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# Comparison of LCA results of low temperature heat plant using electric heat pump, absorption heat pump and gas-fired boiler

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A B S T R A C T

This study compares the life cycle impacts of three heating plant systems which differ in their source of energy and the type of system. The following heating systems are considered: electric water-water heat pump, absorption water-water heat pump and natural gas fired boiler. The heat source for heat pump systems is low temperature geothermal source with temperature below 20 °C and spontaneous outflow 24 $m^3$/h. It is assumed that the heat pumps and boiler are working in monovalent system. The analysis was carried out for heat networks temperature characteristic at 50/40 °C which is changing with outdoor temperature during heating season.

The environmental life cycle impact is evaluated within life cycle assessment methodological framework. The method used for life cycle assessment is eco-indicator '99. The functional unit is defined as heating plant system with given amount of heat to be delivered to meet local heat demand in assumed average season. The data describing heating plant system is derived from literature and energy analysis of these systems. The data describing the preceding life cycle phases: extraction of raw materials and fuels, production of heating devices and their transportation is taken from Ecoinvent 2.0 life cycle inventory database.

The results were analyzed on three levels of indicators: single score indicator, damage category indicators and impact category indicator. The indicators were calculated for characterization, normalization and weighting phases as well. SimaPro 7.3.2 is the software used to model the systems' life cycle. The study shows that heating plants using a low temperature geothermal source have lower eco-indicator than a gas boiler unit. In comparison of two heat pumps the absorption heat pump has a lower environmental impact rather than electrical heat pump. However, in spite of high level eco-indicator, gas boiler has the lowest damage to human health.



## 1. Introduction

Due to growing concern about energy conservation and environmental protection the utilization of renewable energy sources is more and more desirable. For years, high and medium temperature geothermal water was commonly used in district heating systems. The energy and exergy efficiency and environmental issues of geothermal district heating systems were analyzed in many studies [1–5]. In these studies the environmental benefits of deep wells and shallow ground-water systems with temperature higher than 40 °C are assessed. Considered geothermal district systems are mainly based on geothermal water with heat exchangers but often they are supported by peak load boilers based on fossil fuel. Blaga et al. [5] discussed the environmental benefits of shallow geothermal district heating system in Romania. They calculated the $CO_2$ saving in the case of replacing the wood-based heating system with geothermal district heating system. Kecebas [2] examined the geothermal district heating system in Afyon, Turkey. He complemented exergy analysis with economic and environmental issues, which indicated that geothermal energy is much cheaper than the other energy sources and contributes to reduction of greenhouse gases emissions.

Nowadays, the low and very-low temperature geothermal water heating systems become more interesting due to its good availability and growing markets of heat pumps. The use of low temperature geothermal energy in district heating systems is more attractive due to development of heat pumps efficiency for large scale units. However, it is important to notice, that to utilize the low temperature geothermal sources fossil fuels are needed. Electricity to drive compressor in electrical heat pump comes, in Polish conditions, mainly from coal burning. Also heat driven generator of

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absorption heat pumps frequently comes from gas burning. The comparison of heat pumps with alternative heating sources is subject to many studies [6–9]. Generally, environmental impact assessment and ecological effects of heating or cogeneration systems (CHP) are focused on evaluation of carbon dioxide emission reduction and fossil fuels or primary energy savings [10,11].

In order to evaluate environmental benefits from renewable sources, the analysis should take into account a wide range of environmental effects not only during an exploitation stage but also in all life cycle stages. The life cycle assessment (LCA) method enables to assess an environmental aspects associated with a product over its whole life cycle. The LCA studies are currently common practice to evaluate an environmental impact of investigated product or process [12–21]. In the paper [12] Stanek et al. proposed the combination of LCA and Thermo-Ecological Cost (LC-TEC) methodology to evaluate the energy and environmental benefits of biomass energy conversion in CHP. However, the indicators proposed by authors are developed on non-renewable natural resources savings and reduction of greenhouse gasses emissions. Saner et al. [13] made LCA of shallow geothermal system with the use of ReCiPe indicator. Additionally, they included the comparison of environmental impacts with respect to different variants of electricity mixes. Their findings showed the significance of electricity mix to the LCA results of electric heat pumps. Greening and Azapagic [14] also performed LCA study of different types of heat pumps and referred LCA results to the environmental impacts of gas boiler. The comparison was conducted for the UK and included prospective analysis for different electricity mix scenarios. They underlined the significance of seasonal performance factor on environmental impacts of investigated heat pumps.

## 2. The concept of low temperature geothermal heating plant

The idea of low temperature geothermal heating system was created for existing borehole located in Silesia region in Poland, to utilize heat of very low temperature geothermal water to supply the neighbouring buildings in heat. At present, the geothermal water spontaneously flows out from unexploited borehole and runs directly into the nearby river without any use. The concept of heating plant assumed that very low temperature geothermal water at 19.5 °C and spontaneous outflow 24 $m^3/h$ is used by heat pump as low-grade heat and then runs into domestic water supply system. To meet the quality regulation of water for domestic use, the heating cycle was separated from domestic water supply system using geothermal heat exchanger. The scheme of the considered district heating system is shown in Fig. 1.

To evaluate the potential benefits of utilization of very low temperature geothermal water in district heating system, the energy and environmental analysis was carried out. The space heating demand of the buildings was calculated for minimal outdoor temperature equal to −20 °C. It was assumed that heating season duration is 210 days with the average ambient temperature of 2.5 °C that correspond to typical heating season for the considered region.

In this study three types of heat source were considered: electric heat pump (EHP) and absorption heat pump (GAHP) using geothermal water and natural gas boiler as a typical heat source based on fossil fuel. The nominal power of heating devices was 400 kW either. It was assumed that both the heat pumps and the gas boiler are working in monovalent system, meeting the space heating demand during the whole heating season. The heat pumps were designed for the particular needs of this low temperature geothermal heating system. Two stage water/water electric heat pump with semi-hermetically sealed compact screw compressor and R134a as a refrigerant was proposed. The seasonal performance factor (SPF) for electric heat pump was equal to 5.5 and it is correlated with electricity consumption during the whole heating season. It also includes the electricity consumption by geothermal water equipment. The high value of heat pump coefficient of performance is connected with the temperature of geothermal water (which is higher than temperature of typical heat source in ground water heat pumps). In the case of gas absorption heat pump an ammonia/water solution was used as a working fluid. The internal gas burner heats the ammonia and water solution, next ammonia gas enters the condenser, where it condenses and releases heat. Gas utilization efficiency (GUE), expressed as amount of received heat to a gas consumption, of gas absorption heat pump was equal to 1.74. To achieve the required heating power of the heat pumps, the particular amount of heat from lower source (i.e. geothermal water) must be supplied into evaporator. In the considered case the electric heat pump needed more heat from geothermal water than the gas absorption heat pump, so the discharge temperature of geothermal water was assumed to be 9 and 13.5 °C for electric and absorption heat pump, respectively. The temperature characteristic of heating network water is 50/40 °C and it is changing with outdoor temperature (quality regulation). To estimate the gas consumption during the heating season, the energy efficiency of condensing gas boiler was assumed to be 0.96 (correspond with HHV).

## 3. Life-cycle assessment of heating system

The methodology of life cycle assessment is defined by ISO 14044 standard [22] which points at four phases of LCA studies:

- the goal and scope definition phase,
- the inventory analysis phase,
- the impact assessment phase, and
- the interpretation phase.

These basic phases are required in life cycle assessment and were included in this study.

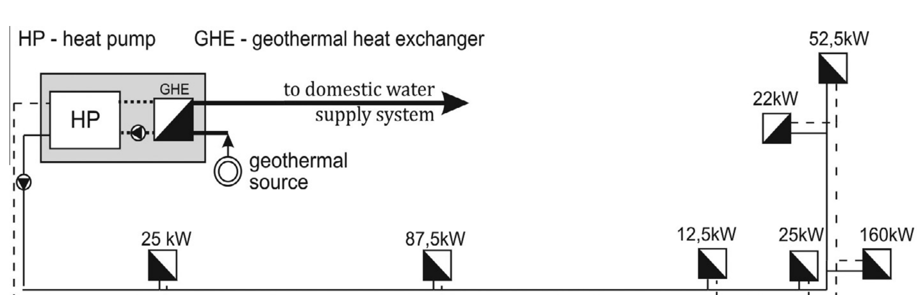


**Fig. 1.** The concept of low temperature geothermal district heating system.

### 3.1. Range and scope of LCA

The scope of the life-cycle was to estimate the life cycle environmental impact of electric heat pump and gas-absorption heat pump and compare them with the most common alternative, natural gas boiler. In this study only heating devices were taken into consideration: electric heat pump and gas-absorption heat pump with geothermal water equipment (i.e. geothermal heat exchanger and circulating pump) and gas boiler as well. The components of the heating system that would be similar for all options have been excluded from analysis (i.e. heating network and its equipment). The functional unit was defined as production of 3185 GJ of heat that corresponds with seasonal heat demand for district heating.

The system boundaries included selected life cycle stages of facility construction, fuels extraction, processing and transport, electricity generation and distribution as well as facility operation. Since the heat pumps are designed specifically for the installation, there is no inventory data for their manufacturing processes. Due to lack of the data, only material flows were included at this stage. Considering that the geothermal water used by the heat pumps is a flowing artesian well and the heat transferred in geothermal heat exchanger is treated as a waste heat, the depletion of geothermal heat source was not taken into consideration in life cycle assessment. A life time of 20 years has been assumed for the facilities. Due to long operation time, it is difficult to predict the recovery technology that may be used in the future. The recycling and recovery processes and technologies are constantly being improved, so the current disposal scenarios can be omitted. Hence, the disposal stage of heating units was excluded from the life cycle.

### 3.2. Life cycle inventory (LCI) data

The life-cycle inventory phase requires collecting input and output data. In order to describe assumed heating systems, two types of data were distinguished:

- Foreground data, which refers to input data describing material needs to be used to manufacture the heat pumps and gas boiler units, energy flows during heat production process, as well as output data which refers to emission to air from burning gas in gas boiler and absorption heat pump. The input / output data used in the assessment is presented in Table 1.
- Background data, which describes data for generic materials, energy and transport in the whole production chain. This data comes from SimaPro ecoinvent 2.0. database.

The general structure of ecoinvent database is described in the report developed by Swiss Center for Life Cycle Inventories [23]. The report described the life cycle assessment methodology, modeling principles for processes, documentation of elementary flows and allocation rules.

The data included in Table 1 was calculated from the energy analysis of the heating system, the ecological analysis (emissions from gas burning) and from the technical data (material flows). The value of electricity consumption is expressed as an amount of electricity in GJ needed to produce 1GJ of heat. In case of EHP this value is related with the seasonal performance factor. The electricity consumption of GAHP and gas boiler came from their auxiliary needs. In the case of AHP it also included energy used by geothermal equipment. The gas consumption of AHP and gas boiler was calculated using the value of their efficiencies. The values of emissions from electricity production for specific Polish conditions were taken from Eco-Invent database. The electricity mix of Poland is presented in Fig. 2. $CO_2$, CO and $NO_x$ emissions from gas burning were assessed using the specific unit emission indicators expressed as an emission quantity in kilograms from burning one cubic meter of natural gas. The values of the indicators were taken from the national database of Polish Institute of Environmental Protection – National Centre for Emission Balancing and Management (KOBZiE) [24].

### 3.3. Life cycle impact assessment

The life cycle impact of all processes and resulted emissions were calculated using the SimaPro7 software. The levels of LCA indicators were assessed on the basis of the Ecoindicator'99 method, which is commonly used for European conditions. In this method category indicators are defined on three endpoint measures, corresponding with three damage categories [26]:

- Damage to Human Health, expressed as Disability Adjusted Life Years (DALYs).
- Damage to Ecosystem Quality, expressed as the loss of species over a certain area.
- Damage to Resources, expressed as the surplus energy needed for future extractions of minerals and fossil fuels.

The values of damage indicators are derived from impact indicators after normalization and weighting phases. Impact indicators are calculated from life cycle inventory data and include such categories as: carcinogenesis, respiratory effects, ionized radiation,

**Table 1**
Foreground data of heating units.

| Unit type | Input data | | Output data | |
|---|---|---|---|---|
| Electrical heat pump and Geothermal water equipment | Steel | 2000 kg | | |
| | Refrigerant R134a | 80 kg | | |
| | Electricity | 0.19 $GJ_{el}/GJ_{heat}$ | | |
| | Stainless steel | 60 kg | | |
| | Cast iron | 10 kg | | |
| Absorption heat pump and Geothermal water equipment | Steel | 2150 kg | $CO_2$ | 31.767 $kg/GJ_{heat}$ |
| | Ammonia | 77 kg | CO | 0.0048 $kg/GJ_{heat}$ |
| | Water | 100 kg | $NO_x$ | 0.0241 $kg/GJ_{heat}$ |
| | Electricity | 0.03 $GJ_{el}/GJ_{heat}$ | | |
| | Gas | 0.57 $GJ_{gaz}/GJ_{heat}$ | | |
| | Stainless steel | 60 kg | | |
| | Cast iron | 10 kg | | |
| Gas boiler | Steel | 1200 kg | $CO_2$ | 57.680 $kg/GJ_{heat}$ |
| | Stainless steel | 25 kg | CO | 0.0086 $kg/GJ_{heat}$ |
| | Electricity | 0.02 $GJ_{el}/GJ_{heat}$ | $NO_x$ | 0.0438 $kg/GJ_{heat}$ |
| | Gas | 1.04 $GJ_{gaz}/GJ_{heat}$ | | |

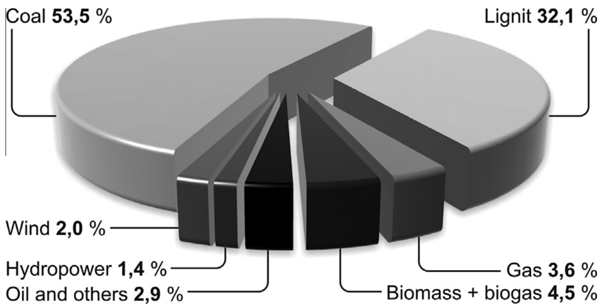


**Fig. 2.** The electricity mix of Poland [25].

ozone layer depletion, climate change, ecotoxicity, acidification and eutrophication, land-use, fossil fuels and minerals use. In Fig. 3 the phases of Ecoindicator damage calculation method are shown. More details about calculations and models used in Ecoindidator'99 method are presented in PRe Consultants report [27]. Annex 1 includes the normalization values, damage factors, normalization factors and weighted damage factors for all categories.

A comparison of three different heat sources with respect to different damage criteria is given in Fig. 4. Using electric heat pump can be seen as more damaging than other heating sources in carcinogenesis, respiratory inorganics, radiation, ozone layer, ecotoxicity and acidification and eutrophication as well. It is concerned with higher electricity consumption by EHP and electricity mix with a significant percentage of coal. Respiratory inorganics damage, acidification and eutrophication are mainly due to nitrogen oxide, sulfur dioxide and particulates <2.5 μm emissions to air from electricity generation.

Damage to ozone layer is concerned with refrigerant R134a used in electric heat pump. R134a is thought to be safe and would not cause ozone depletion, but other substances emitted in its life cycle contribute to this damage.

Due to volatile organic compounds emission, gas boiler is the most damaging in the respiratory organics category. Natural gas combusted in gas boiler cause the highest climate change indicator, due to carbon dioxide emission along with fossil fuels damage. As it is shown in Fig. 4 absorption heat pump has a higher impact on minerals due to its size and number of components.

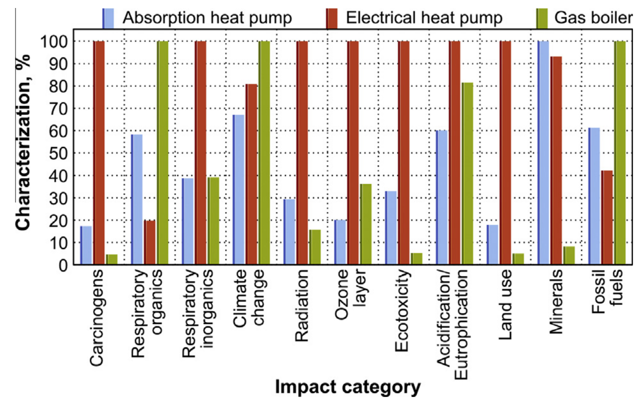


**Fig. 4.** Comparison of impact category indicators in characterization phase.

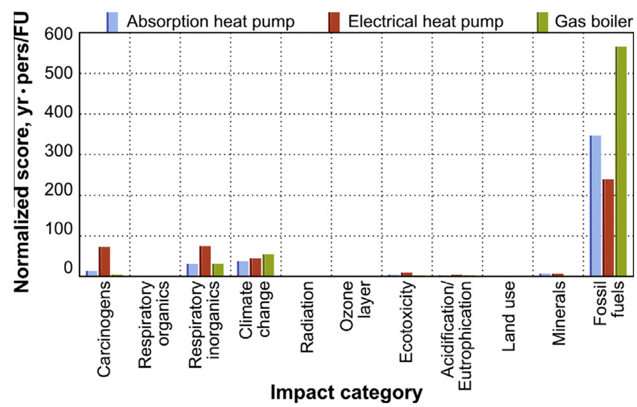


**Fig. 5.** Comparison of impact category indicators in normalization phase.

Normalization shows the difference between the quantity of damage in different impact categories, while the characterization shows only a relative comparison within one impact damage, assuming the highest quantity as 100% of damage. Fig. 5 depicted the contribution of damage category indicators after normalization

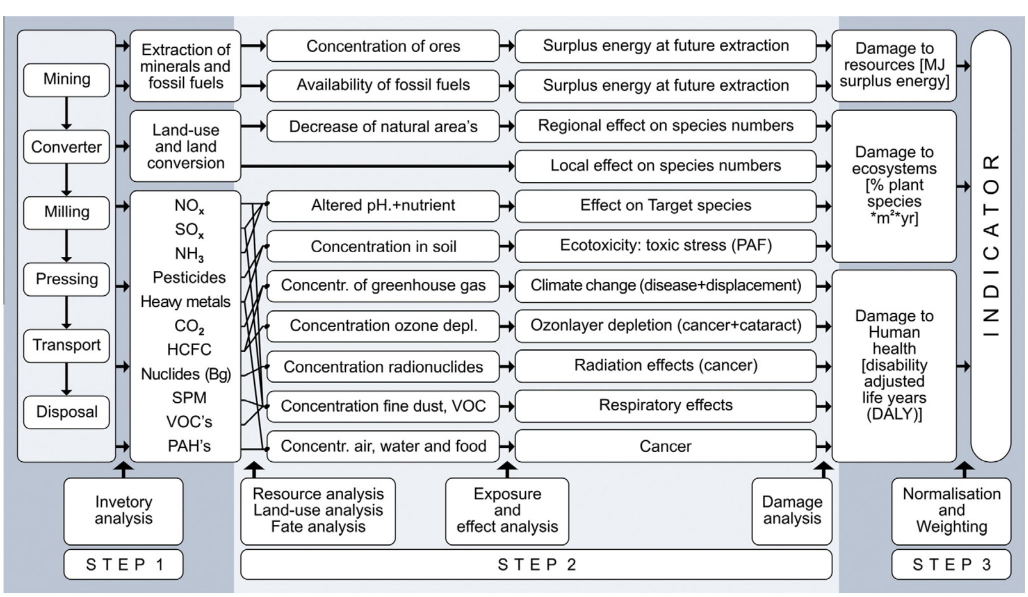


**Fig. 3.** Schematic of damage method phases [26].

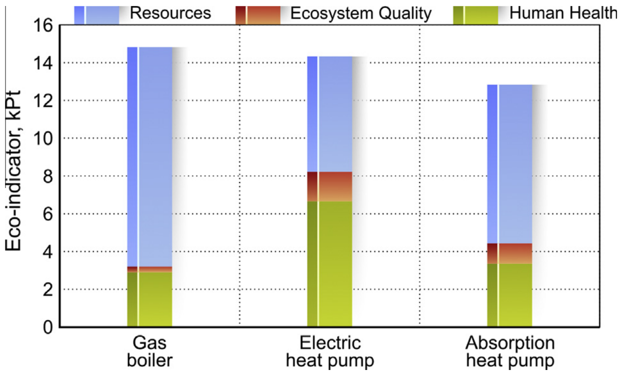


**Fig. 6.** Comparison of single score for different heating system source.

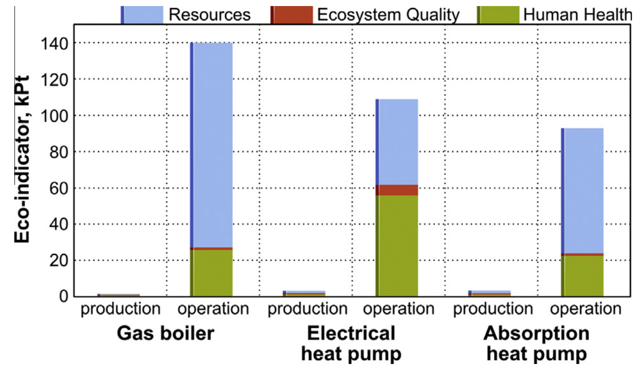


**Fig. 8.** Comparison of production stage and 10 years operation time (endpoint phase).

phase. It shows the highest damage to fossil fuels for each of the heating sources considered. The environmental impact in respiratory inorganics, radiation, ozone layer, acidification and eutrophication categories are negligibly small.

Comparison of LCA endpoint categories of the heat source options (Fig. 6) shows that gas boiler has a higher environmental impact than other options. The gas boiler has the highest damage to resources due to natural gas consumption during operating time. However, damage on human health is the lowest in gas boiler and the highest in electric heat pump. It is caused by the relatively high electricity consumption by heat pump and emission into air due to electricity generation. However, the electricity consumption by EHP is strictly connected with their efficiency measured by the SPF. The SPF of heat pump depends mainly on the outlet temperature and geothermal water parameters as well. It can vary for different heating systems and solutions of heat pumps construction. In Fig. 7 the influence of seasonal performance factor on the environmental impacts of GAHP is shown. The comparison shows that any increase in SPF value would improve the environmental impact of electric heat pump. However, the environmental impact is significantly increasing with the decreasing of the SPF value. In the case where SPF is lower than 5, the impact of EHP is even higher than the gas boiler.

In Fig. 8 the damage during a unit production and 10 years facility operation stage is compared. It is clearly shown that environmental impact of construction of facilities is relatively small in comparison to their impact during operation time.

For the gas boiler, damage to resources is dominating during the operation time and because of that it gets the highest impact. In this comparison the absorption heat pump has the lowest environmental damage. The impact to human health during operation time is much lower than in the case of electric heat pump and comparable to the gas boiler. The highest damage to human health is related to electricity consumption and emissions from electricity production and also from hard coal and lignite extraction.

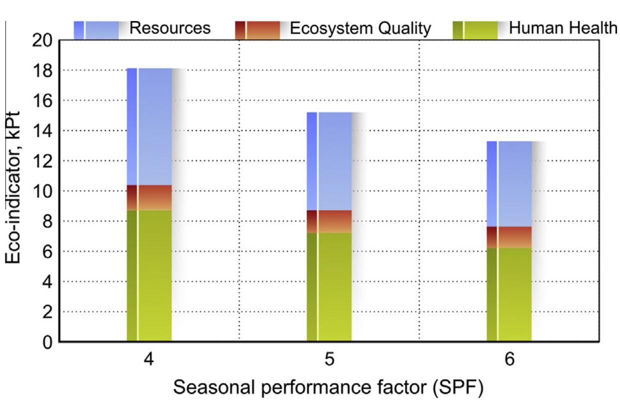


**Fig. 7.** The influence of seasonal performance factor on the environmental impacts of EHP.

## 4. Conclusions

The life-cycle assessment shows the difference between environmental impact of two heat sources using geothermal water and gas boiler. It is shown that using low temperature geothermal source can bring environmental benefits even though it is connected to fossil fuel usage. From the environmental point of view, the most attractive is absorption heat pump, which has the lowest eco-indicator score.

The environmental impact of electrical heat pump strictly depends on its efficiency (COP) and electricity generating profile. The higher COP, the lower electricity consumption and emissions from its production. In Polish conditions, where electricity is generated in almost 90 per cent from coal, the damage to human health is significant. With growing efficiency and renewable sources contribution to electricity system, the environmental impact of electrical heat pump will decrease. Saner et al. [13] showed that in countries with low-carbon electricity mixes (Switzerland) can achieve six time higher greenhouse gases emission saving than in Poland. The study shows how huge is the potential of environmental impact decrease by changing electricity mix. We could expect that in countries with low-carbon electricity mixes the environmental impact of EHP will be lower especially in human health category. The specificity of changes in impact and damage indicators will depend on the electricity mix structure.

In this comparison the highest eco-indicator level is obtained for gas boiler. The significant level of fossil fuel damage and the highest impact on climate change in comparison to heat pumps results from the high amount of natural gas used by the gas boiler. On the other hand, gas is much cleaner from a point of view of emissions and it caused much less damage to human health and ecosystem quality.

It is worth noticing that the value of heat pump COP has a significant influence on the difference between the gas boiler and electric heat pump environmental impact. In case of changing heat pump performance conditions that cause the decrease of COP (e.g. the increase of outlet water temperature) the environmental impact of electrical heat pump can be similar or even higher than the impact of gas boiler.

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