sum of the damage values expressed in Pt/FU at the beginning of the analyzed period (2000 through 2050), it was found that in both the Czech Republic and Poland, reduction of negative impact on the environment will take place. In the Czech Republic, this is expected to be by 57.98% (from 78.30 to 31.00 Pt/FU) and in Poland by 60.4% (from 105.47 to 44.31 Pt/FU). Comparative analysis of the damage categories of current and future energy generation systems in the Czech Republic and Poland showed that all categories of damage, including Human Health, Ecosystems, and Resources, were lower for the Czech Republic in all the years analyzed.

In the Czech Republic, the Human Health category represented an average of 50% of all damage categories. In 2000, it was 52% while in 2050 it is expected to decrease to 49%. The Ecosystem category represented about 21% of all damage categories each year. On the other hand, in the case of impact categories, Resources showed a projected increase from 26% in 2000 to 30% in 2050.

In Poland, the Human Health category in 2000 was 49% and in 2050 is expected to decrease to 46%. The Ecosystem category represents about 21% of all damage categories each year. On the other hand, in the case of impact categories, Resources showed a projected increase from 30% in 2000 to 33% in 2050.

3.1 Sensitivity of the results of the assessment of environmental indicators resulting from the selected perspective of impact assessment

Sensitivity analysis to the applied LCA methodology was conducted regarding the prospect of assessing adverse environmental effects resulting from the life cycle of power systems in the Czech Republic and Poland.

In the LCA during the standardization and weighting stages, which needed to be conducted to obtain a single ecoindicator, the subjectivity of results appears. Subjectivity is related to ascribing weights to impacts related to human health, ecosystem damage, and the use of non-renewable resources. These weights were selected by expert method, thus representing the views of the scientific community on what environmental issues are considered more important: the protection of human health, species diversity, or preservation of natural resources for future generations.

There are three groups of weighting factors based on the system of values of three averaged archetypal personalities: individualist/average (I/A: individualist/average), egalitarian (E/A: egalitarian/average), and hierarchist (H/A: hierarchist/average). Hierarchist perspective (H/A), takes into consideration mechanisms, models and the impacts widely accepted in the world. The hierarchists perspective is the result of a compromise between the perspective of individuals and egalitarian attitude. Individualists perspective (I/A) pursue a "business as usual" scenario, accept only those restrictions which have a sound scientific basis, they are society and science oriented, prefer a short-term perspective and non-intervention policy. Egalitarian perspective (E/A) uses long-term perspective. This is characterized by caution, in the case of doubt this takes into account the potential impacts, this does not accept scientific and political organizations advice, nor the attitude that future problems can be avoided. The characteristics of these perspectives were presented previously (Burchart-Korol 2016). The LCA analyses of energy systems in this work were from a hierarchical perspective (H/A). Figure 5 shows the results of the sensitivity analysis of the obtained ReCiPe 2008 indicators according to the adopted assessment perspective: E/A, H/A, I/A.

The sensitivity of the obtained results to the evaluation perspective is high. Environmental impact assessed from the

Table 7 Damage category of current and future energy generation systems in the Czech Republic (Pt/FU)

Damage category	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Human health	41.08	34.75	32.12	30.14	30.46	29.71	28.89	22.74	15.42	11.33	15.10
Ecosystems	16.65	14.07	13.02	12.37	12.29	12.25	12.16	9.80	7.08	5.52	6.66
Resources	20.57	17.49	16.04	15.67	15.26	15.57	15.96	13.43	10.54	8.70	9.25
Total	78.30	66.31	61.18	58.18	58.02	57.53	57.01	45.97	33.03	25.55	31.00

Table 8 Damage category of current and future energy generation systems in Poland (Pt/FU)

Damage category	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Human health	52.13	49.95	48.15	45.89	44.56	40.86	39.60	32.50	25.84	22.98	20.26
Ecosystems	21.15	20.56	19.91	18.80	18.48	17.32	17.04	14.25	11.73	10.50	9.24
Resources	32.19	31.45	30.10	27.87	27.69	26.48	26.35	22.32	18.67	16.89	14.82
Total	105.47	101.96	98.15	92.56	90.74	84.66	83.00	69.07	56.24	50.37	44.31

egalitarian perspective (E/A) was the highest; in this case, the assessment model takes into account all the factors that potentially contribute to environmental pollution. On the other hand, the environmental assessment from the perspective of the individualist resulted in the lowest environmental impact indicators, because in this case, the assessment model omits all the factors that have not been proven, and assigns less importance to the use of resources, assuming that the problem of resource depletion will be solved in the future owing to new technologies. Although the differences in the results are high, they did not significantly affect the current and future electricity generation systems studied.

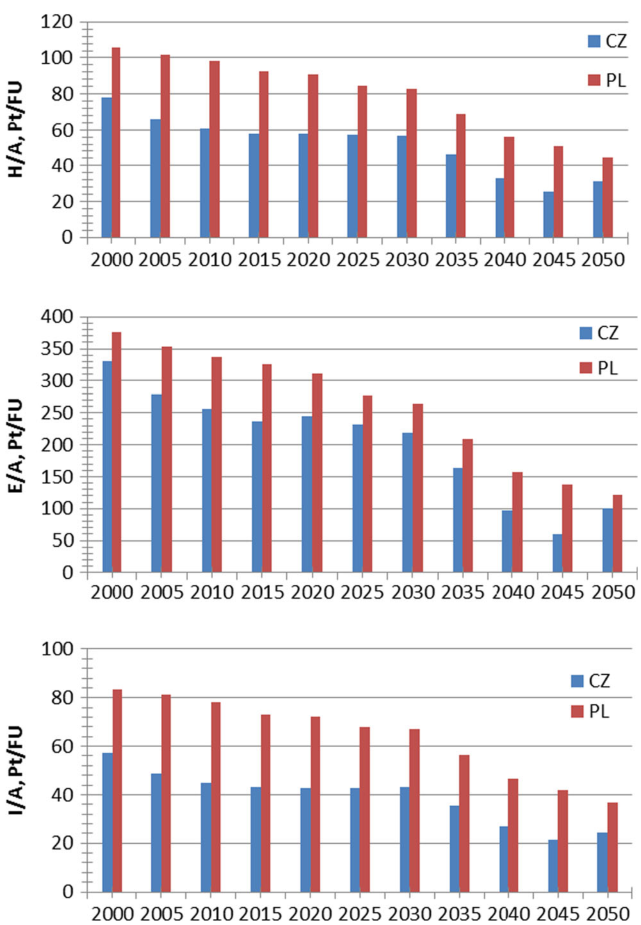

Fig. 5 Results of the sensitivity analysis of the obtained ReCiPe 2008 indicators according to the assessment perspective (E/A, H/A, or I/A) adopted

4 Conclusions

1. As a result of the environmental life cycle assessment, data for current and future electricity generation in the Czech Republic and Poland were identified and documented.
2. Environmental analysis using the LCA technique made it possible to assess the potential environmental impact during the life cycles of current and future electricity generation systems in the Czech Republic and Poland.
3. Comparative analysis of the LCA results shows that current and future electricity generation systems in Poland cause greater environmental impact than in the Czech Republic in all impact categories: climate change, human toxicity, particulate matter formation, and fossil depletion.
4. The environmental assessment of electricity sources in the Czech Republic showed that the main determinant of the negative impact on the environment of energy systems is the consumption of solids, in particular lignite coal.
5. Despite reducing the share of solid fuels in electricity generation, both in the Czech Republic and in Poland, their share has the greatest impact on the environment. On the other hand, the increase in nuclear share does not negatively affect the environment in the electricity production systems analyzed.
6. The environmental assessment of electricity sources in Poland showed that the environmental impact is determined by the consumption of solids, including both hard coal and lignite.
7. It has been shown that the use of lignite, both in Poland and the Czech Republic, for the production of electricity determines the impact on human toxicity.
8. Comparative analysis of damage categories in current and future energy generation systems in the Czech Republic and Poland showed that all categories of damage, including Human Health, Ecosystems, and Resources, are lower for the Czech Republic in all the years analyzed.

Recommendations and perspectives

1. The analyses carried out so far will be used for economic analyses and eco-efficiency analyses of energy systems in the European Union countries.

2. In order to increase environmental efficiency, the reduction of solids consumption should be considered the most important measure for better electricity generation systems.

Acknowledgements This research was conducted within the framework of project LO1404: Sustainable development of the ENET Centre and the project CZ.1.05/2.1.00/19.0389: Research Infrastructure Development of the CENET, supported by project Interreg V-A Czech Republic-Poland, Microprojects Fund 466 2014-2020 in the Euroregion Silesia (reg. no. 467 CZ.11.4.120/0.0/0.0/16_013/0000653).

Compliance with ethical standards

This research did not involve human or animal participants.

Conflict of interest The authors declare that they have no conflict of interest.

References

Adamczyk J, Dzikuć M (2014) The analysis of suppositions included in the Polish Energetic Policy using the LCA technique—Poland case study. Renew Sust Energ Rev 39:42–50

Bieda B (2011) Life cycle inventory of energy production in ArcelorMittal steel power plant Poland S.A. in Krakow, Poland. Int J Life Cycle Assess 16:503–511

Burchart-Korol D, Korol J, Czaplicka-Kolarz K (2016) Life cycle assessment of heat production from underground coal gasification. Int J Life Cycle Assess 21:1391–1403

Czaplicka-Kolarz K, Burchart-Korol D, Krawczyk P (2014) Analiza wrażliwości ekoefektywności technologii produkcji energii w procesie opartym na naziemnym zgazowaniu węgla. Przem Chem 93:1910–1915 (in Polish)

Dzikuć M, Adamczyk J (2015) The ecological and economic aspects of a low emission limitation: a case study for Poland. Int J Life Cycle Assess 20:217–225

Electricity Information Overview (2017) The International Energy Agency http://www.iea.org

Energy Policies of IEA Countries - Czech Republic (2016) Review (2016). The International Energy Agency http://www.iea.org

Energy Policies of IEA Countries - Poland (2016) Review (2016) The International Energy Agency http://www.iea.org

EU Reference Scenario (2016) Energy, transport and GHG emissions—trends to 2050 (2016) The European Commission report

European Commission (2011a) Energy Roadmap 2050, Communication from the Commission to the European Parliament, The Council, The European Economic and Social Committee and the Committee of the Regions. COM(2011) 885 final, Available online at http://ec.europa.eu/

European Commission (2011b) Communication from the Commission to the European Parliament, The Council, The European Economic and Social Committee and the Committee of the Regions, A Roadmap for moving to a competitive low carbon economy in 2050, COM(2011) 112 final, Available online at http://ec.europa.eu/

European Commission (2011c) Energy Roadmap 2050 – Impact assessment and scenario analysis. Commission Staff Working Paper. SEC(2011) 1565 final, Available online at http://ec.europa.eu/

European Commission (2011d) Report from the Commission to the European Parliament and the Council - Two years after Paris – Progress towards meeting the EU's climate commitments, COM(2017) 646 final, Available online at http://ec.europa.eu/

European Commission (2017) Report on European Electricity Markets, Directorate-General for Energy, Market Observatory for Energy, Available online at http://ec.europa.eu/

Goedkoop M, Heijungs R, Huijbregts M, De Schryver A, Struijs J, Van Zelm R (2013) ReCiPe 2008 A life cycle impact assessment method with comprises harmonised category indicators at the midpoint and the endpoint level, Ruimte en Milieu, Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer

Honus S, Kumagai S, Němček O, Yoshioka T (2016a) Replacing conventional fuels in USA, Europe, and UK with plastic pyrolysis gases—part I: experiments and graphical interchangeability methods. Energy Convers Manag 126:1118–1127

Honus S, Kumagai S, Yoshioka T (2016b) Replacing conventional fuels in USA, Europe, and UK with plastic pyrolysis gases—part II: multi-index interchangeability methods. Energy Convers Manag 126:1128–1145. https://doi.org/10.1016/j.enconman.2016.08.054

Koci V, Trecakova T (2011) Mixed municipal waste management in the Czech Republic from the point of view of the LCA method. Int J Life Cycle Assess 16:113–124

Kulczycka J, Pietrzyk-Sokulska E (2012) Evaluation of energy sector in Poland. Mineral and Energy Economy Research Institute of the Polish Academy of Sciences, Krakow

Lelek Ł, Kulczycka J, Lewandowska A, Zarebska J (2016) Life cycle assessment of energy generation in Poland. Int J Life Cycle Assess 21:1–14

Lewandowska A, Noskowiak A, Pajchrowski G, Zarebska J (2015) Between full LCA and energy certification methodology—a comparison of six methodological variants of buildings environmental assessment. Int J Life Cycle Assess 20(1):9–22

Mikołajczyk U, Bujak-Pietrek S, Szadkowska-Stańczyk I (2010) Narażenie na pył w górnictwie węglowym. Analiza na podstawie pomiarów wykonanych przez laboratoria badań środowiska pracy w Polsce w latach 2001–2005. Med Pr 61:287–297 (in Polish)

Pang MY, Zhang LX, Wang CB, Liu GY (2015) Environmental life cycle assessment of small hydropower plant in China. Int J Life Cycle Assess 20:796–806

World Energy Resources Report (2016) World Energy Council, Available online at https://www.worldenergy.org

World Energy Scenarios Report (2016) World Energy Council, Available online at https://www.worldenergy.org