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Heat pumps integrated with photovoltaic systems as a basic solution for new housing estates during the energy transformation in Poland

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Abstract

The paper considers the possibility of using heat pumps integrated with photovoltaic systems as a basic solution for energy systems in new housing estates on the outskirts of Polish cities. The necessity of energy transformation in countries such as Poland, which for years were dominated by a centralized energy economy based on coal, was emphasized. One of the possible energy-efficient and environmentally clean ways is to implement the idea of creating districts based on renewable energy. As the analyses showed, in Polish conditions it is most advisable to use solar energy to gain heat, as well as to generate electricity to cover the demand for electricity to home receivers and to drive heat pumps. It is possible to send the energy generated on site (photovoltaic) to the grid, as well as to take electricity from the grid, when needed. Two basic configurations of heating systems with ground heat pumps were considered. In the first one, each building of the hypothetical housing estate is equipped with its own heating installation with a heat pump associated with its own individual photovoltaic system. In the second configuration, a small heating plant with several heat pumps that can operate individually or in parallel, with several central heat tanks, was considered. Heat pumps and auxiliary devices are powered by the photovoltaic systems. In the first configuration, a photovoltaic self-energy consumption index of 25% was obtained, in the second at 45%. The self-energy consumption index is the share of PV generation that is directly consumed on site. The high index is recommended, due to cooperation with the network, which should not be overloaded of renewable energy in the same time. In the considerations, electricity storage was not taken into account, only heat storage and matching heat use to electricity generation.

Keywords: Heat pumps; Photovoltaics; New housing estates; Energy transition based on heat pumps; Integration of heat pumps with photovoltaics.

1. Introduction

The energy transformation of countries such as Poland, whose economies have long been dependent on large, centralized, coal-burning energy systems, is imperative. Improving the energy efficiency of energy generation processes is as crucial for fuel and raw material conservation as it is for environmental protection. However, the transformation process is not simple, and various methods are possible. One possibility is to create energy-self-sufficient districts equipped with their own energy systems based on local renewable energy sources [1] - [2]. In Polish conditions such a way is neither easy nor quick [3]. However, the creation of such areas can be treated as demonstration projects. Once the proposed solutions prove successful in considered locations, they can be replicated in other locations. These new areas can be created with confidence, being well-defined and proven, giving effective solutions for energy transformation in the micro and middle scale.

Heat pumps, particularly compressor-based heat pumps, have long reached technological maturity, but only recently has there been significant interest in their use in Poland. This is, of course, due to economic considerations, but also to the role they can play in a modern, low-emission energy economy. There are no emissions at the point of their use and operation. Significant technological advances enable their operation even at relatively low temperatures of heat source and relatively high temperatures of heat sink. Nowadays, even under unfavorable operating conditions, significant savings in energy consumption are possible, both on a micro scale, i.e., in single-family homes; on a medium scale, in multi-family buildings and public buildings; and on larger scale, when heat pumps can provide heat for entire housing estates, villages, and districts of cities.

The use of heat pumps enables the implementation of nearly self-sufficient energy systems in small facilities, e.g. single family houses, urban districts, and even in isolated urban areas in housing estates. Generation and consumption of energy take place in the same location. Currently, this occurs primarily on a micro scale and is known as prosumer energy generation and use [4]. However, it is also the future of larger energy systems, including centralized systems, regardless of latitude, climate, and availability of renewable energy and conventional fuels. Heat pumps are therefore increasingly becoming a key component of distributed energy systems, and can also be a key element of centralized systems [5]. They can utilize renewable and waste heat sources, but importantly, electrically driven heat pumps should be powered by electrical energy gained from renewable sources.

As mentioned, one possible energy-efficient and environmentally clean path for energy transition is implementing the idea of creating districts (areas) based on renewable energy, which can become positive energy districts [6]. The implementation of distributed energy systems based on renewable energy sources in Polish cities equipped with central heating systems and power grids is quite difficult for both economic and technical reasons. Smaller cities operate local heating plants, while larger cities have combined heat and power plants that primarily use coal combustion to generate heating energy or combined heating and electrical energy. Heat is distributed to consumers via a 2nd-generation high-temperature heating network. Then thermal energy is supplied to buildings in residential areas and other premises through appropriate heat exchanger stations. Buildings are equipped with high-temperature heating installations (with high temperature radiators), which are usually characterized by large heat losses. Therefore, energy transition requires not only fuel replacement and complex, comprehensive modernization of heating plants or combined heat and power plants, but also the replacement of very inefficient district heating networks and heating installations in buildings, which poses a significant logistical, technical, and economic challenge.

Cities are expanding, with new housing estates being built on the outskirts of cities. Typically, the only electricity available on the outskirts of Polish cities is electricity from the power grid. Supplying heat from central heating networks to such new housing estates is economically unviable and technically very difficult. Therefore, such estates should utilize their own local energy sources. Since electricity is widely available in such estates, electric heating can be used, but to assure the final energy savings, it is advisable to use a heat pump for heating. To reduce primary energy consumption from fossil fuels (which dominate the national electricity mix, including electricity from the grid), it is advisable to utilize renewable energy sources as much as possible.

2. Concept of the energy system for single family houses in a housing estate on the outskirts of the city

A detailed analysis of the potential use of renewable energy sources for heat pumps in micro-scale systems in Polish climatic conditions has been conducted [7]. A hypothetical single-family house located in the suburbs of Warsaw has been considered. The time-varying climatic conditions have been considered with a time step of one hour. The main climatic parameters have been taken into account, i.e. ambient air temperature, solar irradiation and wind speed. Based on climatic conditions, the building's heating demand has been determined, as well as the energy demand for domestic hot water and energy needed for electrical appliances. The determination of the building's energy balance and its components is based on a model of physical phenomena occurring in the building and its surroundings, as well as a data-driven model for electricity consumption (by domestic electrical appliances, lighting, and the heat pump). Applicable standards and appropriate heat consumption profiles, depending on the residents' lifestyles, were used to determine the heat demand for domestic hot water. The combined physical and data driven model and its solution procedure are described in detail in [7]. The building energy balance components, including those describing heat exchange through the building envelope, the heat demand component for ventilation, and the solar radiation gain component, were modeled for quasi-static conditions, using a time step of one hour. Standard structural and material parameters for the building envelope components and the operating parameters of the ventilation system with heat recovery were assumed. Solar radiation gains were determined using an anisotropic model of solar radiation reaching surfaces of different inclination. Considering the energy sources available on the outskirts of the city, it has been assumed that the building's location would allow for the use of electricity from the grid, but not heat from a municipal district heating network.

To reduce conventional energy consumption (from the grid), the possibility of utilizing locally available renewable energy sources has been analyzed. The hypothetical building has been assumed to be one of many buildings in a single-family housing estates on the outskirts of the city, as illustrated in Fig. 1. Typically, such housing estates consist of several dozen buildings, each having a living area of around 100 m², and a small garden of 20-50 m². The buildings are constructed in accordance with present standards to be considered near-zero-energy buildings [8]. Buildings of the local small housing estates are located close to each other, limiting the area available for ground-based energy installations, although some installation components can be located close to the buildings. Some devices may be located on roofs or attached to the building envelope. Such location constraints influence the selection of renewable energy technologies to be used in new residential suburbs area.

Figure 1. Typical new housing estates on the outskirts of a city (Warsaw) in Poland.

A detailed analysis showed that in Polish conditions it is most advisable to use solar energy for domestic hot water heating [7], [9]. In the case of space heating an electrically driven heat pump is the best solution. Due to the location constraints of residential buildings, heat pumps should utilize ambient air or the ground as a heat source. In the case of air source heat pumps used for space heating in winter, due to climatic conditions (low air temperatures), they operate significantly less efficiently than ground heat pumps with vertical heat exchangers. In the case of air source heat pumps, seasonal coefficients of performance SCOP are around 3-3.5, while in a case of ground source heat pumps, they reach values of 4.5-5 [10]. Furthermore, in the latter case, the simplest and most suitable low-temperature solution for space heating system is underfloor heating. Therefore, ground-source heat pumps equipped with vertical ground heat exchangers and combined with an underfloor water heating system have been considered in the study.

Regarding the electricity required to drive the heat pump compressor and power other household appliances, two sources of electricity were considered: energy generated by a wind turbine and a photovoltaic system. A simplified diagram of the electricity generation system in a single-family house considered is shown in Fig. 2. (wind turbine) and Fig. 3 (photovoltaics).

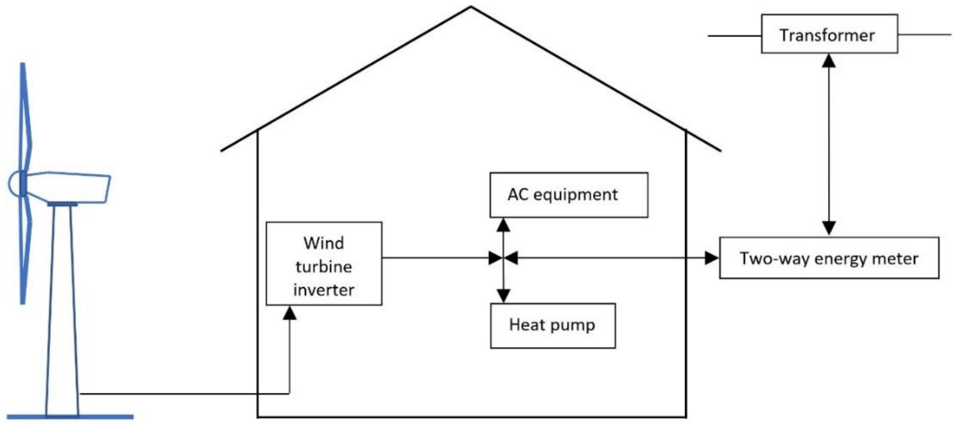

Figure 2. A simplified scheme of the energy system with a wind turbine to supply electricity to the considered single family house.

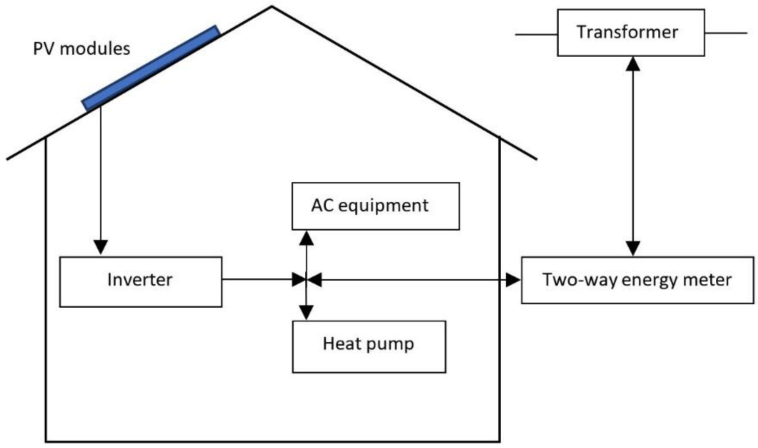

Figure 3. A simplified scheme of the energy system with photovoltaics to supply electricity to the considered single family house.

In summary, based on the conducted analysis, it was assumed that the energy system of a hypothetical house in a housing estate on the outskirts of the city consists of a solar thermal system with solar flat plate collectors, a water buffer tank, a domestic hot water tank with an electric heater, and a low-temperature (underfloor) space heating system and a ground-source heat pump (with vertical U-tube heat exchangers). Electricity to power the heat pump compressor and the home's electrical appliances is generated in a system using renewable energy sources. Electricity generation from a photovoltaic and/or wind systems have been considered. The next section presents some selected results of simulations studies of the operation of such installations in Polish climatic conditions (Warsaw conditions).

3. Some results of simulations studies of the energy systems operation in the considered single-family house in new housing estates under Polish climatic conditions

This section of the paper focuses on presenting selected results of simulation studies of energy systems operation. The energy systems supplying electricity to a building are based on renewable energy sources: solar or wind. They provide electrical energy to meet the energy needs of a single-family house in a modern residential area on the outskirts of the city (Warsaw). The central element of the space heating system is a ground-source heat pump with vertical heat exchangers. For the determined space heating demand of a building thermal capacity of a heat pump has been assumed. The thermal capacity of the heat pump was set taking the space heating demand into consideration and using the standard heat pump sizing method, i.e. the peak power of any space heating device is determined for design conditions (climate zone III in Poland, with an outside ambient air temperature assumed to be -20°C). For ground-source heat pumps, 70% of the peak power is typically assumed. So based on the building's design heat balance, the heat pump's heating capacity was determined to be 5.8 kW. To achieve this capacity, three boreholes, each 50 meters deep, are to be used, with 30 W of heat extracted from each meter of borehole.

Simulation studies of the building's energy balance were conducted, which allowed for the determination of the variability of heat demand for space heating of a hypothetical building, energy demand for domestic hot water (DHW) of that building, and electricity demand for powering various electrical appliances, including a heat pump. The calculations were conducted with a time step of one hour and utilized multi-year averaged climate data [11] (wind data), [12] (solar radiation and ambient air data). Standard parameters of currently constructed buildings, consistent with the requirements of relevant legal regulations [10], have been used to calculate the heat demand. The space heating demand for a hypothetical single-family house in the housing estate under consideration is shown in Figure 4.

Thus, the annual heat demand for space heating and for domestic hot water in a building amounts to: 11540 kWh and 3400 kWh, respectively. The electricity demand for electrical appliances amounts to: 4377 kWh. Of course, as mentioned before energy demand is changing hour by hour. Based on the conducted analyses of energy demand for space heating purposes, a 5.8 kW ground source heat pump has been proposed. It uses about 2327 kWh of electricity annually. A small portion of the space heating demand is met by solar collectors (369 kWh of heating energy). The solar collectors operate primarily for domestic hot water (DHW) needs and provide 2431 kWh annually for this purpose. The remaining heat is covered by an electric heater located in the DHW tank, which corresponds to 969 kWh annually. The building under consideration consumes (apart from heat from solar thermal collectors) only electricity for all energy purposes (as assumed), the amount being 7673 kWh per year.

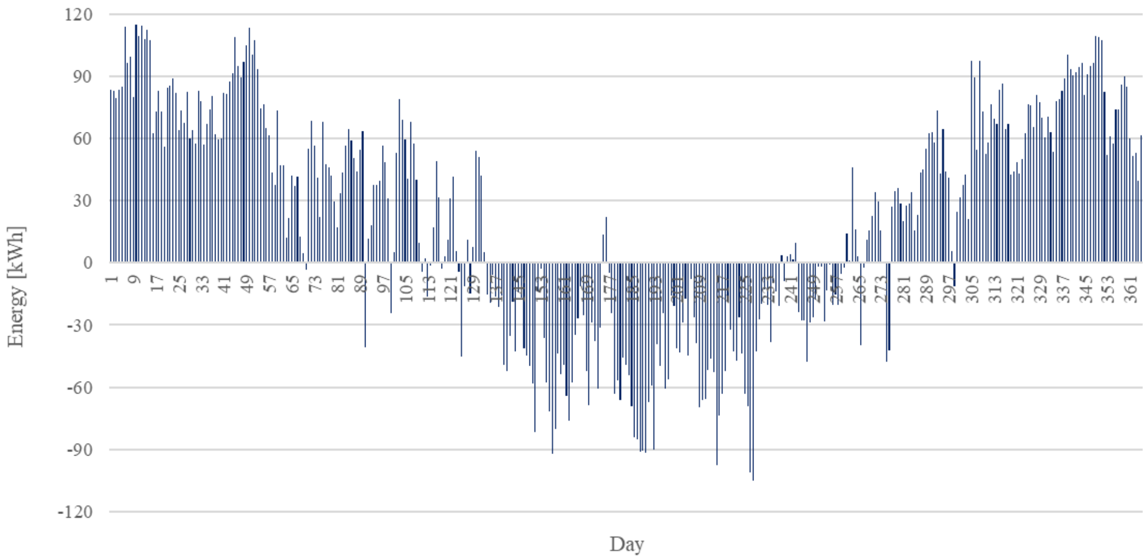

Figure 4. Distribution of the space heating demand for a hypothetical single-family house in a housing estate on the outskirts of the city.

Analyzing Figure 4, it can be seen that there is a cooling demand in summer. However, it has been assumed that this demand would be naturally reduced by the use of external shading elements.

Figure 5 shows the electricity consumed by the heat pump on subsequent days of the year to cover the time-varying heating loads of the building. This electricity should be provided as much as possible by energy generated by renewable energy systems, which in this case are solar energy (photovoltaics) or wind energy systems.

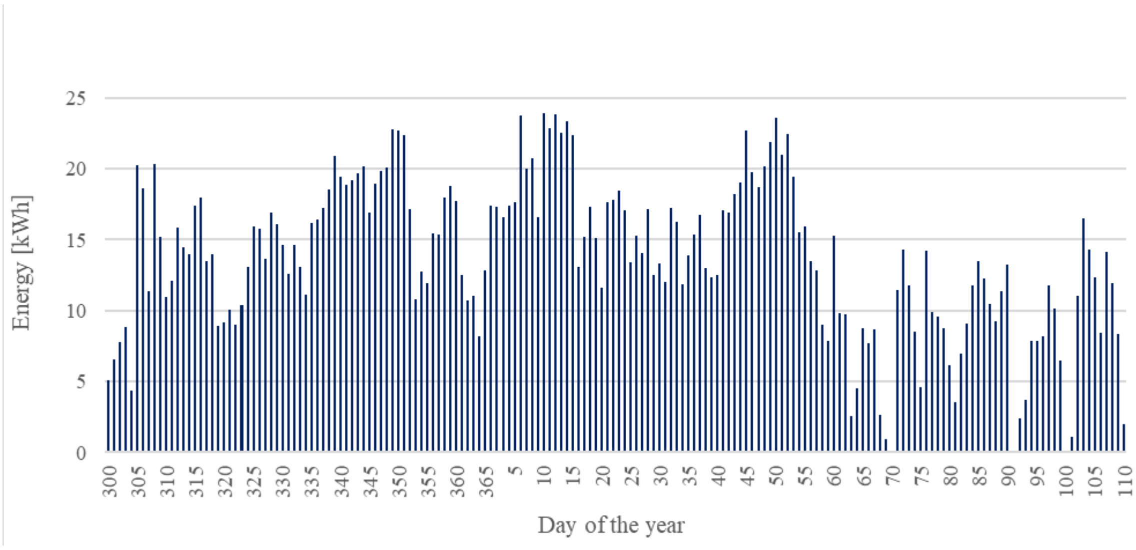

Figure 5. The electricity consumed by the heat pump on subsequent days of the heating season to cover the space heating loads of the building.

Analyzing Fig. 5, it can be seen that the time marked on the horizontal axis corresponds to the subsequent days of the heating season, starting on the 300th day of the year (27^{th} of October) and ending on the 110th day (20^{th} of April).

It has been assumed that for the given building's electricity demand, the installed capacity of the photovoltaic system should be 8,4 kW and it should be located on a roof of the building. Calculations were performed on the operation and energy efficiency of the photovoltaic system. The results of the electricity gained on subsequent days of the year under the given climatic conditions are presented in Fig. 6. The total annual amount of electricity gained by the PV system is around 7650 kWh annually. According to the conducted research studies on the operation of the wind turbines, to achieve similar energy yields to those of the PV system, a wind turbine with an installed capacity of 15 kW should be used and then energy generated by such a wind turbine accounts for 7010 – 7320 kWh annually depending on the average wind speed in the year. A significant problem may be where to place (install) such a turbine. Figure 7 shows the energy generation on subsequent days of the year for a 15 kW wind turbine and for 8.4 kW_p photovoltaic system operating under the assumed climatic conditions in Warsaw's suburbs.

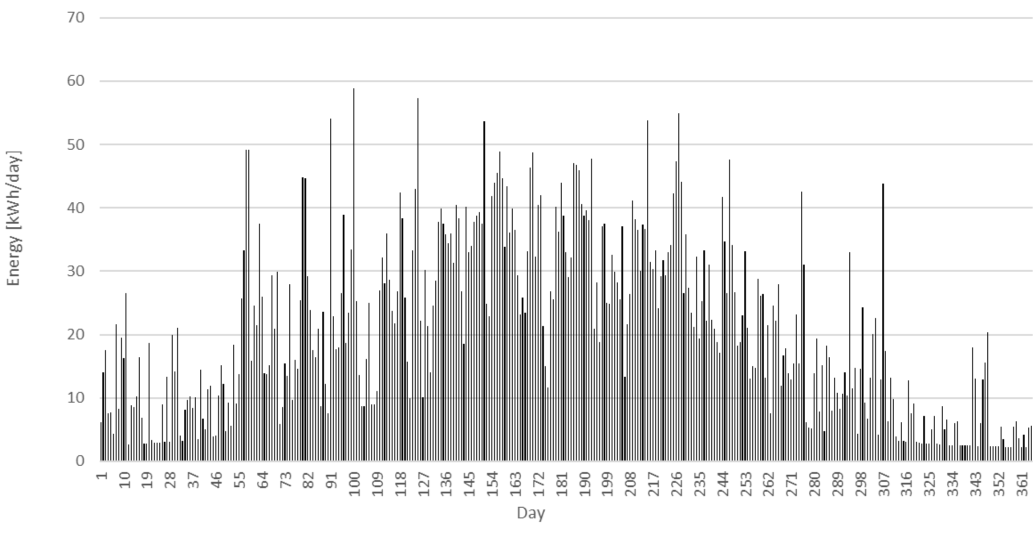

Figure 6. The electricity gained by the photovoltaic system on subsequent days of the year.

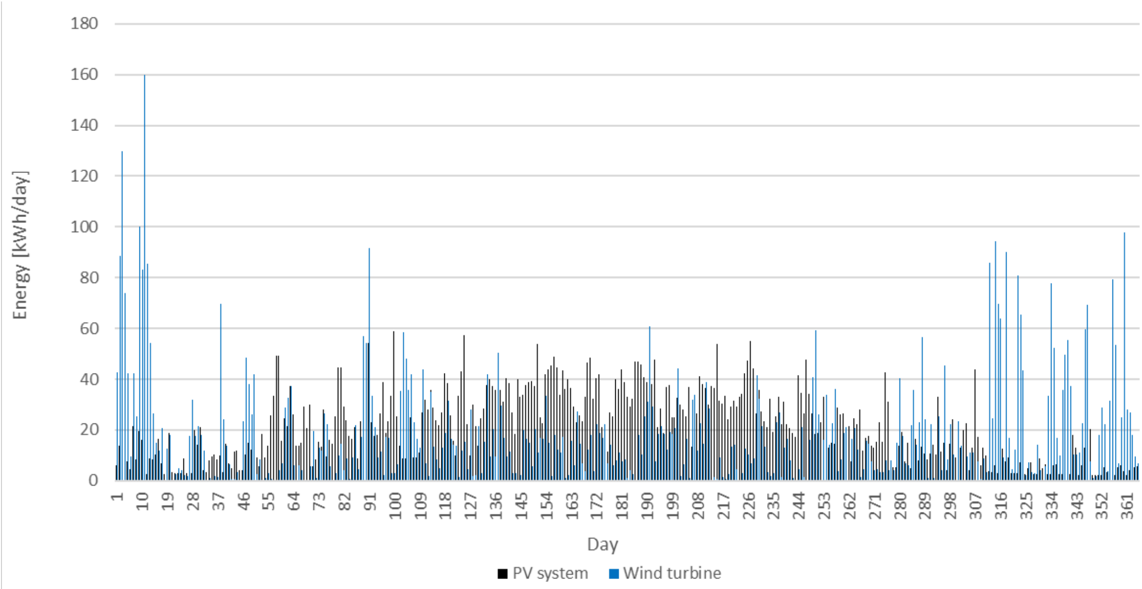

Figure 7. Comparison of the electricity gained by the wind turbine and the PV system on subsequent days of the year.

As can be seen, the differences in the installed capacities of both energy systems are significant, more than two and a half times. Lower electricity gains from small wind turbines result from low wind speeds at low altitudes. This calls into question the feasibility of using a wind turbine, whose size translates into higher investment costs than a PV system. Moreover, a power plant of this capacity requires appropriate siting. The small ground area on which the buildings are located makes it practically impossible to install wind turbines, primarily due to legal regulations (to close to houses), but also aesthetic considerations, noise, vibrations, etc. Using both energy technologies simultaneously would be advisable because the wind and PV installations would complement each other in terms of time and amount of energy generated, what can be seen in Fig.7. However, ignoring the limitations of locating a wind turbine right next to a building, it would not be economically viable due to the high capital costs.

Based on these considerations, it was decided that the building in question would be equipped with a photovoltaic system, the operation of which would be integrated with the heat pump so that it would have priority to be supplied by the PV electricity. It means that during heating season nearly all the electricity generated by the PV system will be consumed by the heat pump. Thus, during the day, when solar energy is available and the photovoltaic system generates electricity, the building's heating control system activates the heat pump, which supplies heat directly to the underfloor heating system. Underfloor heating operates primarily during the day, while systems powered by electricity from the grid are often set to night mode due to lower nighttime tariffs. Simulation studies conducted for the year-round operation of the PV installation and all electrical appliances showed that the photovoltaic system would operate with a self-consumption index of 25%. This means that 25% of the energy generated by the photovoltaic system would be directly consumed on site by the electrical appliances and a heat pump. The remaining electricity required to power the heat pump and other devices would be drawn from the grid. It should be noted that a less favorable energy usage profile was adopted, according to which the residents are not at home during the day, i.e., when the photovoltaic system is operating.

To make the proposed solution more energy-efficient and more convenient for the estate's residents, a centralized design for the energy system of the housing estate has been considered. Instead of equipping each building separately with a ground-source heat pump and its own photovoltaic system, as is standard practice in such estates in Poland, the operation of heat pumps and PV systems can be coupled in one centralized plant and one energy transmission network. All buildings in the estate could be connected by a common low-temperature heating network, which would supply heat to the building's heating systems. Heat would be generated in a central, local heating plant equipped with a sufficiently powerful ground-source heat pump or several smaller heat pumps operating in parallel, the number depending on the estate's heating requirements at a given time. The heat gained at central heating plant can be transferred directly to the local low-temperature network or stored in water storage tanks, from where it can be used as needed. At the same time, the photovoltaic modules located on the buildings' roofs would form a shared photovoltaic system operating as a local power plant. The operation of heat pumps would be linked to the operation of the photovoltaic installation, i.e., both of them should operate at the same time when solar energy is available. Thus, the heat pump operates when solar radiation is present, either directly transferring heat to the residents of the housing estate or storing it in water tanks in the solar thermal/ power plant.

Initial analyses have been conducted on the operation of a small local solar heating plant (with a heat pump) and solar power plant supplying heat and electricity to a residential estate consisting of 20 houses. The considerations for this housing estate represent the first preliminary approach to solving the problem of modeling modern, energy-independent rural areas utilizing their own renewable energy sources. The estate was modeled by aggregating 20 identical individual buildings that have identical solar irradiation conditions. In this case of a housing estate, the total heating capacity of the heat pump/ pumps is approximately 116 kW, and the PV system's capacity is 168 kW_p. Furthermore, it was assumed that the central heating plant contains storage tanks with a total volume of 10,000 m^3, and the low-temperature network operates at a heating water temperature of 35-40°C. Heat losses in the network have been neglected. It was found that, thanks to the centralized operation of heat pumps and photovoltaic installations, as well as the use of central storage tanks, the share of solar energy used directly on-site increased to 45% (the self-consumption index reached 45%). In summary as the number of customers increases, the energy consumption profile in the estate as a whole becomes more even, i.e. energy is used throughout the whole day, with no interruptions in consumption (always somebody is at home). This means that energy from the PV system can be directly used on-site for extended periods. Furthermore, the use of water storage tanks allows the heat pump to operate not only directly to supply heat to the low-temperature network but also to store excess heat in these tanks, with the possibility of utilizing the stored heat when the PV system is not in operation. This is a very beneficial solution, increasing the share of renewable energy in meeting the estate's energy needs and reducing the use of electricity transmitted via the power grid.

It's worth mentioning here that the energy consumption analyses for a single building were performed for two extreme profiles of energy consumption distribution throughout the day. The first profile assumed that household members were away from home for eight hours a day, when solar radiation energy was available, usually at its highest level. The second profile assumed that some household members were home during the day. In the first case, the previously mentioned self-consumption index was achieved at around 25%, while in the second, it was close to 35%. Considering a housing estate of 20 houses, the consumption profile becomes more even, and it was estimated that this would allow for an increase in the self-consumption rate to at least 30%. Furthermore, the use of central storage tanks could increase this rate to 45% (as mentioned earlier, in the case of individual houses, storage tanks were not used in the space heating system. The heat pump operated directly, powering the underfloor heating system).

4. Conclusions

Energy transition process is particularly challenging in countries that have long relied on fossil fuels, and in many cases, often relying on a single energy resource: coal. Large, centralized energy systems had to be centrally managed. Individual end users had no influence on energy generation, distribution and use. The transition to distributed, locally managed energy systems, utilizing their own energy sources, with the end-user playing a significant role as an active participant in the energy market, is completely new idea in such countries. It requires not only an energy transition from a technical perspective but also a societal psychological transformation.

The paper points to the possibility of creating new housing estates on the outskirts of cities that would utilize their own local resources, i.e., energy from renewable sources, and create their own distributed energy systems. The simplest solution is to power such estates with electricity, including to meet heating needs. The most effective solution in this case is the use of a heat pump powered by electricity from solar energy systems, i.e., photovoltaic systems.

The analyses conducted showed that during winter, the photovoltaic installation transfers nearly all collected energy to power the heat pumps. However, this energy is insufficient to cover heating demand, requiring the use of the electricity grid. It would also be advisable to use wind turbines, which are a compatible solution for photovoltaics, as the highest yields are achieved in winter, unlike solar installations. However, the installed capacity of wind turbines would have to be more than 2.5 times greater to generate the same amount of energy year-round in micro scale systems. This implies relatively high capital expenditures, as well as other challenges mentioned in the paper.

Increasing the share of renewable energy can also be achieved through appropriate energy storage. Until the prices of electrical storage facilities drop significantly, a simple and effective solution is to store energy in the form of heat in water storage tanks. Further increasing energy self-sufficiency can be achieved through local centralization of energy generation and transmission. This could involve building centralized, local micro-power plants and heating plants equipped with heat pumps, storage tanks, and their own electricity generation systems, primarily photovoltaic and perhaps wind turbines. It may seem like we are reaching a paradox: we are supposed to eliminate centralized systems only to return to them, albeit on a much smaller scale. Sometimes it's difficult to convince end users that centralization makes sense. However, centralization on a small scale is a completely different solution, and it requires convincing the public and demonstrating that it is an effective path to local energy transformation.

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