Environmental aspects of energy supply of buildings in Poland

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Abstract. The article presents the assessment of the environmental impact of 9 variants of building heat supply for heating purposes. The building energy standards and the main primary energy carriers being in use in Poland were taken as input data. The subject of analysis was a single-family house characterized by a utility energy demand of 47 kWh/(m² year). An environmental impact analysis was made using the specification for LCA in damage categories encompassing human health, ecosystem quality and natural resources depletion. From the obtained results it has been found that coal-based technologies in Poland's building energy supply systems are capable of reducing the noxious environmental impact. An example of such a system is the effective heat distribution network with a coal-based cogeneration energy source. From the point of view of radical low emission reduction, an interesting solution is the effective heat distribution network with a gas-based cogeneration energy source. Nevertheless, forecasts about the development of renewable energy source installations in Poland indicate that a significant role in building heat supply systems will be played by solar systems and geothermal systems using heat pumps. Achieving the environmental acceptance of heat pumps in Poland's conditions requires a decisive intensification of efforts to increase the share of renewable energy sources in electric energy generation processes in the central electric power system and in local and individual systems, as well as the continuation of the processes of thermal insulation of already existing buildings.

1 Introduction

The building industry is among the largest energy consumers in Poland. Its share of the total energy consumption is 40%. Buildings are supplied with electric energy from the power network which in over 90% relies on primary energy from hard coal and brown coal. On one hand, such a state guarantees Poland's energy safety for the years to come, which is a positive effect; on the other hand, however, in the light of the increasingly strict environmental protection requirements and the need for increasing the energy efficiency, it poses numerous challenges. The provision of heat to buildings is carried out both from heat distribution networks (centralized systems – 61% of the thermal power), as well as

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from individual systems (26% – individual heating, 12% – stove heating, and 1% – the others). The main primary energy carriage in building heat supply systems is coal, which accounts for over 70%. As reported in study [1], the development of Poland's building engineering has evolved over the last thirty years towards the reduction of the demand for and the consumption of non-renewable primary energy. This process has enabled the development of energy-efficient and often innovative construction and installation technologies, as set out in studies [1–6]. Ultimately, these activities have resulted in low-energy buildings which are characterized by a heating energy demand of 15–45 kWh/(m² year), and so-called passive buildings that are distinguished by the aforementioned indicator being at a level below 15 kWh/(m² year). An important role at this point starts to be played by the aspect of selecting the primary energy carrier and the heat generation and delivery system. Poland's heat generation and supply processes involve chiefly the use of conventional resources and generate the emissions of harmful substances that adversely affect the natural environment. During the entire life cycle of building energy supply systems, essential interactions with the environments occur due to materials acquisition, production, transport, assembly, utilization or disposal. These interactions lead to a depletion of natural resources, the greenhouse effect, acidification, eutrophication, etc. [7–12]. Considering the constant technological development in centralized thermal systems (effective heat-generating systems) and heating boilers, and the dynamic growth of solar and geothermal installations, including in particular low-temperature geothermic using heat pumps, a question arises about the environmental impact of these solutions, not only from the point of view of the direct emissions arising on the installation's operation site, but also from the point of view of the overall impact on the environment. One of the basic tools used for environmental impact assessment, as set out, e.g., in reference [12], is life cycle analysis (LCA). The essence of such assessment is not only the determination of the type and quantity of indices with an adverse impact on the surrounding nature, but also the efficient management of resources. The use of LCA has been presented, e.g., in studies [13–21] for comparison and the determination of the environmental impact of apartment buildings of a different energy standard, different building and insulation materials, as well as HVAC plants and equipment.

2 Material and methods

As the object of analysis, an apartment building with an EU utility energy demand of 47 kWh/(m² year) was taken. Nine heat source variants were considered for the building taken for analysis. The proposed variants and the assumed data are given in Table 1. For each variant, an environmental impact assessment was made and the annual demand for non-renewable primary heating energy was calculated. The environmental impact analysis was performed using the LCA specifications provided in standards PN-EN ISO 14040:2009 [22] and PN-EN ISO 14044:2009 [23]. For this purpose, the software program SimaPro was used. The data presented in the works [10, 12] were used for the analysis. Within the life cycle impact analysis, the evaluation of the potential impacts on the environment and human health was made. The environmental profile concerned 11 impact categories modelling the environmental impact on the level of final Eco Index points (Eco-Indicator), which were then related to the building surface area and a one year¹ period, Pt/(m² year). All impact categories were assessed with respect to three main damage categories, namely: human health, ecosystem quality and natural resources depletion. The damage categories and their corresponding impact categories are shown in Table 2. The environmental impact model was adopted in an egalitarian cultural version, in which a long-term perspective was assumed.

Table 1. Variants selected for analysis and their basic specifications.

Variant	Symbol	Description	Demand for usable energy for heating, EU kWh/(m ² year)	Efficiency of regulation and use	Transmission efficiency	Demand for final energy for LCA analysis, EK _{LCA} , kWh/(m ² year)	Conversion efficiency	Annual demand for final energy, EK, kWh/(m ² year)	The needs of the installation kWh/(m ² year)	Coefficient of non-renewable primary energy for EK	Coefficient of non-renewable primary energy for the needs of the installation	Demand for non-renewable primary energy for heating, EP, kWh/(m ² year)
1	DH-CHP-CB	An efficient district heating system with a coal-fired co-generation heat plant	47	0.89	0.96	55	0.98	56	3.9	0.8	3	57
2	CB-55/45	Individual high-performance coal-boiler - emission class 5 - working temperature 55/45 °C	47	0.89	0.96	55	0.85	65	3.9	1.1	3	83
3	DH-CB	District heating system with a coal-fired boiler	47	0.89	0.96	55	0.98	56	3.9	1.3	3	85
4	HP-35/28	Heat pump - working temperature 35/28 °C	47	0.89	0.96	55	4	14	3.9	3	3	53
5	DH-CHP-GB	An efficient district heating system with a gas-fired co-generation heat plant	47	0.89	0.96	55	0.98	56	3.9	0.8	3	57
6	HP-45/35	Heat pump - working temperature 45/35 °C	47	0.89	0.96	55	3.5	16	3.9	3	3	59
7	GB-45/35	Individual condensing gas boiler - working temperature 45/35 °C	47	0.89	0.96	55	0.94	59	3.9	1.1	3	76
8	GB-80/60	Individual gas boiler - working temperature 80/60 °C	47	0.89	0.96	55	0.87	63	3.9	1.1	3	81
9	CB-90/70	Individual coal boiler - working temperature 90/70 °C	47	0.89	0.96	55	0.65	85	3.9	1.1	3	105

Table 2. The process of grouping damage categories and impact categories [10–12].

DAMAGE CATEGORIES	Human Health, DALY	Carcinogenic effects on humans (Carcinogens)	IMPACT CATEGORIES
		Respiratory effects caused by organic substances (Respiratory organics)	
		Respiratory effects caused by inorganic substances (Respiratory inorganic)	
		Damage caused by climate change (Climate change)	
		Effects caused by ionising radiation (Radiation)	
		Effects caused by ozone layer depletion (Ozone layer)	
	Ecosystem Quality, PDF·m ² ·year	Damage caused by ecotoxic effects (Ecotoxicity)	
		Damage caused by the combined effect of acidification and eutrophication (Acidification/Eutrophication)	
		Damage caused by land occupation and land conversion (Land use)	
	Resources, MJ excess energy	Damages caused by extraction of minerals (Minerals)	
		Damages caused by extraction of fossil fuels (Fossil fuels)	

The boundaries of LCA encompassed the stages of the winning of materials, processing of fuels, generation and distribution of electric energy, and the manufacture and operation of heat generation equipment. In the case of manufacturing processes, emissions from processes along with emissions arising from the use of energy were taken into account. In the case of the winning and processing of energy materials, the average level of process efficiency was considered. Electric energy consumed in the phase of manufacturing the systems under analysis is wholly generated in Poland. In the system's boundaries assumed for the analysis, with respect to transport processes, the transport type and the impact of the emission associated with the production and consumption of fuel in transport were taken into consideration. As a functional unit, the quantity of heat corresponding to the final energy demand was taken, without taking into account the generation efficiency, EK_{LCA} , i.e. 55 kWh/(m² year). The operation period was assumed as 15 years. In the LCA analysis, the heat generation efficiency for individual variants was included directly in the impact assessment. The calculation of the annual heating primary energy demand was made in accordance with the methodology for energy performance of the building [25], being the implementation of Directive [26] into the Polish law. In this case, for each variant, the calculations of the final energy (EK) demand included the heat generation efficiency. When calculating the EK index, the primary non-renewable energy input coefficients were assumed according to [25]. Their values are given in Table 1. Considering the conceptual

nature of the study, the obtained LCA results are only estimated values, and the obtained results are only indicative in character.

3 Results and discussions

3.1 Results and the analysis of damage categories

Table 3 and Figure 1 show Eco-Indicator values, broken down into individual damage categories of the heat sources under discussion. Based on the obtained results, the adopted building heat supply system variants can be divided into three groups. Group I includes variants with the greatest Eco-Indicator value; Group II consists of variants having the medium Eco-Indicator value; while Group III is made up of variants with the smallest Eco-Indicator value.

Table 3. Eco-Indicator values with division into damage categories of the variants under analysis.

Variant	Symbol	Eco-Indicator, Pt/(m² year)				Demand for non-renewable primary energy for heating, EP, kWh/(m² year)
		Damage categories			Total	
		Human Health	Ecosystem Quality	Resources		
1	DH-CHP-CB	3.242	0.185	1.551	4.978	57
2	CB-55/45	3.943	0.244	2.129	6.316	83
3	DH-CB	4.189	0.259	2.262	6.711	85
4	HP-35/28	5.432	0.409	3.881	9.722	53
5	DH-CHP-GB	2.740	0.130	8.610	11.479	57
6	HP-45/35	6.848	0.474	4.344	11.667	59
7	GB-45/35	3.742	0.159	10.567	14.469	76
8	GB-80/60	3.891	0.184	12.249	16.323	81
9	CB-90/70	12.723	0.562	4.186	17.470	105

Fig. 1. Comparison of the Eco-Indicator values for individual damage categories of the variants under analysis.

In the first group, the greatest Eco Index value of approx. 105 Pt/(m² year) is exhibited by the coal-fired boiler (CB-90/70), while the gas-fired boiler solutions (GB-45/35 and GB-80/60) attained values from 76 to 81 Pt/(m² year). The main areas of coal-fired boiler impact are the damage categories related to human health and natural resources. In the case of the gas-fired boilers, the main damage category refers to natural resources. The human

health-related damage is approx. 3 times smaller for gas-fired boilers compared to the coal-fired boiler. The Eco-Indicator value for the damage related to natural resources consumption is greater for the gas-fired boilers by 2.5 to 2.9 compared to the coal-fired boiler. This effect results from the, adopted in the model, indices of the additional quantity of energy necessary for winning a given material, which for hard coal and brown coal assume much lower values than for natural gas. Medium Eco-Indicator values (Group II) were shown by variants using compressor heat pumps (HP-35/28 and HP-45/35) and the variant with the effective heat distribution network relying on a natural gas-supplied cogeneration system (DH-CHP-GB). Eco-Indicator values for the compressor heat pumps were 9.722 Pt/(m² year) for heat pump operation temperatures of 35/28°C and 11.667 Pt/(m² year) for heat pump operation temperatures of 45/35°C. The main area of HP impact in the damage categories is the human health damage which accounts for almost 60% of the total Eco Index value (respectively, 56% and 59% for the heat pumps under analysis). The system's heat produced in gas cogeneration attained an Eco Index value comparable to that of the compressor heat pump with plant operation parameters of 45/35°C, i.e. 11.479 Pt/(m² year), with the main area of environmental impact in this variant being natural resources-related damage. It accounts for 74% of the Eco-Indicator value. The lowest Eco Index values were exhibited by variants from Group III that used coal as a primary energy carrier, i.e. heat from the effective heat-generating system relying on coal cogeneration (DH-CHP-CB), an individual coal-fired boiler operating in a medium-temperature installation with a 5 Class certificate (CB-55/45), and heat from the heat distribution network with a coal-fired boiler (DH-CB). The Eco-Indicator values were: 4.978 Pt/(m² year) for DH-CHP-CB, 6.316 Pt/(m² year) for CB-55/45 and 6.711 Pt/(m² year) for DH-CB. The main area of impact in the damage categories for this group is human health damage, which accounts for, respectively: 65%, 59% and 62% of the total Eco Index value. Variants 2 and 3 are characterized by comparable results. The analysis of the ecosystem quality has found that variants with the greatest share in this damage category was the low-performance coal-fired boiler (CB-90/70) and the compressor heat pump (HP) installations. It should be underlined that the damage category related to quality ecosystem has a small share of the total Eco Index value. From the obtained analysis results shown in Table 3 and in Figure 1 it can be inferred that the current values of the primary non-renewable energy input coefficients included in [25], and given in Table 1, do not fully correspond to the harmful environmental impact of these solutions. The obtained EK values for the first group of heat sources are clearly disproportionately larger compared to the results obtained from LCA.

3.2 Results and the analysis of impact categories

The Eco Index values of individual impact categories of the discussed heat sources are presented in Table 4. As not all impact categories significantly affected the environment, the comparison of the obtained results in Figure 2 was limited to significant impact categories. The obtained results show that for all of the discussed variants, the impact on mineral resources is negligibly small in the final Eco Index values. It can therefore be inferred that the share of impacts in the equipment manufacture phase is small compared to the phase of operation over the assumed 15 years. A significant share of impact categories was exhibited by: carcinogenicity, inorganic respiratory, climate change, ecotoxicity and fossil fuels. The significant effect of the impact categories 'carcinogenicity' and 'inorganic respiratory' occurs in variants that use coal as a primary energy carrier.

Table 4. Eco-Indicator values for individual impact categories of the heat sources under discussion.

Variant	Symbol	Eco-Indicator, Pt/(m²·year)											
		Impact categories										Total	
		Carcinogens	Respiratory organics	Respiratory inorganics	Climate change	Radiation	Ozone layer	Ecotoxicity	Acidification/ Eutrophication	Land use	Minerals		Fossil fuels
1	DH-CHP-CB	1.167	0.000	1.524	0.549	0.001	0.001	0.106	0.057	0.023	0.021	1.530	4.978
2	CB-55/45	1.448	0.000	1.734	0.759	0.001	0.001	0.148	0.065	0.031	0.030	2.099	6.316
3	DH-CB	1.539	0.000	1.842	0.806	0.001	0.001	0.157	0.069	0.033	0.032	2.230	6.711
4	HP-35/28	2.053	0.001	2.140	1.235	0.002	0.002	0.267	0.089	0.053	0.064	3.817	9.722
5	DH-CHP-GB	0.120	0.003	0.981	1.635	0.000	0.001	0.020	0.073	0.037	0.010	8.600	11.479
6	HP-45/35	2.590	0.001	2.696	1.557	0.002	0.002	0.309	0.104	0.061	0.069	4.276	11.667
7	GB-45/35	0.149	0.004	1.206	2.007	0.001	0.001	0.024	0.090	0.045	0.012	10.555	14.094
8	GB-80/60	0.170	0.004	1.393	2.321	0.001	0.001	0.028	0.104	0.052	0.014	12.235	16.323
9	CB-90/70	4.580	0.001	5.980	2.156	0.003	0.003	0.320	0.171	0.070	0.056	4.130	17.470

Fig. 2. Comparison of the Eco-Indicator values of individual impact categories of the heat sources under discussion.

For the 'climate change' impact category, the Eco Index value will be significantly influenced by low-performance coal-based systems (HP-35/28; HP-45/35; CB-90/70) and systems using natural gas (DH-CHP-GB, GB-45/35; GB-80/60). In the 'fossil fuels' impact category, the largest share is exhibited by solutions using natural gas.

3.3 Discussion of the analysis results

The analysis of the obtained results has demonstrated that a variant of the lowest environmental impact is the variant of supplying a building from the heat distribution network with a coal-based cogeneration energy source (DH-CHP-CB). As an individual energy source, the emissivity Class 5 coal-fired boiler solution (CB-55/45) is worth noting. With increasingly stringent standards for permissible atmospheric pollutant emissions and the need for increasing the energy-efficiency of electric energy and heat generation processes, in the perspective of several dozen years, the share of carbon will be decreasing. Because of their low emission of normalized atmospheric pollutants, low carbon dioxide emission, short construction time and operational flexibility, installations using gas as a primary energy carrier are expected to continue growing, especially in the municipal building energy supply sector. The technologies of using gas in electricity, heat and cool generation processes can become bridge technologies between coal-based technologies and future renewable energy source technologies, especially as they significantly contribute to

the liquidation of low emission and smog events. As shown by the obtained results, the most advantageous solution using natural gas is heat derived from the effective heat-generating system with a cogeneration energy source (DH-CHP-GB). This variant is distinguished by the lowest environmental impact in the human health damage area. However, considering the dynamic growth of renewable energy source (RES) installations in local and individual building heat supply systems, an increasing use of heat pumps in HVAC installations should be expected. Currently, in spite of using RES energy, this solution burdens the environment to a considerable degree, as exemplified by the results obtained for the HP-35/28 and HP-45/35 variants. In those cases, the detrimental impact covers chiefly the human health damage area in three impact categories, namely: carcinogenicity, inorganic respiratory and climate change. It should be emphasized, though, that for heat pumps these impacts in Poland's conditions are closely related to the use of coal in the processes of electric energy generation in centralized sources. A huge advantage of using heat pumps is the elimination of low emission.

4 Conclusions

Rational energy policy should seek to improve the prosperity of society in the long run by maintaining the balance between: energy safety, the satisfaction of social needs, the competition of the economy and environmental protection. Considering the latter aspect, i.e., environmental protection, new technologies using coal in building energy supply systems in Poland are capable of significantly reducing the detrimental impact. An example of such a system is the effective heat distribution network with a coal-based cogeneration energy source. From the point of view of the radical reduction of low emission, especially dust emission, an interesting solution is the variant of the effective heat distribution network with a gas-based cogeneration energy source. Nevertheless, forecasts about the growth of renewable energy source installations in Poland and other EU countries show that a significant role in building heat supply systems will be played by solar and geothermal systems, especially low-temperature systems using heat pumps. As has been demonstrated by the results of the analyses presented in this article, achieving the environmental acceptance of these types of installations in Poland's conditions requires a decisive intensification of efforts towards increasing the share of renewable energy sources in electric energy generation processes both in the central electric power system and in local and individual systems, as well as the continuation of the processes of thermal insulation of already existing buildings.

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