

Article

Possibilities of Transition from Centralized Energy Systems to Distributed Energy Sources in Large Polish Cities

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Abstract: The main aim of this paper is to evaluate the possible transition routes from the existing centralized energy systems in Polish cities to modern low-emission distributed energy systems based on locally available energy sources, mainly solar energy. To evaluate these possibilities, this paper first presents the current structure of energy grids and heating networks in Polish cities. A basic review of energy consumption in the building sector is given, with emphasis on residential buildings. This paper deals with the evaluation of the effectiveness of operation of central district heating systems and heat distribution systems; predicts the improvement in the effectiveness of the energy production, distribution, and use; and analyzes the possible integration of the existing system with distributed energy sources. The possibility of the introduction of photovoltaic (PV) systems to reduce energy consumption by residential buildings in a big city (Warsaw) is analyzed. It is assumed that some residential buildings, selected because of their good solar insolation conditions, can be equipped with new PV installations. Electricity produced by the PV systems can be used on site and/or transferred to the grid. PV energy can be used not only for lighting and electrical appliances in homes but also to drive micro- and small-scale heat pumps. It is assumed that the PV modules are located on roofs of residential buildings and are treated as individual micro scale energy systems of installed capacity not larger than 50 kW for each of the buildings. In such a case, the micro energy system can use the grid as a virtual electricity store of 70% or 80% efficiency and can produce and transfer electricity using a net-metering scheme. The results show that the application of micro-scale PV systems would help residential buildings to be more energy efficient, reduce energy consumption based on fossil fuels significantly, and even if the grid cannot be used as a virtual electricity store then the direct self-consumption of buildings can reduce their energy consumption by 30% on average. Development of micro-scale PV systems seems to be one of the most efficient options for a quick transformation of the centralized energy system in large Polish cities to a distributed energy one based on individual renewable energy sources.

Keywords: centralized energy systems; district heating systems; energy demand in buildings; distributed energy sources; photovoltaic systems

1. Introduction

The idea of smart cities is not new for Poland. However, the concept of smart cities has been developed mainly from the standpoint of the global aspects of the smart management of a city. The global key indicators are as follows: the efficient administration of the city, cooperation between the city (administrative bodies) and inhabitants, service availability, transport access, social life, clean environment, and land use. The focus is put on social aspects to assure good standards of living and

comfort, combined with a sense of security in everyday life as a citizen. Energy aspects such as energy efficiency, the safety of energy supply, and the utilization of renewables are also considered, but less stress is put on them. Such a situation has been caused by good access to energy networks, mainly centralized heating networks and grids, in most of the cities since socialist times. However, nowadays, society—especially young people—is becoming more interested in climate change issues, and therefore energy availability and the efficient use of energy has become one of the most important issues for sustainable development.

During the transformation from the centrally planned to free market economy, at the end of the last century (in the 1990s of the XX century) the restructuring and privatization processes of the Polish centralized economy, including the energy sector, started. The energy power sector was segmented into generation, transmission, and distribution. Competition among independent companies in each sector was introduced at the end of the 1990s. The central heat supply used to play and still plays an important role in the Polish energy economy. Heat is mainly generated in Combined Heat and Power (CHP) stations and in heat plants (which used to be public/state-owned). The fuel structure of direct consumption has been changing very slowly. Large cities and factories are supplied by coal-fired Combined Heat and Power stations. New trends can be seen as the solid fuel share (hard and brown coal) reduces in favor of liquid and gaseous fuels. The share of renewable energy is still very small. Up to now, district heating has been a major component of Poland's energy infrastructure. District Heating Networks (DHN) supply more than half of Poland's residential heating needs, with 75% in urban areas. The largest district heating network in Europe (and second in the world) is in Warsaw. It is noticeable that, since the last century, the heating demand has been decreasing continuously, mainly because of the intensive thermal refurbishment of buildings. However, electricity demand is growing. The reasons for this are mainly connected with an observed tendency for rapid increase in the penetration of electric appliances in the tertiary sector as well as in households.

Taking into account the existing situation in big cities, where energy systems and urban networks are very complex and most of them are centralized, it seems very difficult to assure the efficient transition from centralized energy systems to distributed energy sources in large Polish cities. Now, it is almost impossible to switch off the cogeneration power plants located in big cities, but it is necessary to modernize them to create low-emission plants, mainly through switching from coal to another (low emission) fuel. It is also not possible to cease using the central district heating networks, but it is possible to make them more efficient (e.g., through reduction in heat losses) and connect them not only with the central cogeneration plants but also with modern low-emission distributed energy systems based on locally available energy sources, such as renewables or waste heat (e.g., from industry or the tertiary sector). However, this can appear rather difficult, because central district heating systems are high-temperature networks (in Poland). When distributed energy sources such as renewables or waste heat sources are available, they supply heat at a medium or low temperature level. Therefore, when such sources can be utilized it is good to consider the possibility of the development of distributed local heating systems and distributed local electrical grids, not connected to large centralized energy systems but connected to each other. In such a way, low-temperature distributed local heating systems based on different renewable energy sources or waste heat sources can be developed to create local small- or even micro-scale centralized heating systems.

The transition from centralized mono-energy (based on coal) systems to integrated multi-energy source systems represents a great challenge, but it is a necessity in the present day. In countries like Poland, after so many years of constructing and using central high-temperature heating networks, which are used to supply heat to nearly every part of the city, it seems difficult or even impossible to switch to low-temperature distributed heating networks based on renewables in a short time. What is more, the heat is generated in cogeneration heating plants and such plants is promoted by EU energy policy [1]. Therefore, this process should be organized not very rapidly, rather than step by step, starting from small city areas (e.g., for a district of a few new buildings), which can be termed

new housing estates of zero-net energy consumption, and then in a further step including positive energy districts.

Due to the existence of a central power grid and centralized district heating systems, the integrated management of energy in cities is a well-known process. However, it is not easy to determine the real reduction in energy consumption when the energy system is based on coal-fired plants. The transition of the centralized energy economy to a modern circular economy based on renewables is something completely new for the Polish energy sector at large and medium scales. To present the background of the present energy situation in cities, this paper evaluates the effectiveness of the operation of central district heating systems and heat distribution systems to predict the improvement in the effectiveness of energy production, distribution, and use. Then, it analyzes the energy effectiveness of the existing CHP plants in Warsaw. This paper evaluates the modernization possibilities of the existing central district heating systems in terms of reducing primary energy consumption and greenhouse emissions. A broad analysis of the possibilities of upgrading and developing district heating systems in Poland was presented by Wojdyga [2]. His paper deals with the history of the development of Polish heating systems and the current conditions. The diagnosis from 4 years ago states that district heating systems will continue to develop, but the development of the complementary elements in the form of dispersed small energy systems will be necessary.

It should be pointed out that the problem of the modernization of the centralized energy sector and especially of district heating systems has been problematic for many past socialist countries, including Poland. An example of the transformation of traditional district heating systems in Chemnitz (Germany) has been presented by Urbaneck and co-authors [3]. In the paper, the authors analyzed the possibility of separating a part of the heating network and switching it to a low-temperature section of the heating network with the use of a solar plant. In the conclusions, they state that the integration of solar heat requires special concepts. This applies in particular to areas with conventional districts. This applies in particular to areas with conventional district heating. Competition between solar heat and cogeneration should be avoided. Lygnerud discussed the situation of the district heating in Brasov (Romania) [4]. Inefficient infrastructure and the problem of loss of consumers due to unreliability of supply over previous decades were observed. The assessment of the impact of different policies on the feasibility of renewable energies and efficient heating was performed. The possibility of transformation into an efficient system was presented. The analysis showed what kind of politics should be applied. Problems of post-communist district heating systems were also discussed in [5]. The paper focused on the legal aspects of this kind of district heating system. Nowadays, Polish cities are expanding into new areas—country land (mainly agricultural in origin). The way of life is changing. People want to work in a city, but they want to live outside it, in new clean suburbs having some of privacy compared with high-rise multi-apartments housing estates. The new suburbs are developing very quickly.

Very often, such new suburbs do not have access to the central district heating system and other energy media such as gas, and sometimes they are even quite far from the power grid. Such a situation gives a unique opportunity for the introduction of distributed energy systems based on renewables for the generation of heat and electricity. In this way, the new districts of a city can be based fully on their own energy sources, where renewables can play the most important role.

A new trend, the electrification of the heating sector, is also evident in Poland and can be effectively applied in new districts. Electrification in this new sense means the application of electrically driven heat pumps for the hot water and space heating and using the heat pumps in a reverse cycle for cooling demand, if applicable. Heat pumps can be based on renewable energy heat sources (ground, water, air) or waste heat available at the location. Electrical energy supplied to heat pumps can be generated by local photovoltaic or wind turbines systems located on buildings or in their vicinity. On a larger scale, such districts can be supplied by the biomass or biogas CHP plants.

In most European countries, the concept of distributed energy systems in cities has been developed mainly towards the modernization of existing heating systems and extending them to new territory, but in the form of low-temperature heating systems based on renewables [6–8].

Most of such low-temperature heating systems are supplied with heat generated in solar thermal plants [8,9]. Solar thermal plants as distributed energy systems are a very promising solution for low-temperature district heating systems in most western European countries. However, coupling them to high-temperature district heating systems as is common in Eastern European countries is not yet possible because of technological but mainly economic reasons [3]. The energy sector and especially the district heating systems in the large cities of past socialist countries are completely different to the systems in other European countries. The path towards the deployment of distributed energy systems based on renewables must be based on energy roadmaps developed especially for different regions of Europe, even if there is one common EU target to reach the 80% reduction in annual greenhouse gas emissions in 2050 compared to the 1990 levels [7]. Sustainable energy generation and supply is expected through moving to decentralized and smart energy grid solutions [10]. The paper shows one of the possible routes for East European countries to reach the goal of sustainability.

This paper deals with the problem of the possible transition from the existing centralized energy systems in Polish cities to modern low emission distributed energy systems based on locally available energy sources, mainly solar energy. To evaluate these possibilities, the paper first in Section 2 presents the schematic idea of the existing energy structure in large cities and their suburbs. In Section 3, the current structure of the energy sector—mainly power and heating networks—in Polish cities is presented. Then, in Section 4 a basic review of the energy consumption in the building sector is given, with emphasis put on residential buildings. This is due to the fact that the hypothetical new low-energy district in the suburbs of the city proposed for consideration here is composed mainly of residential buildings. Such a new suburb housing estate and its distributed energy system based on renewables is presented in Section 5. The effectiveness of operation of the proposed energy system is analyzed, and the expected reduction in energy consumption is evaluated. The last chapter presents the conclusions of the studies conducted and some recommendations for transition steps to achieve low-energy or even positive-energy districts in large cities previously with a monopoly of large centralized energy systems.

2. Schematic Picture of the Energy Sector in Large Polish Cities

Nowadays, the phenomenon of cities spilling into rural areas can be seen in many countries. Such a situation is also typical for large Polish cities and their new suburbs, which can be called new green residential districts. People want to move out of the busy, noisy, and polluted cities to live in a clean and quiet habitat. It is much easier to assure low energy consumption in such new districts because it is easier to build new buildings with new energy sources according to the energy efficiency and clean environment standards than to transform (refurbish) old highly energy-intensive buildings supplied by inefficient centralized energy systems constructed on the basis of past technology.

The paper tries to show how difficult it is to transit the energy economy from centralized mono-energy fossil fuels systems, mainly based on coal, to distributed energy systems based on renewables. To give the basis for discussion, it is necessary to present the situation in the energy sector in large cities in a schematic way. Figure 1 presents such a schematic picture of the centralized energy sector typical for large Polish cities and its influence on other main sectors. This picture also shows what is happening in the new suburbs of these cities. Such new urban districts are developing quickly and they are supplied by their own energy systems. This is an indication of how cities are evolving.

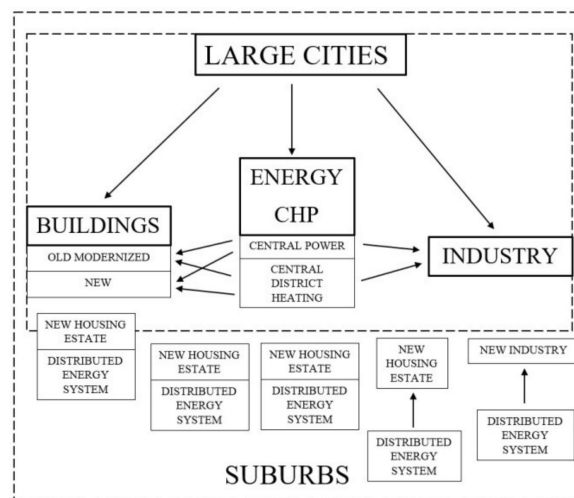


Figure 1. A schematic picture of the centralized energy sector typical for large Polish cities as well as its influence on other sectors and the city's suburbs with new housing estates coupled with distributed energy systems.

Figure 1 gives a basis for consideration and explains why specific sectors are analyzed in the following chapters of the paper. As can be seen in the figure, in large cities buildings depend completely on the energy sector. There is an impact of energy plants and networks on buildings, but not the opposite. In new districts in suburbs, there is mutual interaction between houses and energy systems. This is especially true when buildings are equipped with energy devices and installations which generate energy just for the building themselves. What is more, the elements of such systems can be installed using building integrated technologies (e.g., BIPV—building integrated photovoltaics).

The transport sector is not included in Figure 1 and in consideration in the paper. This is due to the fact that the present energy sector in large cities is not connected in a direct or indirect way with the transport sector. However, the transformation of the transport sector towards electrical vehicles is becoming a reality. It can be expected that electrical cars driven by renewable energy will be one of the important elements of future energy systems in cities. Such vehicles will be present in new low-energy city districts in the suburbs of the cities, acting as stores of electricity gained by micro renewable energy systems such as photovoltaic and wind systems.

3. Polish Energy Sector

3.1. District Heating Systems

The current situation of Polish district heating systems with a focus on heating networks in Polish cities is presented in this chapter.

Polish district heating systems have a long history. The biggest development of Polish district heating systems was carried out in the sixties and seventies of the last century. In those years, a very large development of heat demand was planned. In the 1980s and early 1990s, there was a significant decline in the development of industry and construction in Poland. As a result, the dynamics of the increase in heat demand decreased. In the late nineties of the last century, there was a great wave of thermal modernization of buildings. This caused the capacity of the systems to be much greater than the heat demand. Due to the excess of installed capacity, it was not necessary to modernize the heating systems. The history of development and decisions made over time has influenced the current structure of heating systems. Political decisions about the development of the DHN (District Heating Network) caused almost all cities in Poland to have heating systems. Poland is a leading supplier of heat for district heating networks [11]. The total district heat sales are presented in Figure 2.

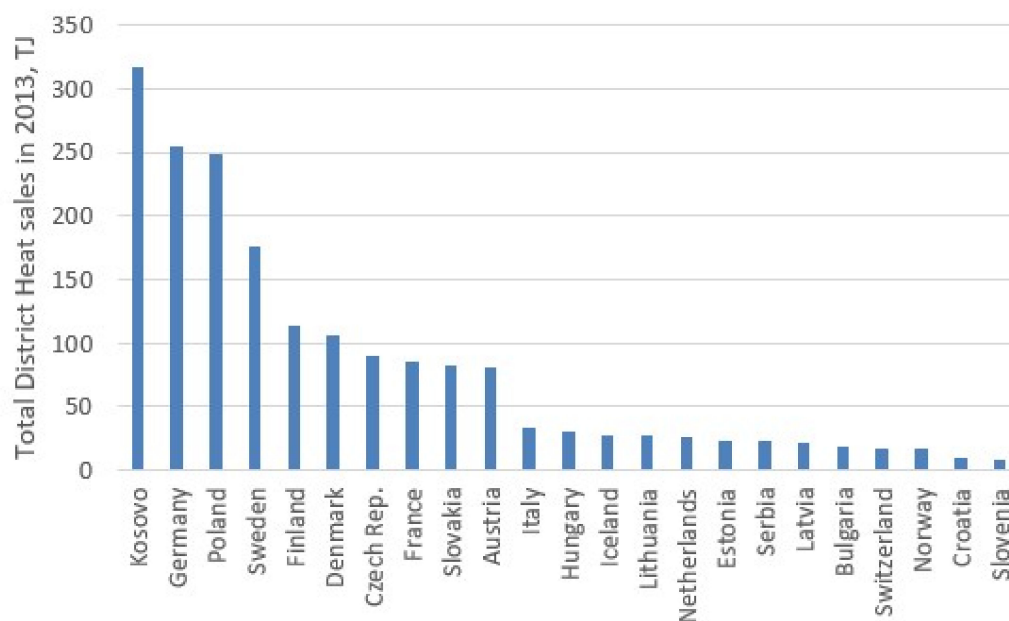


Figure 2. Total district heat sales in 2013 in European countries.

The great potential of the district heating systems in Poland is an important advantage. The same situation caused there to be a very unfavorable fuel structure for heat production for DHN. The fuel structure of the heat production for district heating systems with a capacity above 5 MW (in fuel) is shown in Figure 3 [12]. The presented data show that over 70% of the heat for DHN is produced with the use of hard coal, and the heat from renewable energy sources—i.e., biomass—is below 10%.

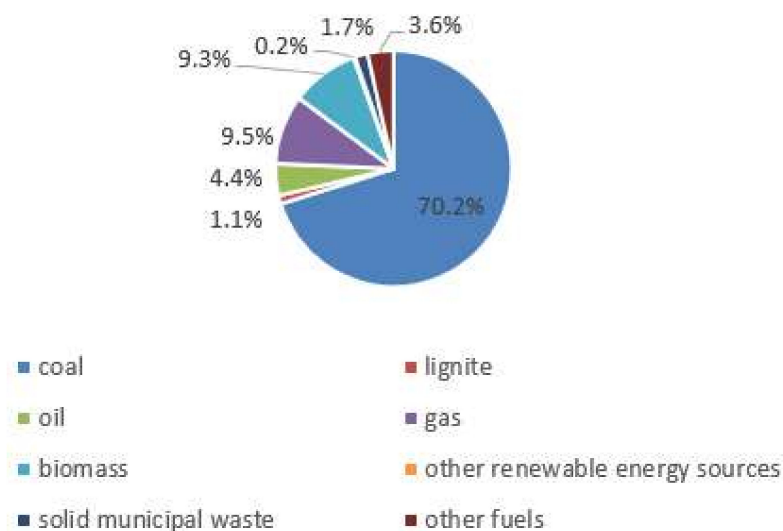


Figure 3. Fuel consumption for heat production.

The effectiveness of the system is very low because of the structure of the technology used in the systems. In the large power plants (from 100 MW to more the 2000 MW of thermal capacity), there are steam pulverized-fuel boilers with steam turbines. In the typical structure of medium and small systems, there are water stocker-fired boilers (coal-fired). The average efficiency of the transformation of prime energy to the used form of energy is presented in Figure 4. The specific emissions for unit of the heat are presented in Figures 5 and 6 [12]. In Figure 4, we can see that it is no significant progress in the efficiency of the Polish district heating systems. However, we can observe a decrease in the emissions of the SO_2 as a result of the installing desulphurization.

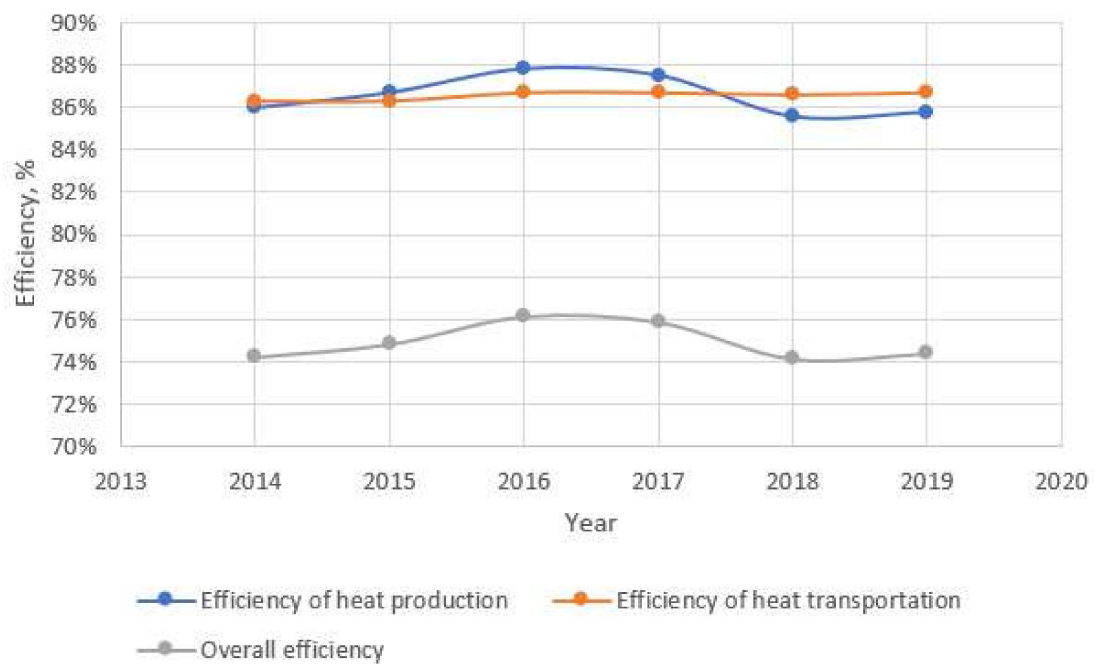


Figure 4. The efficiency of heat production and heat transportation—an average value for all Polish district heating companies over the last 6 years.

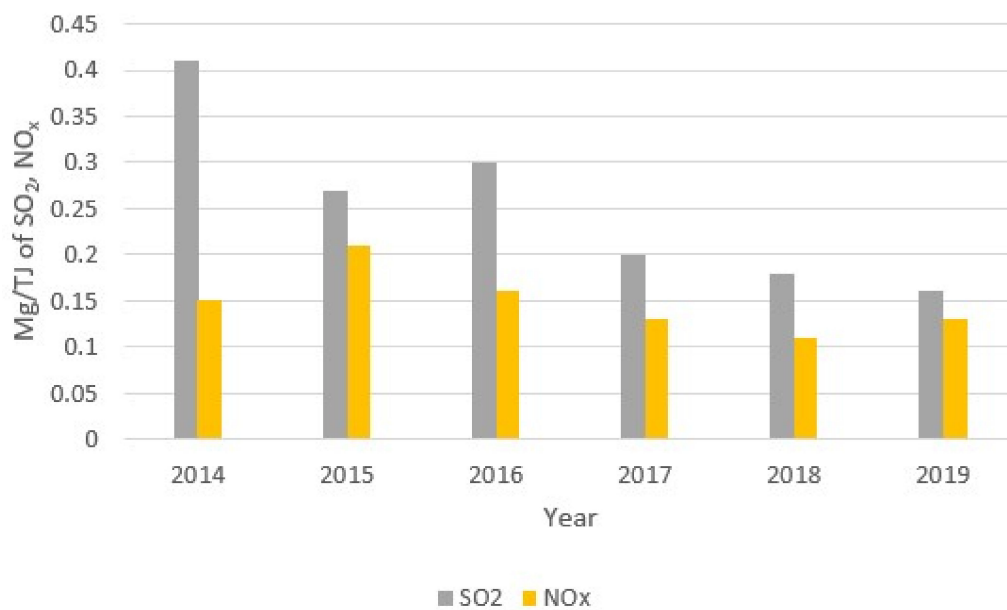


Figure 5. Average emission factors of SO₂ and NO_x per unit of heat over the last few years.

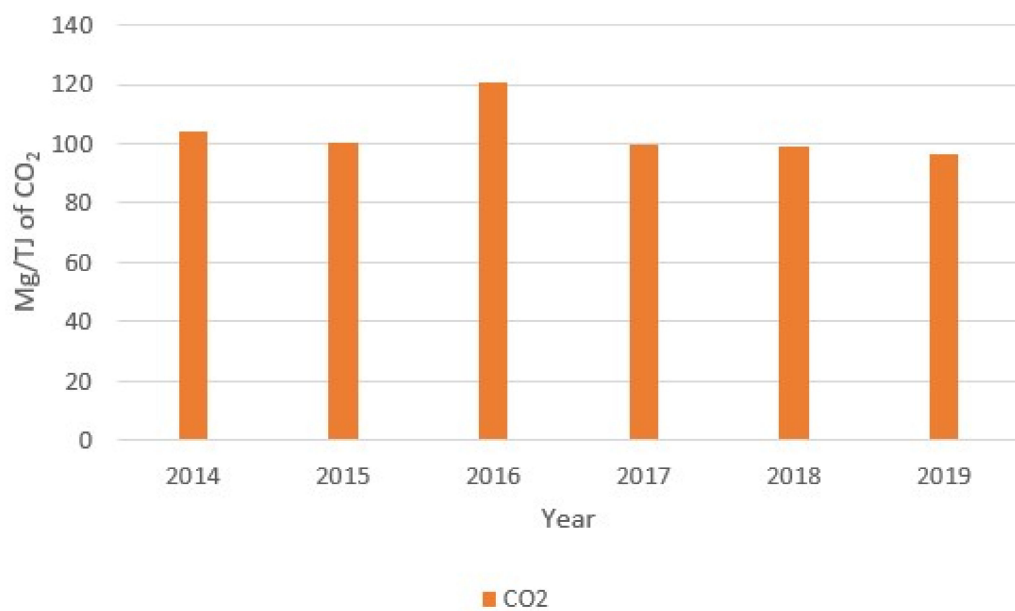


Figure 6. Average emission factors of CO₂ per unit of heat over the last few years.

A comprehensive description of the Polish district system must be preceded by an analysis of the structure of CHP, non-CHP, and renewables in heat generation in Poland. Figure 7 illustrates the structure of heat production in Polish district heating companies. Most of the heat (57%) is generated by CHP units, because the large-capacity CHP units, which deliver heat to DHN, are the most suitable heat source for heat generation in Poland. Medium- and small-capacity plants are facing problems due to the lack of CHP units or renewables.

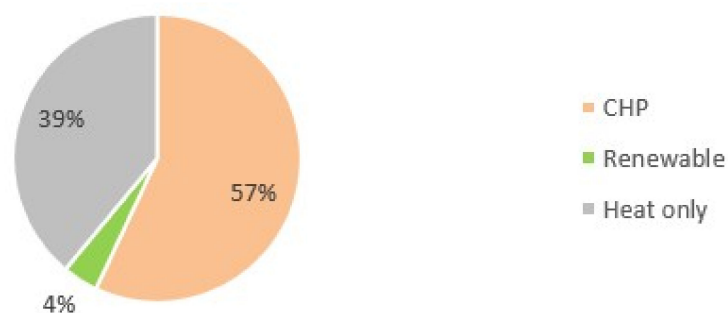


Figure 7. Structure of heat production in heating systems with a capacity greater than 5 MW in 2018—estimates based on data from the Energy Regulatory Office.

The indicators of the development of district heating systems is a debatable issue due to the lack of common methods for their definition. Authors suggest using the length of the district heating systems as a reliable indicator, because the length of DHN reflects the development of the district heating systems. The change in the overall length of Polish district heating systems over the last few years is depicted in Figure 8 [12]. The constant increase in the length of the district heating systems is observed over many years—i.e., 1% per year.

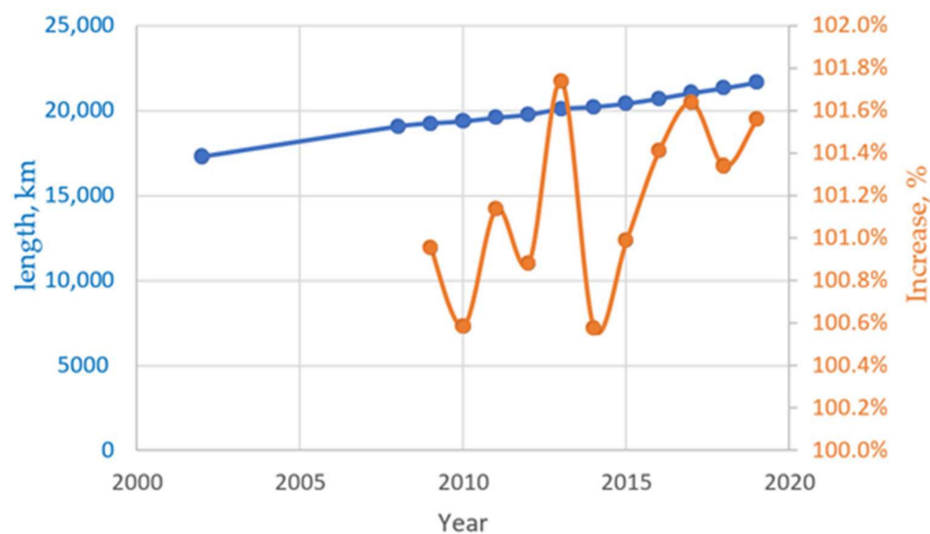


Figure 8. Overall length of the district heating network over the years.

Up to this moment, it seems that the overall condition of the Polish district heating system is good, however scrutiny of its efficiency and pollutant emissions reveals the need to change the heat production portfolio.

3.2. Power Sector

A similar situation applies to the power sector, which has not been significantly modernized for many years. Figure 9 presents the structure of electricity production in the years 1990 to 2019 [13]. It can be observed that over 90% of electric energy was generated by thermal power sources, while most of them are coal-fired power plants. In the years 2010 to 2015, an increase in electricity generation from renewable sources (i.e., wind power plants) is noticed. However, as a result of the change in legal regulations in 2016 (limitation of the height of the wind power plant depending on the distance from the buildings), this growth was stopped and currently the share of renewable energy is still very low.

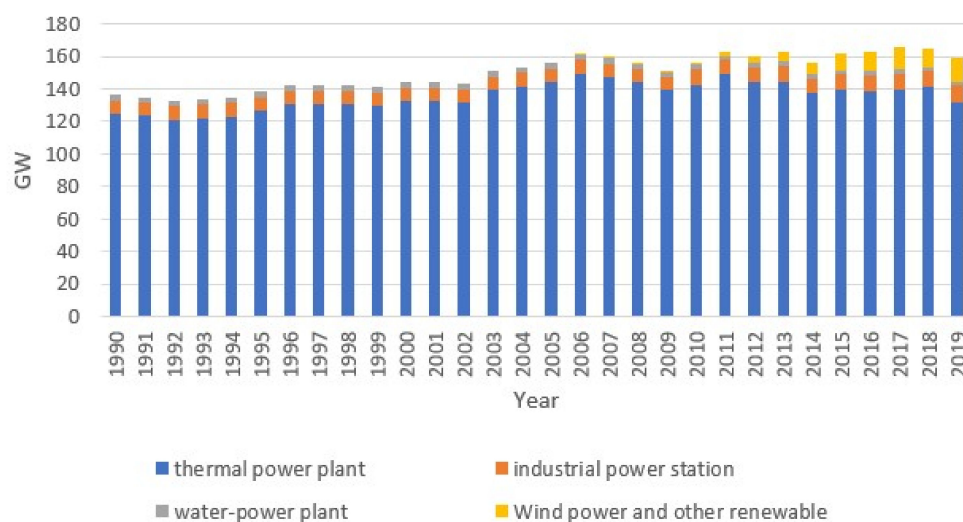


Figure 9. Electricity production in Poland in the years from 1990 to 2019 (GWh).

Recently, a rapid growth in the installed capacity in photovoltaic systems has been observed, which was caused by the introduction of a governmental support program. Figure 10 shows the increase in the installed PV capacity in recent years [14].



Figure 10. Installed capacity in photovoltaic in Poland in the years from 2010 to 2019.

On the other hand, dynamic changes in the way electricity is used are observed. The main change is a significant increase in power demand during the summer period, which results from an increase in air conditioning needs. The change in the value of the monthly average power demand in the last 10 years is shown in Figure 11 [13].

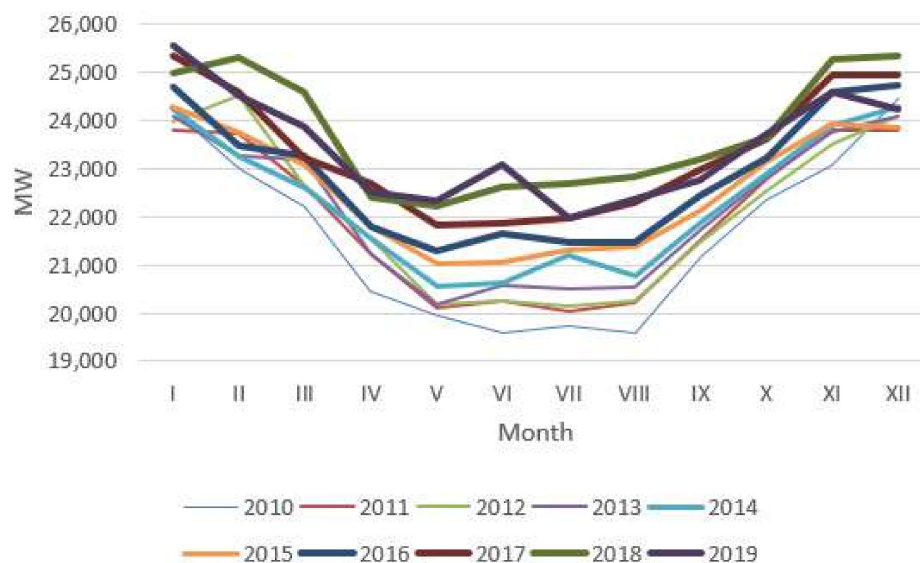


Figure 11. Average monthly domestic power demand in daily load peaks on working days from 2010 to 2019 (MW).

The discussed data shows that the Polish power system is based on outdated and inefficient technologies. On the other hand, the environmental forces are changing. Warsaw seems to be a good example. In Warsaw, most of the buildings are connected to the high-temperature district heating network, which is supplied by heat sources (in the year 2020, coal-fired CHP). Those CHP units are an important element of the city's electricity supply. It is obvious that, in the future, the district heating system will have to undergo transformation to fourth [15] and fifth generation systems [16]. The development of heat storage will be an essential element of the system transformation [17].

For technical reasons, it will be difficult to change the way the power is supplied. On the other hand, cities are developing intensively and new areas are being created which are located far beyond the network's coverage and are strongly urbanized. This creates a place for the intensive development of smart energy regions and positive energy districts (PEDs) in the future.

4. Building Sector in Poland

4.1. Old Buildings

As described in the previous chapter, changes in the energy sector are progressing slowly and are mainly concentrated on the modernization of the large coal-fired power plants. The power grids and district heating systems still need major upgrading. Much more is going on in buildings and the reduction in energy consumption is noticeable, as is presented in this chapter.

A basic review of the energy consumption in the building sector is presented at the beginning of this chapter, with the stress placed on residential buildings.

In Poland, as in many EU countries, the building sector is responsible for around 40% of the final energy consumption. The high heat demand in existing buildings is caused by past (mainly socialist) energy policy. In those days, energy prices were very low and there was no need to save energy. As a result, nobody was thinking about reduction in energy needs and energy consumption. The previous codes for buildings took into consideration only the heat transfer coefficients for walls and windows. As a result, the energy consumed in buildings was huge. In addition, the energy supplied to buildings was generated in inefficient plants fired by coal. Such a situation caused a high consumption of primary energy, as is presented in Table 1.

Table 1. Changes in the heat transfer coefficients for walls and windows and the indices of the final and primary energy consumption for heating energy (for space heating only) in the years 1966 to 2014.

Time of Construction	Heat Transfer Coefficients for Walls and Windows [W/m ² K]	Final Energy Needs for Space Heating [W/m ² K]	Primary Energy Needs for Space Heating [W/m ² K]
–1966	1.16/– 1.40 */–	240–280 300–350	364–447 489–569
1967–1985 (1983 ^w)	1.16/–(2.6) ^w	240–280	364–447
1986–1992	0.75/2.6	160–200	244–325
1993–2001 (1998 ^w)	0.55/2.6 (2–2.6) ^{w2}	120–160	203–244
2002–2008	0.30/2–2.6	90–120	69–183
2009–2013	0.30/1.8–1.7	90–120 **	69–183 **

* Two values of the heat transfer coefficients connected with a type of the building construction; ^w for windows, the limits for heat transfer coefficients were introduced for the first time in 1982 by the national standards; ^{w2} for windows, the range of limits for heat transfer coefficients were introduced in 1998 by the national regulations for buildings. ** Indices for the final and primary energy used to be dependent on the so-called “shape coefficient” of a building, which was the building surface area to volume ratio of a building.

It should be underlined that only the limits for the heat transfer coefficients for walls in the 1960s to 1980s were regulated by the official codes. For windows, official regulations were introduced in the year 1992. Extremely high indices of the final energy needs for space heating were caused by the very high values of these coefficients and very high air ventilation rates (very poor leak tightness of building envelopes). The high indices of primary energy needs resulted in using low-efficiency coal-firing in the heat and power (or CHP) plants. It is important to notice that the indices presented in Table 1 present the values of energy needs rather than of energy consumption, as are commonly used nowadays. In reality, in those days it was not possible to supply such a large amount of heat to buildings to assure internal thermal comfort. As a result, the thermal comfort was very poor. The indoor air temperature

used to be much lower than that required for thermal comfort and living comfort. The indoor air humidity was high and condensation problems were very bad. As a result of the condensation, mold and fungus appeared. When, at the turn of the century, the transformation of the national economy started, most of the buildings constructed in the 1960s to 1990s went through an intensive thermal refurbishment process. As a result, since those days the energy demand of Polish buildings has decreased significantly. However, they still consume much more energy than new buildings. It is much easier to introduce modern energy systems in buildings where energy effectiveness has been introduced from the beginning (design and construction phase), and thanks to that they need less energy for running all their energy systems.

4.2. New Buildings

According to the EC directive of the energy performance of buildings [18,19], it is necessary to reduce energy consumption significantly and to achieve nearly zero-energy buildings by the beginning of 2021. Polish regulations set the limit of primary energy consumption indices for domestic hot water (DHW) and space heating for residential and non-residential buildings. Since the year 2021, multifamily buildings and single-family houses cannot consume more primary energy than 65 and 70 kWh/m² per year, respectively [20]. However, there are no restrictions on the final energy consumption. Table 2 presents all the recent changes (since the year 2014) in the official regulations for the indices of primary energy consumption for heating energy (space heating + DHW) and the heat transfer coefficients for walls and windows.

Table 2. Changes in the heat transfer coefficients for walls and windows and the indices of primary energy consumption for heating energy since the year 2014.

Type of a Building and Duration of the Regulation	Heat Transfer Coefficients for Walls [W/m²K]	Heat Transfer Coefficients for Windows [W/m²K]	Indices of Primary Energy Consumption for Heating Energy, [kWh/m²]
2014–2016			
multifamily buildings	0.3	1.3	105
single-family houses			120
2017–2020			
multifamily buildings	0.23	1.1	95
single-family houses			85
since 2021			
multifamily buildings	0.2	0.9–1.1	70
single-family houses			65

There are no official regulations for the limits of electrical energy consumed by electrical appliances and lighting and for cooling energy. In previous decades, because of the climate and poor thermal quality of residential buildings, there was no problem with the overheating of buildings. Even when heat was gained quickly during the day in summer due to high solar radiation, it was also lost very quickly because of the low thermal insulation quality (thin layers of insulation without the proper technology for attaching it to the building structure) of buildings' envelopes (high heat-transfer coefficients). Nowadays, when buildings are very well insulated and well-constructed, the heat cannot leave (be lost) so easily and quickly in a natural way, and a cooling system to remove the gained excess heat (excess quantity) has to be used to keep the indoor thermal comfort at the required level in summer [21]. Table 2 presents the changes in the official regulations for the indices of primary energy consumption for heating energy and the heat transfer coefficients for walls and windows, respectively.

Analyzing the data in Table 2, it can be seen that the present building codes require a high thermal quality of buildings and that, as a result, the heat transfer through envelopes is very much reduced. As a consequence, the heat demand for space heating can be very small even if the winters are quite severe.

It can be added that there are no limits for electricity consumption by electrical appliances and lighting. However, people have started reducing electrical energy consumption mainly because of economic reasons. The prices of electricity have started to increase significantly in recent years.

As mentioned regarding the new hypothetical housing estates considered in this paper, all buildings are constructed according to the present building codes and regulations, which means they can be called nearly zero-energy buildings (from the Polish building sector perspective).

5. New Warsaw's Suburb Supplied by Distributed Solar Energy Sources

5.1. A Micro-Scale PV System as Distributed Energy Source in Polish Conditions

As mentioned, the new residential areas in the suburbs of large cities are characterized by relatively low energy needs and more often than not use their own energy systems. Heating is mainly based on gas boilers, which can use liquid gas from tanks, or fireplaces (wood fired) coupled with air ducts to distribute the heat gained inside a house. The electrical power grid is available nearly everywhere in the country, so it is used to supply energy to electrical appliances. Sometimes electricity is used for space heating, and this is mainly in cases when residents install their own micro-PV system. The utilization of PV systems at the micro-scale has become quite popular recently, mainly because of the financial incentives supported by generous national regulations and also as a result of the increasing awareness of the environment and climate change.

In this chapter, the possibility of the introduction of PV systems as distributed energy sources to reduce energy consumption by residential buildings located in the new green area of Warsaw's suburbs is analyzed. It is assumed that residential buildings in that area have good solar irradiation conditions (roofs have good exposure to solar radiation, there are no shading devices on the roof and no shading obstacles in the vicinity (trees, other buildings, etc.)) and the PV installations can be used in effective way. In recent years, PV technology has become relatively cheap in Poland. Installing micro-scale PV systems has also become a very simple solution, not only because the technical method of installing the PV modules is simple, but also because PV modules are widely available and, as mentioned above, legal regulations positively support the use of this technology [22]. Micro wind power plants are not a popular technology. However, in aiming to achieve nearly zero- or even positive-energy districts, perhaps it is good to take into account the possibility of installing such systems to be complementary to PV installation.

The electricity produced by PV systems can be used on site and/or transferred to the grid. PV energy can be used not only for lighting and electrical appliances in homes but also to drive micro- and small-scale heat pumps. The potential for heat pump deployment is considered taking into account the existing district heating connections, which are located in the cities, but not in the newly emerging housing estates in the suburbs. The operation of heat pumps in a reversed cycle to supply cooling energy can be also applied (but is not analyzed in the paper). The approach is based on the existing regulation and support scheme for the application of renewables. Analysis is performed on the basis of calculations determining the energy needs of the considered buildings and the energy gains and effectiveness of energy systems. It is assumed that the PV installations are located on roofs of residential buildings and are treated as individual micro-scale energy systems of an installed capacity not larger than 50 kW for each of the group of buildings. Polish regulations put this capacity limit on micro-scale energy systems based on renewables. In such cases, the micro energy system can use the grid as a virtual electricity store of 80% (up to 10 kW of installed capacity) or 70% (between 10 and 50 kW of installed capacity) efficiency, and can produce and transfer electricity on the basis of a net-metering scheme [22]. Treating the grid as a store means that the energy not used in a building at the time when it is produced (there is no so called self-consumption) can be sent to the grid, and later

when the PV system is not operating 80% or 70% of the energy transferred to the grid is taken out of the grid when it is needed. The maximum storage time is half a year, but with strictly defined dates. A year is divided into two halves, with the first starting on 1 January and the second on 1 July. However, there is official limitation of the storage capacity of the grid. The amount of energy transferred to the grid must be equal to energy consumed in a building which produces such energy. When more energy is transferred to the grid, it is treated as very cheap extra energy gained by the grid. The extra energy supplied to the grid can be sold by the energy producer to the energy distribution company (the owner of the grid), but the price for 1 kWh of such extra energy is at least ten times smaller than the regular price of electricity for individual consumers.

5.2. General Description of a Hypothetical Suburb Housing Estates

New single and multi-family housing estates are being built in the suburbs of large cities. They are built in rural areas. Such a location of a built housing estate is associated with certain limitations. As mentioned, such buildings usually do not have access to the central district heating or the gas network. At the initial stage of construction, the estates only have access to cold water from the mains and electricity from the grid. This creates the conditions to use renewable energy sources to cover the needs for domestic hot water and space heating. Figure 12 shows a typical new suburb housing estate.



Figure 12. A typical new housing estate in the suburbs of Warsaw.

This chapter describes a hypothetical estate of terraced single-family houses. A system with heat pumps has been proposed to ensure the needs for space heating and domestic hot water. The estate is supposed to produce the same or more energy than it consumes. This means that systems generating electricity should be installed in the buildings covering all available surfaces exposed to the solar radiation. Photovoltaic systems located on the roofs of houses can be used to power devices located in the buildings. In addition, small wind turbines can be located in the vicinity. The energy produced by renewable energy systems can be used by the household members or sent to the power grid.

First of all, basic assumptions about the location and orientation of the buildings of the housing estate under consideration have been made. As the estate is located in the suburbs of Warsaw, then meteorological data for this location are used for the calculation [23]. It has been assumed that the estate consists of 25 terraced houses divided into four buildings. Each of the houses has an area of 120 m² (of the heating space) and two floors. The schematic location of the buildings is shown in Figure 13.

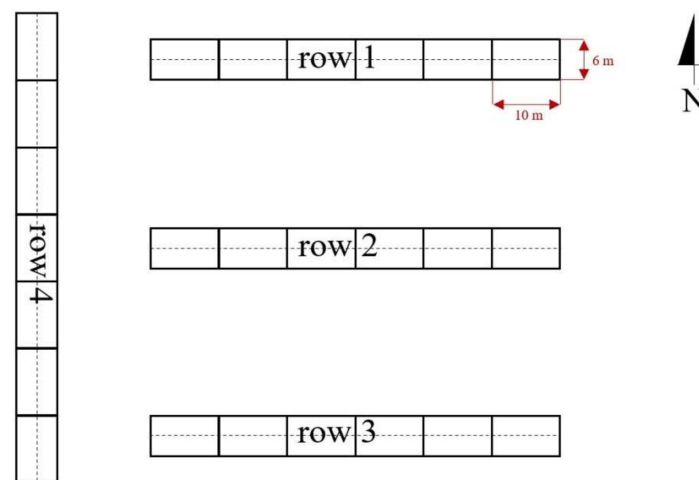


Figure 13. Location of buildings of the hypothetical estates.

Eighteen of the terraced houses have their roofs facing south/north and seven towards the east/west (this is one of the most typical arrangement for such estates). All the roofs are inclined at an angle of 30° . These are important data relevant to determining PV systems gains.

5.3. Methodology of Determination Energy Performance of Building and Energy Systems

To analyze the application of distributed energy systems based on renewables in the new suburbs of Warsaw, it was first necessary to conduct a study on energy needs of such a new housing district and then to select a renewable energy system to provide the energy needed. Next, the operation of the energy systems was modelled and simulated to determine the energy performance of the district. A special simulation code has been developed to simulate the building dynamics and renewable distributed energy systems.

The dynamics of the buildings have been considered taking into account changing weather conditions (ambient air temperature and solar irradiation). The energy balance of the building was formulated with all energy fluxes flowing out and in. Calculations of space heating (or cooling) needs are performed with a time step equal to one hour. The methodology of calculations is generally based on standards for the determination of energy performance of buildings [24]. The main difference between the standard method and model applied for the simulation is the time step of the calculations. The standard method uses average data for every month, while the model used in the study requires the hourly values of climatic data for the whole year. What is more, solar irradiation is calculated with regard to the specific orientation and inclination of a surface exposed to solar radiation using the Liu–Jordan isotropic diffuse solar radiation model [25]. To determine such solar irradiation, hourly values for direct and diffuse solar radiation on horizontal surface for given location are taken from the official data base [23]. Such a detailed model of the availability of solar radiation has been used because the solar radiation impact on the energy balance of buildings is especially high in new buildings that are very well insulated and airtight [21]. Solar radiation enters the interior of a building through transparent elements—windows—then is absorbed by the internal surfaces of a room, furniture, etc. As a result of the photo-thermal conversion of solar radiation, the indoor air temperature increases. Too much solar gain can cause the overheating of rooms.

The detailed calculations of solar irradiation are also important for calculations of energy gained by the photovoltaic systems. Operation of all energy systems is analyzed on hourly basis. Hourly values of wind speed in given location are taken from the official data base [23]. They are used for determination of energy generated by micro wind turbines. Operation of the heat pumps used for space heating and domestic hot water also changes in time depending on changing demands for both energy needs. As result performance of the heat pump also changes in time.

5.4. Energy Demand of a Hypothetical Suburb Housing Estates

To determine the electricity demand, it is necessary to assume an appropriate energy consumption profile. In the case of the estate in question, the total demand consists of two components. The first is the demand for energy to power household appliances and lighting. For the calculations, two different electricity consumption profiles were assumed depending on the lifestyle of the household members. The self-consumption of the energy produced by the PV system depends on the characteristics of electricity consumption in a given building. The self-consumption means that the electricity generated by the PV system at a given time is used by inhabitants at the same time. Figures 14 and 15 show the two proposed variants. Variant A represents the situation when some members of family are at home during the day. Variant B represents the situation when all members are out of the home (working, learning, etc.)

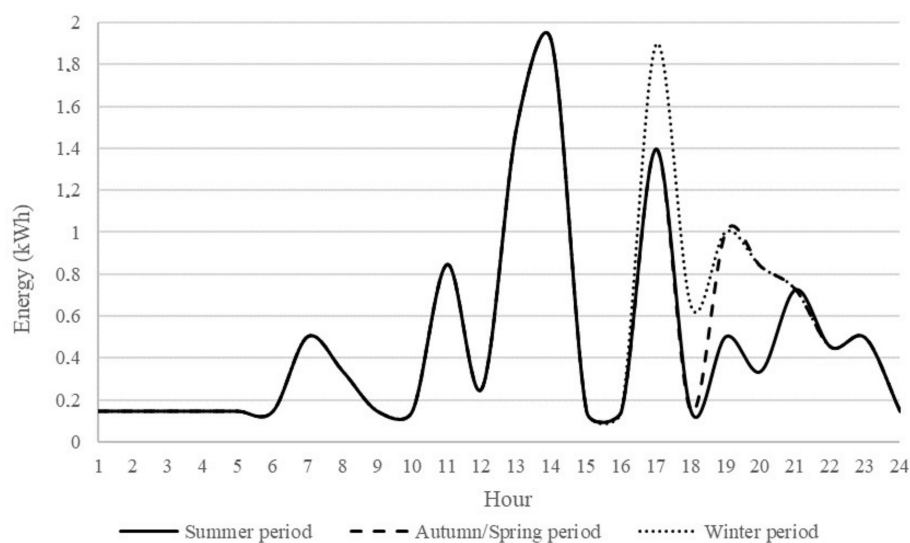


Figure 14. Electricity consumption profile (A).

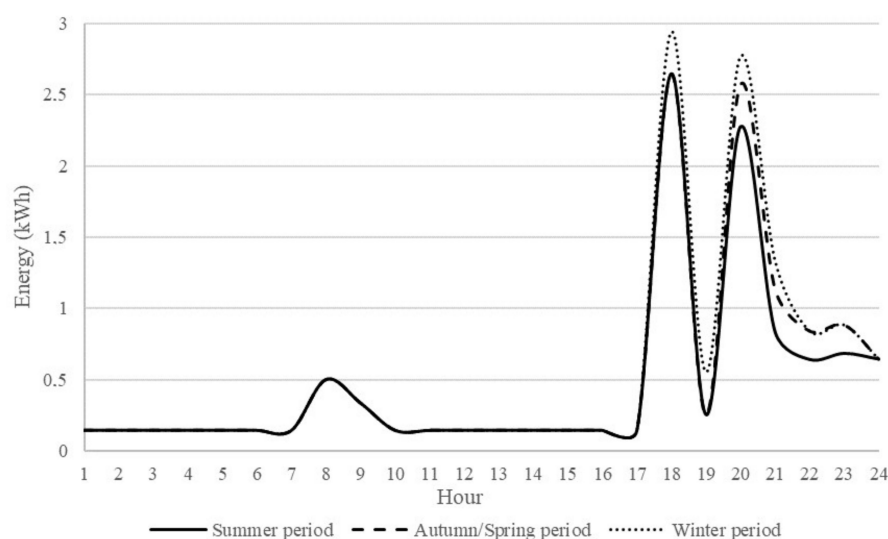


Figure 15. Electricity consumption profile (B).

It was assumed that 25% of the residents of the housing estate use energy according to profile A and 75% according to profile B. The daily electricity consumption in both cases is the same and amounts to approximately 12 kWh. The second factor is the energy required to power the heat pump.

In order to determine the demand for energy to power the heat pump, the demand for space heating, ventilation, and domestic hot water was determined with an hourly time step, as mentioned before. The demand for domestic hot water was calculated assuming that every household member consumes 40 L of domestic hot water of 50 °C temperature every day. The daily demand for domestic hot water for a family of four is approximately equal to 9.3 kWh. For domestic hot water consumption, two different water consumption profiles have also been taken into account. As the water is heated by a heat pump that uses electricity, the DHW consumption has an impact on the self-consumption of the energy generated by the PV system. Figures 16 and 17 present the assumed DHW consumption profiles, which are relevant to previous variants A (when some members of family are at home during daytime) and B (when all members are out of the house).

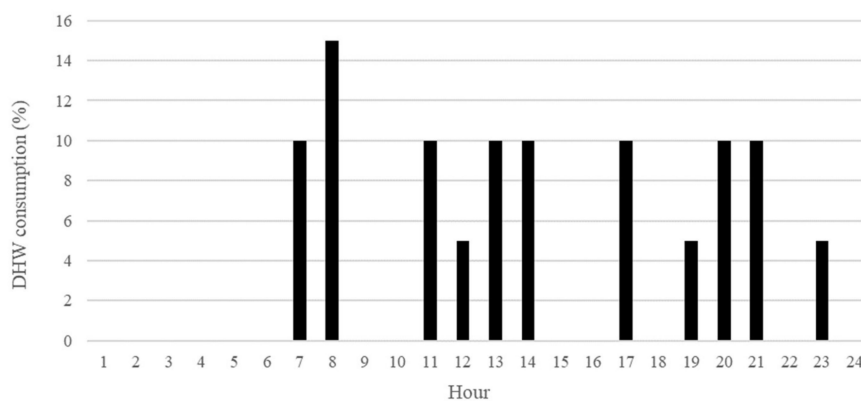


Figure 16. Domestic hot water consumption profile (A).

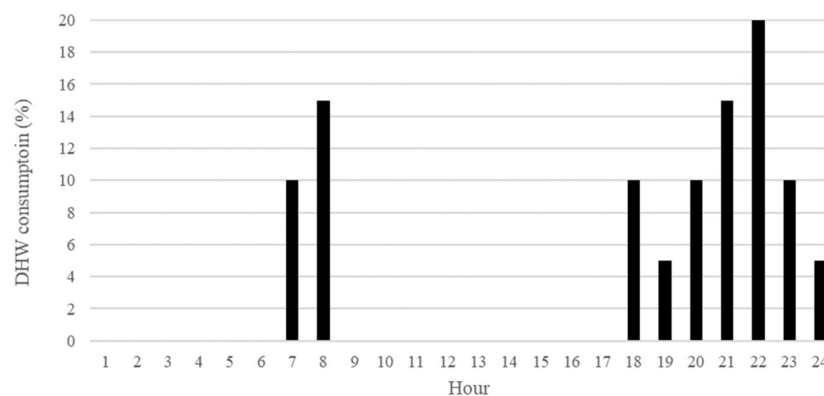


Figure 17. Domestic hot water consumption profile (B).

The demand for space heating has been determined as described in Section 5.3. The standard values of heat transfer U coefficients have been used according to the existing regulations published in “Technical Conditions for buildings” for the year 2021 [20]. This document contains the values of heat transfer coefficients that must be met by the individual building partitions. The heat transfer coefficient (U value) for external walls should be lower than 0.2 W/m²K. The U coefficient for windows should be at a level of 0.9–1.1 W/m²K. For the ground level floor, the U coefficient has been estimated to be equal to 0.17 W/m²K. Knowing the dimensions of the individual partitions of a building, it was possible to determine the heat loss coefficient H_{tr} W/K for such a building. Additionally, based on the volume of the ventilated space of a building and the air exchange rate, the value of the heat loss coefficient for ventilation H_{ve} W/K was calculated.

The window area of each house accounts for 25% of the floor area—i.e., 24 m². The window area for the entire row of six houses is 144 m². The surface of the walls is 408, the roof is 403, and the floor on the ground is 360 m². The fourth row of houses inhabited by seven families has a correspondingly

larger area of individual partitions. The H_{tr} and H_{ve} coefficients determined thanks to these data are 1530 and 1375 W/K. Based on these values, the power of the heat pump has been calculated. In the considered case, the heat pump supplies for the needs of space heating and domestic hot water; however, in the period of the highest energy demand much more energy is used to heat the building than to heat the domestic hot water. Therefore, when determining the heat pump capacity, the heat losses of the building are the most important factor. The total heat power of the heat pump appropriate for the housing estate should be about 70 kW.

Taking into account the location of the housing estate, it is possible to use four smaller heat pumps; one for each row of houses (i.e., three heat pumps of 17 kW of thermal power and one heat pump of 19 kW for the row extending from the south to the north direction). It can be added here that, apart from solar gains, the internal gains also have been taken into account and assumed to be at the level of 3 W/m² for the living space area [20]. On this basis, the heat balance was created for the entire estate, taking into account all components of energy losses and gains. Figure 18 shows the daily heat demand distribution for the space heating and ventilation.

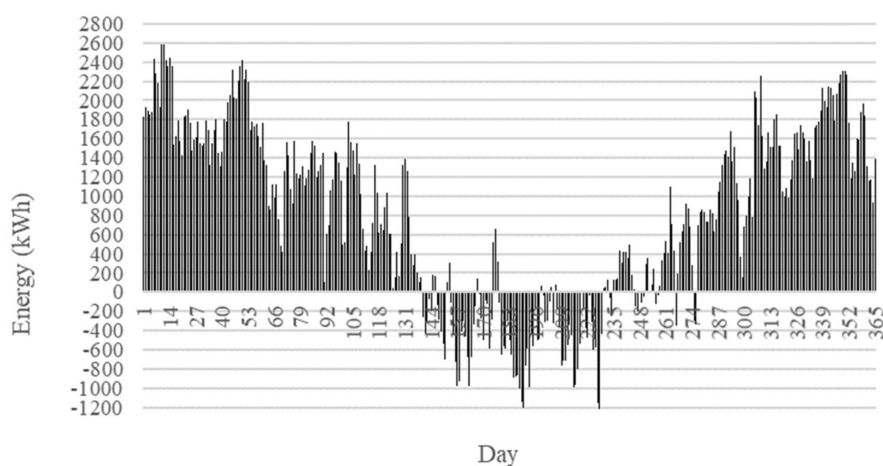


Figure 18. Daily heat demand for space heating and ventilation.

5.5. Operation of the Distributed Renewable Energy System

The calculations take into account that one of the rows of buildings faces a different direction than the others (see Figure 13). The total heat demand for heating and ventilation during the heating period is 315,500 kWh.

The previously presented assumptions for the calculations show that the approximate demand for electricity to power household appliances and lighting is 1.1 MWh per person per year. Assuming that the buildings are heated by ground brine-water heat pumps, the seasonal coefficient of performance (SCOP) was at the level of 5.3 (this is the averaged value of all calculated COPs). In the case of domestic hot water heating, the heat pump's SCOP is usually much lower [26]. The temperature to which the water should be heated is much higher than temperature of water required for underfloor heating systems. For domestic hot water heating, the SCOP coefficient is equal to 3. The annual heat demand for domestic hot water heating for the whole estate is approximately equal to 85,000 kWh. Using the above data and calculation results, the annual electricity demand of the housing estate has been determined. The annual demand for electricity in the discussed housing estate is approximately equal to 200 MWh. It turns out that the estate generates more electricity than it consumes; PV systems or small wind turbines installed in the estate should produce more than 200 MWh of energy. The wind conditions near Warsaw are not the best and allow the production of about 500 kWh of energy per year per 1 kW of rated power of the wind turbine. Figure 19 shows the average wind speeds in Warsaw in the year 2015 (Figure was elaborated using data presented in [27]).

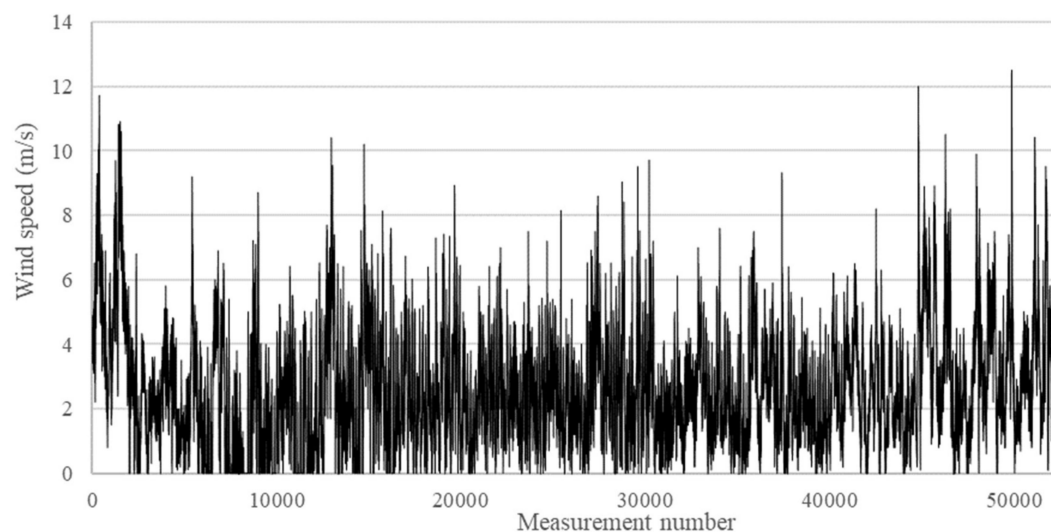


Figure 19. Average wind speed in Warsaw in the year 2015.

For this reason (low wind speed), the use of PV modules on the roofs of the housing estate has been considered as the priority. The results of the calculations show that the PV modules of the nominal power 1 kW_p directed to the south and inclined at an angle of 30° can generate 1.15 MWh of energy per year. This means that such a system with a capacity of approximately 174 kW_p can generate 200 MWh of energy per year. Currently, the most common photovoltaic modules have dimensions of $1 \times 1.64 \text{ m}$ and a power of 320 W_p . On the southern roofs of three rows of houses, 360 modules with a power of 115 kW_p can be installed. This means that, in order for the estate to become positive energy, it is also necessary to install photovoltaic modules on the fourth building. The roof of this building faces east and west.

The annual energy gains from the installations installed on these sides is lower than in the southern side. The 115 kW_p installation located on the southern roofs of the buildings generates approximately 130 MWh of energy. The systems on the fourth building must produce a total of 70 MWh of energy per year for the estate to be considered as zero or positive energy. In the Polish solar conditions, higher energy gains from PV installations are obtained from the west sides of buildings than the east (because of their better solar irradiation conditions [21]). Up to 140 modules can be installed on the west side. They will produce 38.7 MWh of energy annually. Due to the lower solar irradiation, a system of the same size located on the eastern side of the roof will produce 36 MWh of energy.

If all southern, eastern, and western roofs of buildings in the housing estate in question are fully covered with photovoltaic modules, the PV system has a power of 204.8 kW_p . It can generate about 207 MWh of energy throughout the year. The photovoltaic installation can be divided into five smaller systems, and then each of them has a power of less than 50 kW_p . Each roof slope can be a separate PV system. Systems with south-facing modules have a power of 38.4 kW_p . The installations located on the roof of the fourth building have a capacity of 44.8 kW_p . Figure 20 shows the total energy gains from all the considered PV systems.

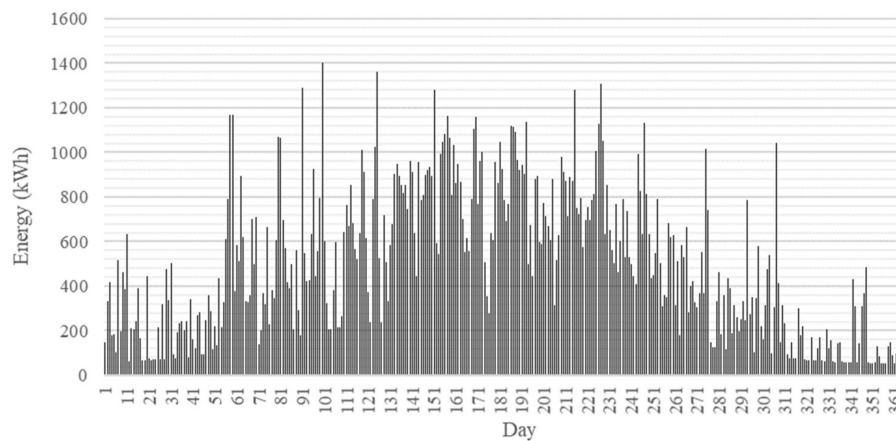


Figure 20. Energy gains from the photovoltaic (PV) system.

In order to summarize the results of the operation of the considered systems, Table 3 has been included. This table contains selected physical and energy parameters of the considered systems, as well as the annual energy demand for heat and electricity and the energy generated by the photovoltaic systems.

Table 3. Selected parameters and annual energy demand of the considered systems.

	Building					Σ
	1	2	3	4		
				East	West	
PV system area [m ²]	200	200	200	230	230	1060
PV system capacity [kW _p]	38.4	38.4	38.4	44.8	44.8	204.8
PV system energy gains [MWh/year]	44.1	44.1	44.1	36	387	207
Electricity consumption [MWh/year]	48.6	48.6	48.6		54.2	200
Heating demand [MWh/year]	76.6	76.6	76.6		85.7	315.5
DHW demand [MWh/year]	20.64	20.64	20.64		23.08	85
Heat pump capacity [kW]	17	17	17		19	70
HP SCOP (heating)	-	-	-		-	5.3
HP SCOP (DHW)	-	-	-		-	3

On the basis of these calculations, the self-consumption of the generated energy has been determined. For the energy consumption profile A, it is 35%, and for B it is 27%. The self-consumption for the entire estate can be approximately equal to 30%. The rest of the energy is transferred to the grid. When there is no energy generated by the PV system (low solar irradiance or nighttime), electricity is taken from the grid. The amount of energy sent to the grid by the PV system is higher than the energy taken by the housing estate from the grid.

6. Conclusions

One of the most important conclusions of the analysis of the energy sector in Poland is connected with the present situation of the district heating sector. This sector faces very great challenges. They result from the fact that for many years the heating sector (district heating systems) was practically not modernized. As such, there is currently a tremendous amount of work to do to transform it into a modern ecological heat source for consumers. In the opinion of the authors, this means that district heating systems will not develop territorially. Therefore, it is important to look for solutions for new areas of construction where the district heating systems will not reach. This paper presents a solution that seems to be technically simple, as well as energy efficient, giving a significant reduction in primary energy consumption that, moreover, it is in line with the latest trends in achieving energy self-sufficiency in new housing estates and sustainability in energy systems.

The paper has considered a hypothetical housing estate using ground source heat pumps for space heating and domestic hot water. It turns out that photovoltaic modules installed on the roofs of buildings can generate the same or even more energy than household members consume. The so-called self-consumption of generated energy (electricity) for the entire new housing estate in the suburbs of Warsaw can be at a level of 27–35% depending on the daily profile of energy consumption by the residents of houses. It gives on average of around 30% of total daily energy consumption. The results of the calculations show that, in Polish climatic conditions, it is possible to build housing estates based only on their own distributed energy sources, but nowadays they should be connected with the national power grid. When the self-generation of energy is not possible, then the energy from the grid is used. Most of the energy (70–80%) generated by the distributed energy systems cannot be used at the same time by residents, and energy is sent to the grid to be used by other end-users. It is evident that cooperation with the grid is necessary. The power grid is treated as a source of energy, a sink of energy, and an energy store. In such a case, it is not necessary to be connected to the central district heating system. Every building can be supplied by its own energy system, especially when heat pumps are applied. It can be concluded that, without the heat pumps and good cooperation between the PV systems and the power grid, it would not be possible to assure so effective an operation of the distributed renewable energy systems.

The next important conclusion is related to the buildings themselves. The new housing estates in the suburbs of large cities are designed and constructed according to new building standards and codes. This means that they need comparatively little energy to run their heating systems. In the case of single-family houses, there should be less than 65 kWh/m² (of living area) of annual primary energy used by the heating systems (see Table 2). To further reduce the primary energy consumption and make the new housing estates really independent of the central power grid, it is necessary for them to use their own distributed energy sources based on renewables. Nowadays, the utilization of solar energy is relatively simple and inexpensive. The conversion of solar radiation into useful thermal or electrical energy can be achieved thanks to mature and effective solar energy technologies. However, to assure the effective operation of such solar systems the solar irradiation conditions must be as good as possible. This means that the location of buildings in the new housing estates should be carefully chosen. All the area should be well exposed to the sun, with no shading obstacles in the surrounding such as trees and other buildings. An open area is recommended. Building houses in woods is not advisable (however, many new housing districts are located in such places). Roofs should be inclined (about 30°) and directed to the south to have enough surface for the installation of solar receivers (PV modules and solar thermal collectors). Buildings should be extended from east to west so that a sufficiently large area is exposed to solar radiation and it is possible to locate PV modules and solar thermal collectors there. Using solar energy in an active way makes the architectural and construction design of a building favorable for the use of solar energy in a passive way. As a consequence, the space heating demand is naturally reduced.

The results show that the application of micro-scale PV systems would help residential buildings to be more energy efficient and reduce energy consumption based on fossil fuels significantly. As a result, the buildings reduce their energy consumption by 30% on average in a direct way, and fully if the grid is treated as an energy store. The development of micro-scale PV systems seems to be one of the most efficient options for a quick transformation of the centralized energy system to a distributed energy one, based on individual renewable energy sources, in large Polish cities. In such a way, the traditional CHP plants and district heating networks located in the cities can be modernized step by step, giving room for actions to implement new investments in distributed energy sources based on renewables.

It can be mentioned that problem of transforming district heating systems (old systems) into modern energy systems is a very broad issue. Issues such as Demand Side Response (DSR), energy management and planning in cities, and control systems in buildings (e.g., Supervisory Control And Data Acquisition (SCADA) systems) are some of the top issues for this kind of research. However,

this paper focusses on a much smaller problem. Two main aspects are analyzed: the great effort which has to be made to transfer the old district heating system to the modern one and an explanation of why it can be predicted that in Poland the district heating networks will not expand to the new areas. Cities will grow and new districts and housing estates have to be supplied with heat (and electricity, of course); that is why outside of the cities—in the cities' suburbs—another solution should be developed. This paper focusses on one of the possible solutions. This solution is for new housing estates to be supplied only by the electrical energy gained by PV systems and energy transferred from the national grid.

As a final conclusion, it can be stated that, paradoxically, the poor state of central energy systems, the complicated process of their modernization, and the lack of energy infrastructure in the suburbs of large cities favor the use of renewable energy sources in distributed energy systems in new housing estates constructed in remote, previously rural, areas.

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