The impact of selected heat pumps on CO₂ emissions

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Abstract. The increase in energy consumption in the world, with the decreasing resources of conventional energy, is increasingly leading to campaigns aimed at limiting the acquisition of energy from non-renewable sources to intensify the use of alternative energy sources. The paper presents the possibilities of obtaining heat energy using a heat pump for heating purposes, ventilation and hot water preparation. Hot heat sources for the heat pump are discussed and their energy possibilities in relation to the geographical conditions of the territory of Poland. Variants of heat pump cooperation with renewable sources in the form of air, soil and water were adopted for analysis. Two cases of co-operation of the ground collector with the heat pump are also considered, in the form of vertical and horizontal wells of the heat exchanger type. Based on the known methodology of seasonal heat demand, the final and primary energy consumption was determined for each analyzed case together with auxiliary energy. Based on the calculations carried out, the final emission of carbon dioxide was determined for individual cases and they were compared with the emission that would be generated when producing heat using a gas boiler and heating network.

1 Introduction

Industry produces most of the energy needed from minerals. Currently, these are the basic sources of energy. The amount of minerals is limited and their resources are decreasing year by year, which in the near future will contribute to the total depletion of raw materials. Mining costs are continuing to grow and the demand for minerals is growing, especially in developing countries. All this translates into an increase in the cost of energy produced from traditional sources. The high requirements for the reduction of carbon dioxide emissions causes many countries to decide to significantly increase the share of energy produced from alternative sources in their energy balance, whose production does not have carbon dioxide emissions [1,2]. Alternative primary energy sources are another way of acquiring energy and let them include hydropower and such renewable energy sources as the sun, wind, heat within the Earth, sea tides, high tides and outflows, and other sources of energy that can be obtained in renewable processes [3]. The goal of EU countries is to achieve a 20% share of energy from RES (Renewable Energy Sources) by 2020. In Poland,

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at the same time, it is expected to achieve a 15% share of energy from these sources and increase this share to 20% in 2030. Currently, renewable sources constitute a minimal share in the global energy balance, regardless of the rapid increase in production [2].

2 Alternative energy sources

Table 1 presents the division of alternative energy sources and the technical possibilities of converting primary energy into other ones.

Table 1. Division of Alternative Energy Sources.

Primary energy sources		Natural processes of energy transformation	Technical processes of energy conversion	The form of energy
Sun	Water	Evaporation, melting of ice and snow, precipitation	Hydroelectric power plants	Electricity
	Wind	Atmospheric movement	Wind farms	Electricity and heat
		Tidal energy	Tidal power plants	
	Solar radiation	Ocean currents	Power plants using ocean currents	Electricity
		Heating of the earth's surface and atmosphere	Power plants using the heat of the oceans	Electricity
			Heat pumps	Heat
		Solar radiation	Collectors and thermal solar power plants	Hest
			Photovoltaics and solar power plants	Electricity
			Photolysis	Fuels
	Biomass	Biomass production	Heating and thermal power plants	Heat and electricity
			Processing devices	Fuels
Ground	Isotope breakdow n	Geothermal sources	Heating and geothermal power plants	Heat and electricity
Moon	Gravitatio n	Tidal waters	Tidal power plants	Electricity

Currently, about 20% of the world's electricity production comes from hydropower. The energy of water that is needed to generate electricity is obtained by using either the natural flow of water in rivers, or the difference in levels between the channel in which water flows further and the water stored in reservoirs or lakes. Another possibility of acquiring hydro-energy are the movements of oceanic waters [4].

The first attempts to create electricity with the help of wind had already taken place in the nineteenth century, but it was not possible to implement it on a large scale. It is only in recent years that wind energy is becoming more and more popular. Wind farms are profitable in places with strong and frequent winds. Mostly, they are built on hills, mountain passes, and on banks. The farms are built in regions where the wind speed is not less than 25 km/h in a given region.

Solar energy has been used for a short time. There are three main ways of using solar energy:

- photovoltaic conversion, consisting of converting direct solar energy into electrical energy in a solar cell (solar cell),

- photothermal conversion, consisting of converting solar radiation energy into thermal energy in a solar collector,
- indirect conversion of solar energy into electricity in so-called solar furnaces or the direct use of this energy for industrial purposes [5].

The main disadvantage of solar energy is that it is limited. Sunlight is needed to be able to use it and produce electricity from it. The use of solar energy is possible only during the day and its use depends on the degree of sunlight, which is difficult to predict. Therefore, the ability to store the electricity generated is a very important problem.

Biomass contains stored solar energy. Plants produce carbon dioxide, glucose and oxygen in the process of photosynthesis. Animals and people consuming plants absorb the energy contained in them. The energy that is contained in biomass can also be used for energy purposes. Biomass energy is a renewable source because plants regrow again and again. It is also environmentally friendly, because although carbon dioxide is produced during the production of biomass, it is then absorbed by plants during vegetation. The share of biomass energy in the global energy balance is constantly growing, however only 7% of the global energy potential is used.

Geothermal energy is the thermal energy of the Earth. It comes from two sources. The first source is the heat coming from the core and interior of the earth. This heat is transferred to the surface of the earth. An additional source of heat is the decay of radioactive elements (potassium, uranium and thorium isotopes) within the earth. The second main source of heat is the adsorption of solar radiation through the Earth's surface. As we move towards the center of the Earth from its surface, one can observe that the temperature rises from one degree Celsius every 30-50 meters. Geothermal energy can be used in the form of hot water heated in the interior of the Earth to the appropriate temperature. This water is located naturally at a certain depth in the ground and can be used in various ways depending on its temperature. To use it, you should get to it. Hot water or steam may be used to receive electricity or to heat buildings' rooms. Another way of using geothermal energy is pumping cold water into the ground to the appropriate depth and after heating it, using the heat contained therein for energy purposes. To do this, two holes are drilled in the ground. The first hole is used to pump cold water, while the second one is used to discharge hot water or steam. The advantage of this method is that it can be done practically anywhere, but it should be noted that the entire installation is not economically viable. This means that the cost of drilling and the amount of energy needed for pumping water, as well as the cost of other required equipment and the cost of their operation must be lower than the benefits of using geothermal energy.

Nuclear energy is produced as a result of the controlled decay reaction of atomic nuclei in uranium. Uranium is a slightly radioactive heavy metal that occurs on Earth mainly in two types of isotopes: U-238 and U-235. Uranium ore is mined by opencast mining and underground mines. In order to extract uranium, massive material needs to be extracted and processed. After extracting the uranium ore, it is crushed and then the material is treated with sulfuric acid to separate the uranium. The separated uranium in the form of yellowcake is filtered and dried. After drying, it is submitted to the enrichment process in the U-235 isotope. Uranium enriched in the form of UO_2 , so-called brown powder, used in reactors, it contains 3-5% of the U-235 isotope. This material is supplied to nuclear reactors in the form of tablets with a diameter of 1 cm and a thickness of 1.5 cm. They are laid in a long tube to form a fuel rod. U-235 uranium nuclei release an enormous amount of energy. This energy is used to produce electricity at nuclear power plants. The operation of a nuclear power plant is the same as a regular power plant. The heat released is used to produce steam that drives a steam turbine connected to a generator that produces electricity. The nuclear wastes formed in them are a serious problem in nuclear power plants. They arise both in technological processes as well in the processes for obtaining and preparing fuel [6].

It should be noted that in Poland the share of alternative energy sources is approx. 8%. In electricity, it is a bit more and exceeds 11%. Most fuels such as oil and natural gas are imported because their resources are limited. Some of the major alternative sources of energy are biomass, biogas and water, but hard coal resources owned by Poland represent its energy self-sufficiency, which is not considered a priority in the energy economy. Hence, wind farms became very popular, especially in the southern and central parts of the country.

3 Analysis of the effectiveness of selected types of renewable energy sources cooperating with the heat pump

To analyze the effectiveness of final, primary and additional energy consumption, a typical single-family building with an area of 120 m² located in the Subcarpathian region was adopted. The final energy demand for the heating system, natural ventilation and hot utility water was determined based on the methodology adequate to the energy certificate for the building. Four variants of heat pump cooperation with an alternative heat source were compared. Variants assume cooperation with the following renewable energy sources:

- air - AHP,
- ground GHPH (horizontal collector),
- ground GHPV (vertical collector),
- water WHP (dragged and absorbed well).

Variants are compared in the heating season at the outside air temperature (12 °C to -18 °C) read from the Rzeszów-Jasionka meteorological station database. For all variants, an identical installation inside the building was adopted. Based on calculations of the heat demand for heating and hot water, appropriate sizes of heat pumps were selected, and then the efficiency coefficient of the COP heat pump was determined. Accepting that 4 people resided in the building, the reduced heat demand for preparing domestic hot water at the level of $Q_{HW} = 3.84$ kW with a container volume $V_{HW} = 120$ liters was determined. The heat demand for heating and ventilation is at $Q_H = 12.2$ kW. On this basis, the heat pump was selected assuming 6 hours of regeneration time, necessary for the renewal of the thermal properties of the soil. Analogous assumptions were adopted in the situation of heat pump cooperation with the source in the form of a well-absorbing and absorbing well. Hence, the heat pump's power was set at level $Q_{HP} = 16.5$ kW. In the case of a heat source in the form of air, the regeneration process is not necessary, therefore the heat pump's power is assumed to be equal to the heat demand, i.e. $Q_{HP} = 12.2$ kW. All heat pumps were selected according to the instructions of the Dimplex manufacturer. These are SI 18 TU B0W35 heat pumps for a horizontal and vertical ground collector, type WI 18 TU W10W35 for a heat pump using water from an absorption well and type LA 17 TU A20W35 for an air heat pump [7].

3.1 Coefficient of performance

The ground temperature below 15 m in depth, where the vertical collector is placed, is practically constant throughout the year and amounts to 7 °C, therefore the COP heating coefficient for the ground heat pump is the same at 5.4. An analogous situation occurs when drawing water from a well, where the water temperature in a well is practically constant throughout the year and amounts to 10 °C. Therefore, the COP coefficient for a heat pump with a well for the entire heating period is similar and amounts to 5.8. In the case of a heat pump cooperating with a lower heat source in the form of horizontal collectors placed in the ground, COP values are strongly dependent on the outside temperature. The COP

coefficient for an air heat pump is characterized by larger changes depending on the outside air temperature compared to the horizontal ground collector [8]. Fig. 1 shows changes in the COP coefficient depending on the solution used.

Fig. 1. Dependence of the COP coefficient on the outside temperature for selected types of heat pump sources.

Because the methodology of determining the final energy demand requires one value of the COP coefficient, this value was averaged. The weighted-average value was taken into account, which in the case of heat pumps co-operating with the lower heat source in the form of soil (horizontal collector) and air is a must. The weighted average was calculated using the number of hours of occurrence of a given COP value (depending on the outside temperature). The values of the frequency of occurrence of given temperatures are easy to obtain based on statistical data from the Rzeszów-Jasionka meteorological station [2]. In this way, the obtained values are shown in Fig. 1.

3.2 Final, primary and additional energy

The overall efficiency for individual heat pumps has been calculated as the product of the efficiency of regulation and use, transmission, accumulation and generation. The first three values were adopted according to the type of heat pump, while the production efficiency corresponds to the weighted average COP coefficient - Table 2. An accumulation value of 1 for an air heat pump was assumed due to the 24-hour heat pump operation and no heat storage in the system [8,9].

Table 2. Division of Alternative Energy Sources.

Efficiency of:	AHP	GHPH	GHPV	WHP
control	0,94	0,94	0,94	0,94
transmission	0,8	0,8	0,8	0,8
accumulation	1	0,97	0,97	0,97
preparation	4,1	4,6	5,4	5,8
Total	3,05	3,35	3,94	4,23

The final energy corresponds to the seasonal energy consumption of the building for heating, ventilation and hot water preparation. It has been defined as a quotient of usable energy and total system efficiency for particular types of heat sources.

The values of additional energy are related to the need for the installation of equipment in the form of circulating pumps, electrical control systems of the control system. In the case of heat pumps, it should be noted that they are of the compressor type, which means that they need to be supplied with electricity in the amount resulting from the annual heat production and the seasonal coefficient of heating efficiency SPF. The SPF coefficient in this analysis was adopted at the level of the weighted average COP coefficient according to Figure 1. The above values determine the actual costs incurred in connection with the functioning of the building. Primary energy, on the other hand, determines the amount of energy that will be consumed in energy sources entirely derived from non-renewable sources and does not have a direct impact on the costs incurred by the user. However, it is decisive when it comes to the amount of carbon dioxide emission necessary to produce and supply energy to the end user. The sizes of final, primary and additional energy are shown in Fig. 2.

Fig. 2. Energy consumption for selected heat sources for the heat pump.

It can be seen, that in the case of a heat pump cooperating with an absorption well, energy consumption is the smallest. The largest energy demand occurs in the case of an air-source heat pump, which in turn requires the least investment. Therefore, in such systems a compromised solution based on horizontal ground collectors prevails, as a system generating relatively low energy demand at relatively low costs, much smaller compared to systems based on vertical probes and an absorption well.

3.3 Operating costs

A list of operating costs is presented in Table 3. Energy costs are determined by assuming an electricity tariff typical for a single-family building and a cost of 1 kWh at the level of 0.57 PLN/kWh. The final energy is included in the operating costs. In the case of compressor heat pumps, this is the only cost borne by the user. This energy includes the

amount of electricity needed to run the entire system, including the annual heat pump operating costs.

Table 3. Annual operating costs in PLN.

Air heat pump	Ground heat pump with horizontal collector	Ground heat pump with vertical collector	Heat pump with absorption well
32 133	29 249	24 881	23 165

The dependencies presented in Table 3 are analogous to the energy demand shown in Fig. 2. This is very characteristic for compressor heat pumps, where all the heat demand is covered only by electricity, because there is no heat demand that it could be covered by providing heat as a result of the combustion effect, such as in the case of heat sources in the form of gas boilers, district heating network, etc. From the above, a simple regularity defines the efficiency of the lower heat source inversely proportional to its availability, both geological and technical. Easily accessible heat sources are characterized by their low investment costs and simplicity of installation, nevertheless they imply low efficiency and generate high operating costs. Therefore, in such cases, an additional financial analysis based on more reliable indicators such as SPBT, LLC, NPV is necessary. Such analysis enables a more individual approach to the issue of the profitability of investments and the indirect reference to investment and operating costs.

3.4 Emission of carbon dioxide to atmosphere

The amount of carbon dioxide emissions into the atmosphere was determined for the solutions analyzed above and for the heat production system based on the condensing boiler. It assumed the production of electricity by a solid fuel plant in the form of lignite and gas. The amount of unitary CO₂ emissions from individual systems was determined based on the data presented in the energy certificate methodology. For fuels used in power plants, they are respectively 101,0 kg CO₂/GJ for brown coal and 56,1 kg CO₂/GJ for natural gas [2]. The type of heat source in building heating systems has a significant impact on pollutant emissions. A very large amount of CO₂ is released when burning hard and brown coal, and gas generates even less than half the amount of CO₂ into the atmosphere than coal. However, with biomass, these quantities are minimal. It can be assumed that CO₂ remains in the closed cycle of the power plant and then it is a really small amount of impurities in the form of CO₂. Based on many publication [2], some interesting results have been found – Table 4.

Table 4. Annual carbon dioxide emission for selected heat pump low energy source and typical heat energy sources in tons CO₂/annum.

Power plant fuel	Air HP	GHP with horizontal collector	GHP with vertical collector	HP with absorption well	Local gas furnace	Municipal heating network
gas	15,1	13,5	11,3	10,5	5,40	7,15
hard coal	27,3	24,4	20,4	18,9	9,72	12,9

The analysis of several variants of heating installations in the building has shown that the collector, considered colloquially to be environmentally friendly, does not have satisfactory results in terms of CO₂ emissions. The main reason is the high demand for electrical energy needed to operate the device and a large dependence on its source taking into account the type of fuel. The origin of this energy from popular sources, such as the coal-fired power plant, is associated with significant amounts of carbon dioxide emitted into the atmosphere. The volume of this emission can reach the highest values for power plants using popular raw material in the professional power industry, which is lignite. The

heat pump itself does not emit any pollutants, but it is done by the sources that generate electricity, which are necessary to power the compressor. To reduce this emission and to make the solution with the heat pump really environmentally friendly, auxiliary energy should be obtained from biomass, biogas or other renewable sources [1].

4 Conclusion

On the basis of the calculations presented, it can be seen that the highest final energy consumption in the heating season will be with the air-source heat pump, while the lowest end-use energy consumption with the heat pump with a well. The reason for this is the constant high COP = 5.8 for a heat pump with a dredged well. For an air heat pump, the COP value is variable during the heating season due to the change in outside air temperature. In the case of ground heat pumps, the difference in the demand for final and auxiliary energy is relatively small. A better solution is to install a lower heat source with a vertical collector due to the constant temperature of the heat source, which translates into a high COP = 5.4. A heat pump system with a horizontal collector generates the need for more energy for the building, but it is a less expensive solution, which is more widespread. The values of final energy consumption during the heating season also translate into the cost of generating energy. These costs are analogous to the demand for final and auxiliary energy by the building. The largest operating costs are generated by the air heat pump, nearly 10% larger than the most popular system with a horizontal collector. Comparing the heat pump system with an absorption well to the horizontal system of collectors, annual operating costs allow annual savings of 20%. In the case of CO₂ emissions into the atmosphere occurring during the production of electricity for the analyzed variants of cooperation between the heat pump and the lower heat source, it appears that the differences in emission levels reach over 40%. Comparing heat pump systems with typical heat production systems in housing construction, such as a gas furnace or heat from a district heating network, the differences are even more visible and significant.

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