

Article

Determination of the Energy Performance of a Solar Low Energy House with Regard to Aspects of Energy Efficiency and Smartness of the House

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Abstract: The paper shows how difficult it is to prove technically that a building really is both low energy and smart, and that all aspects of energy efficiency have been treated equally. Regulations connected to the determination of the energy performance of residential buildings take into account only space and hot water heating energy consumption and define the indices of maximal primary energy consumption, but not energy needs based on the architecture of the building. A single family house designed and constructed as a low energy solar house in Warsaw's suburbs is considered. Availability of solar energy and its influence on the architecture of the house is analyzed. A specific solar passive architectural concept with solar southern and cold northern buffer spaces incorporated into the interior of the house is presented. Parameters of the building's structure, construction materials, as well as operation parameters of equipment and heating systems based on active use of solar energy, ground energy (via a heat pump) and waste heat from a ventilation system are described. Results of calculations give values of final and primary energy consumption index levels of 11.58 kWh/m² and 25.77 kWh/m², respectively. However, the official methodology for determination of energy performance does not allow for presenting how energy efficient and smart the building really is.

Keywords: energy performance of buildings; solar passive systems; low energy buildings; energy efficiency; smart buildings

1. Introduction

This paper deals with the analysis of the energy performance of a solar low-energy house, which can also be considered a smart house. The smartness of the house is based on its design and construction with the focus on using the ambient surrounding and energy sources, mainly solar energy, in a passive way to reduce energy demand for space heating and cooling, and then to provide the energy demand in an effective way through the well-planned operation of its energy systems. In other words, to achieve real smartness in a house it is necessary first to create the architectural concept, which from the beginning takes into account energy aspects as well as aesthetics, and assures passive and active utilization of renewable energy and waste heat available to the house. Then the well-designed integration of different energy devices and installations assures their complementarity thanks to effective automatic control of the multisource energy system. It can be said that smartness is achieved through coupling passive and active methods of energy conservation, joining architecture, civil engineering and technical energy aspects. Avoiding energy demand is the best way to save energy. Thanks to the low energy demand concept of a house it is easier to consume less energy living there. The paper presents how difficult it is to technically prove, using standard methods of determination of

the energy performance of buildings, that a building is really both low energy and smart, and that all aspects of energy efficiency have been treated equally.

In most countries in the world there are specific standards and regulations put into place to assure energy efficiency in buildings. In EU countries the formal background for the development of energy efficiency in buildings has been set out by the directive of the European Parliament and of the Council on the energy performance of buildings (Directive 2010/31/EU) [1]. The directive entered into force in 2010 and was a recast of the previous EU Directive on the Energy Performance of Buildings—EPBD, published in 2002. Further amendments have been made in 2018 (2018/844/EU) [2]. Since the beginning of the new millennium the EU Commission has been fostering the development of low energy buildings and the application of energy saving technologies, including utilization of renewable energy. Nowadays, thanks to Directive 2010/31/EU, measures to reduce the energy consumption in buildings have led to the evident improvement of thermal comfort in buildings and a reduction in environmental pollution. According to Article 9 of the directive, from 2021 all new buildings will have to be nearly zero-energy buildings, and in the case of public utility buildings the rule already came into force at the beginning of 2019. Thus, due to the official EU legislative policy to adopt the rules of nearly zero-energy use in the construction and use of buildings, the idea of energy efficiency in buildings is not only a concept of implementing general energy conservation principles and minimizing their environmental footprint, but it has become a national duty and legal necessity. The EU directive promotes the idea of nearly zero-energy for new buildings and stimulates the transformation of existing buildings to be refurbished into nearly zero-energy ones. Energy conservation in buildings has been supported by other EU regulatory frameworks, mainly by the EU directive on energy efficiency [3].

Nearly zero-energy buildings (NZEBs) should have very high energy performance. The low amount of energy which these buildings require for their effective use comes mostly from the use of renewable energy sources. The idea of zero energy buildings and net zero energy buildings was discussed before the EPBD directive came into force [4]. The EU energy legislative policy (through directives) compels national member state regulations to introduce limits for final and primary energy consumption for buildings with regard to their typology. These indices are different in different EU countries depending on climate and energy mix in those countries. The EU policy leaves it open for the member states to make a decision on the quantification of the boundary indices for energy consumption, i.e., what is the maximum quantity of energy to be used in buildings with regard to their final and primary energy.

Thanks to the implemented regulations the energy needs of buildings have been much reduced in recent times, mainly due to the well-designed envelopes and structures of buildings (i.e., shape of the building, types of construction, one layer or multilayered, type of construction materials and insulation applied with the focus on their thermal parameters). Recently, focus has been put on the thermal quality of buildings, mainly on application of thick thermal insulation of very low conductivity, and on windows characterized by low heat loss (transmission) coefficients (U -values). However, it can be mentioned here, that using insulation in a warm climate can reduce the heat losses necessary in summer to limit overheating. Heat losses are necessary during summer nights to release the excess heat gained during the day, because of high solar irradiation and to keep the indoor air temperature at the required level. Therefore, application of insulation must always be adapted to the given climate conditions. In addition, highly efficient and reliable equipment and energy installations, including ventilation systems with heat recovery, have been implemented. Such measures have caused significant drops in final energy demand. Application of renewable energy systems have also reduced the primary energy consumption based on fossil fuels.

Buildings are responsible for approximately 40% of EU energy consumption and 36% of the CO₂ emissions [5]. For many years high energy consumption in buildings was caused by high heat losses through buildings' envelopes [6]. The space heating demand used to be the highest demand component of energy consumption in buildings and is still responsible on average for about 65% of the total energy needs of buildings in the residential sector [7]. Of course, the share of space heating demand was higher in high latitude countries than those of low latitudes. Energy consumed by space heating and domestic hot water systems now accounts on average for 80% of the total (according to EUROSTATS). Therefore, it is not surprising that measures undertaken to reduce energy consumption in buildings have been mainly focused on decreasing the space heating demand.

In many European countries, as in Poland, new regulations connected with the determination of energy performance of residential buildings take into account only heating energy demand for space heating and domestic hot water (DHW). Cooling energy demand and electricity consumption by lighting units and systems, and electrical appliances are not limited by any official regulations. As electricity consumption was relatively small in residential buildings, it was believed that there was no reason to set limits for electricity consumption in houses. In the case of cooling energy it is arbitrarily assumed, that residential buildings in Poland do not require cooling, because of the relatively cold climate. Nowadays, it turns out that supplying cooling energy to residential buildings is sometimes necessary to maintain thermal comfort. Summer cooling demand can be seen especially for south and west facing rooms with large windows [8]. It turns out that cooling demand becomes a challenging issue for new buildings in moderate climates [9].

In Poland, according to existing regulations [10] since 2021 the indices of primary energy consumption for space heating and domestic hot water of all newly constructed residential buildings, called nearly zero energy buildings (NZEB), cannot exceed 70 kWh/m²a or 65 kWh/m²a for single family houses or multi-family apartment buildings, respectively. In addition, the heat transfer coefficients for external walls must not be higher than 0.2 W/(m²K). As a result, external walls have thick insulation of high thermal quality (in the 1970s the recommended thickness of thermal insulation was 6–8 cm, at present it is 20–25 cm). What is more, the heat transfer coefficients for windows will soon not be allowed to be larger than 0.9 W/(m²K) and currently they cannot be higher than 1.3 W/(m²K) (in the 1970s it was 3.2 W/(m²K)). Existing regulations on energy performance of buildings define the indices of maximal primary energy consumption considering only technical issues. They put the focus on energy efficiency, which results in reduction of final energy consumption and gives support for renewable energy sources, which utilize much less primary energy. Unfortunately, they do not show how crucial for energy consumption is the architectural concept of a building. Its shape, structure, location, the sizing of different elements of the building envelope and their orientation to specific directions of the world, and surroundings are of great importance. Without analysis of all the architectural and local settlement conditions, it is like being halfway to the finish line, but with a slow first half and no chance of winning. When a building is designed and constructed without a real vision of maintaining low energy consumption throughout the whole year, then it will not be possible to reduce the final and primary energy consumption to the set limits relying only on the energy efficiency of devices and installations applied. Therefore, such a building will not be a smart low-energy building. To get a real reduction in energy consumption of any building it is necessary to have a global interdisciplinary approach and look at the process of building design, construction and use in a holistic way.

Many energy simulation programs have been developed to determine building energy performance and they are used in many different countries. Comparison of the features and capabilities of twenty major simulation programs determining the energy performance of buildings can be found in the literature [11]. The authors showed how contrasting the building energy performance approaches can be. So it is not surprising that it is difficult to find such a method of determining energy performance of buildings, which would take into account all aspects of the actual energy efficiency of buildings such as those described in this paper.

This paper presents the problem of how the existing regulations supporting the reduction of energy consumption in buildings through an engineering determination of energy performance cannot fully present a true and reliable assessment and evaluate the real impact on energy consumption. The paper shows how difficult it is to prove technically that a building is really low energy and smart, and that all aspects of energy efficiency mentioned above have been treated equally. An example of a single family house designed and constructed as a low energy solar house located in Warsaw's suburbs has been considered. Section 2 describes a general idea of a low energy building and a smart building and shows how some of their main features are similar to each other, whilst others are different. Section 3 presents solar radiation conditions in Poland and a concept of solar passive architecture, which should be taken into account when a low energy smart solar house has to be designed and constructed. Section 4 describes the heating energy demand as well as final and primary energy consumption of the house under consideration. At the end, both the officially calculated and real energy performances of the building are discussed and general conclusions are formulated.

2. Low Energy and Smart Buildings

Low energy buildings are not usually equated with smart buildings. However, it seems that if a building is low energy it must be smart. However, the smartness of a building can be defined by many parameters that are distinct from those usually applied to low energy buildings. If we would like to consider a modern low energy building as a smart building, we should define what both 'low-energy' and 'smart' mean and whether a building can be both. A low energy building can be defined as a building which needs and consumes a small amount of energy during its life-time. It is a building needing a small amount of energy for space heating or cooling, thanks to its architectural and civil engineering design and construction. Low energy needs result from the specific concept of the building envelope, materials used, specific location of different partitions such as opaque walls and transparent glazing in the structure of the building, as well as specific location of rooms of different functions inside the building. It also needs the correct utilization of solar radiation for gaining energy in the winter and protecting from excessive solar gains in the summer. Of course the aesthetic values of the building envelope cannot be forgotten. A low energy building also consumes a small amount of energy because of the use of energy efficient devices and systems applied to fulfill all its energy needs: space and water heating, cooling, ventilation, air conditioning, lighting, electricity for electrical appliances, etc. Moreover, renewable energy sources are used to reduce primary energy consumption of fossil fuels.

Different means of construction and operation of low energy buildings have been developed in recent decades, with the best achievements in the last decade. Kivimaa and Martiskainen [12] conducted a systematic review of case studies on low energy innovations in the European residential building sector from the beginning of this century. They analyzed drivers important for systemic and architectural innovation in low energy buildings and pointed out how different the low energy buildings can be in their main purpose. There are some key words used to describe buildings of low energy consumption, such as: energy efficient, low energy, zero carbon, passive houses, etc. All these keywords express the main features of low energy buildings, i.e., energy, efficiency, environment and architecture; however, according to the names of those buildings the focus can be put on different aspects.

When we search through the Internet trying to find a definition of the smart building, the most common one is as follows: A smart building is any structure that uses automated processes to automatically control the building's operations including heating, ventilation, air conditioning, lighting, security and other systems [13]. This idea is certainly connected to the energy efficiency aspect of low energy buildings, but it seems to be much more closely connected to energy efficiency measures introduced (mainly to office buildings) and known as BMS—building management system [14]. BMS systems are also known as building automation systems (BASs). Such a system is a computer-based control system used in buildings to monitor and control the building's energy systems and other systems such as fire and security. Smart buildings use sensors, data monitoring and collecting systems, which give the information needed for effective operation of different buildings' systems,

including energy systems. Smart buildings use IT—Information Technology and IoT—Internet of Things. Such technology is usually used for office buildings, hospitals, health care and educational facilities, sport centers and sometimes for public buildings, but very rarely for residential houses. There are no standards for smart buildings. Low energy architecture is not one of determinants of the smartness of such buildings. Therefore it can be said, that in many smart buildings like office buildings, the important element of energy efficiency required to reduce energy needs is usually missed. However, without low energy or energy efficient architecture of a building it is really difficult to call any building a smart one.

One more aspect not analyzed in detail in the paper is very important, namely the smartness of building users. Energy consumption in buildings depends on user behavior. It can be said that the inhabitants of residential houses basically want energy savings because they relate to the user costs and directly affect them. The problem with these unthinking building users' behavior is particularly evident in office buildings [15]. Therefore, it should be stated that a smart building also requires smart users.

Taking into account what features should be common to both low energy buildings and smart buildings, it can be seen that energy efficiency is essential. However, it seems that the definition of a smart building should be much wider, especially in the case of residential buildings. The next section presents the concept of a smart low energy building realized at the micro scale, i.e., in a single family house in Polish climatic conditions.

3. Influence of Solar Energy Availability on Architecture of a Building

3.1. Solar Radiation Conditions in Poland

The relation between climate, and especially solar radiation conditions, and architecture of a building should be obvious [16,17]. Unfortunately, nowadays it is quite often forgotten. Any building is under the influence of solar radiation, but the solar building must pay very special attention to solar radiation conditions. In Poland the climate is moderate with the influence of continental climate. The annual average ambient air temperature, depending on the region can be around 8 °C to 11 °C. However, there are relatively large differences in ambient air temperature during the year and especially between summer and winter. Thus in summer, during the daytime, the temperature can be +30 °C or more, as has happened quite often recently. In winter, ambient air temperature can drop to −30 °C, however such a low temperature was last recorded almost 10 years ago. The annual global solar irradiation varies from 900 kWh/m² to 1200 kWh/m². Annual solar hours are on average equal to 1600. Climate is characterized by relatively large differences in solar irradiation throughout the year. For example, in Warsaw in June, the average monthly solar irradiation is about 160–180 kWh/m², but in December only 11–12 kWh/m². What is also typical for the climate is the high share of diffuse radiation. The annual share of diffuse radiation usually accounts for 54–56% of the global and in winter this share is especially high and accounts for 70–80%. Only in summer is the share of direct radiation higher and can be on average equal to 60% of global radiation [18]. Figure 1 presents the averaged distribution of the average hourly global solar irradiance on averaged days of the all months of the average year. Figure 2 shows the distribution of average hourly ambient air temperature for averaged days of all months of the average year for Warsaw.

Relatively large differences in solar irradiation and ambient air temperature in summer and winter can easily be seen in Figure 1. In such climatic conditions not every solar passive system can be used in an effective way. Very uneven distribution of solar radiation during the whole year means that specific passive architectural solutions should be recommended [19].

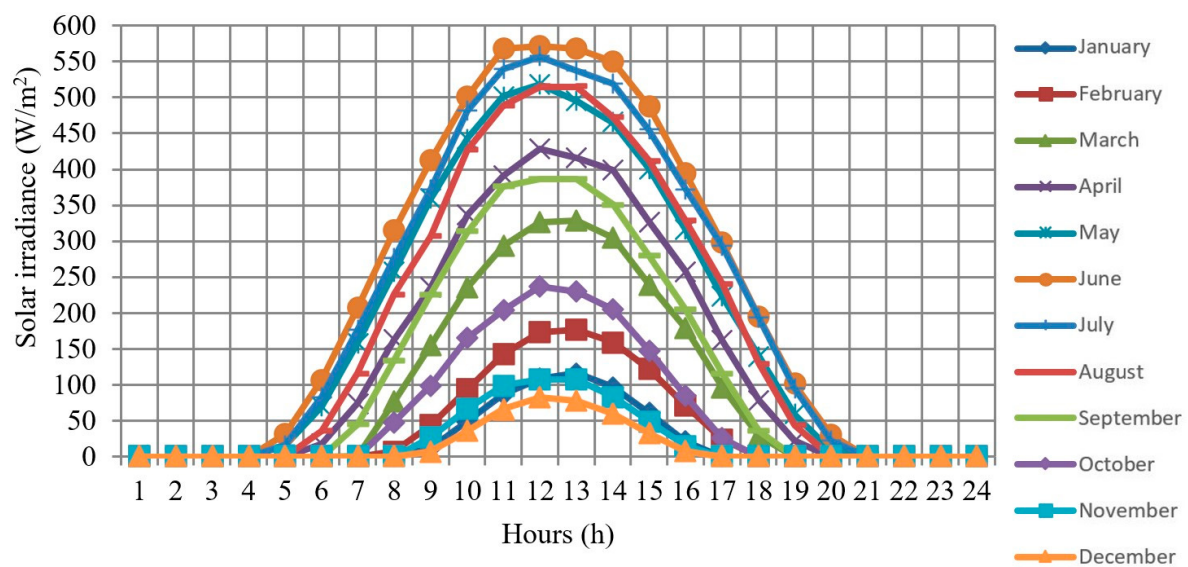


Figure 1. Distribution of average global solar irradiance for every hour on averaged days of different months of the average year in Warsaw.

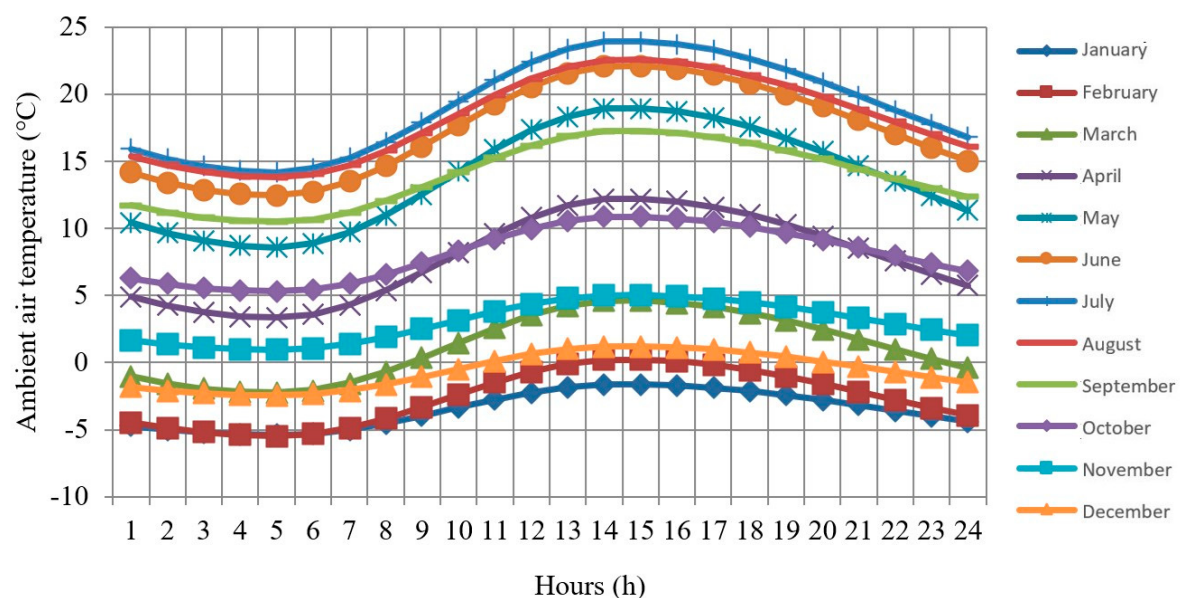


Figure 2. Distribution of average hourly ambient air temperature for averaged days of different months of the average year for Warsaw.

3.2. Buffer Space Incorporated Into Interior of a House as a Specific Solar Passive Architectural Concept

The single family solar house presented here has been designed and constructed with particular attention to passive and active utilization of renewable energy, mainly solar. Availability of solar energy with regard to the climatic conditions and specific location of the building has been considered. It can be mentioned here, that even if the climate is the same, the conditions in a city center are different than in the suburbs and in the country side in the vicinity. The considered house is located in the suburbs of Warsaw. The location of the house was specially selected so that in winter the southern facade of the house is fully exposed to solar radiation. Deciduous trees were planted on the south-east and south-west sides creating shade on these sides in the summer. The south is completely open, as it is beneficial in winter. Elements of building architecture provide shading in summer, as is described in the next section. A plan of the first floor of the house is presented in Figure 3. The main living space area is marked with the red lines.

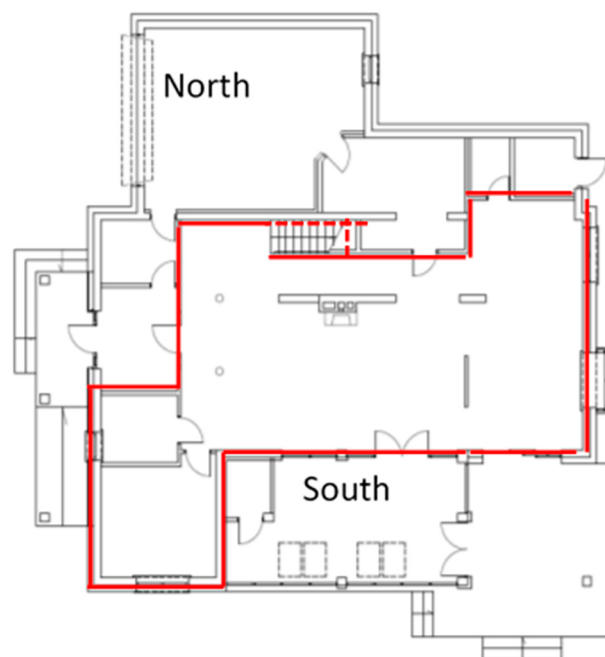


Figure 3. A plan of the first floor of the considered house, main living space area is delimited by red lines.

The south transparent solar buffer space of a special design and north opaque buffer space are described below. Buffer spaces, as the name indicates, create a kind of a buffer between the outdoor and indoor climate. The southern transparent glazed solar buffer space allows solar radiation to penetrate the interior of the house in a planned way. Solar radiation can be fully utilized in winter and significantly reduce the space heating demand, whilst in summer, to reduce solar energy gains, the special architectural form of the southern buffer space is needed. A glazed solar buffer space is incorporated into the interior of the building. This specific architectural concept of a solar passive system is shown in Figure 4. It can be seen that the buffer space contains two theoretical cuboid sub-spaces. The external one is higher and the internal one lower. There is no partition between them. The solar buffer space has external and internal glazed vertical surfaces. External, four meter high glazed partitions are in direct contact with the ambient surroundings on one side, and with the interior of the buffer space, on the other. Internal glazed partitions (regular windows) are at one side in direct contact with the interior of the buffer space on the one side and with the interior of the main living space on the other.

The key architectural concept of the southern glazed façade of the house is to design and plan two overhangs at the south side of the building. The first external overhang is just a regular one being a part of the roof (marked with a symbol E). The internal overhang (marked with a symbol I) is a part of the internal construction of the building. The main point is to properly design (place and size) the internal overhang in accordance with the sizing of the external overhang to protect the interior of a building against too much solar energy gains in summer and to allow solar radiation to penetrate the interior of the house without any obstacles in winter. Of course the size of the external south glazed facade is taken into account. The external overhang of the roof (E) has been designed to shade the buffer space for a few noon hours (between 10 a.m. and 4 p.m.) in the warmest part of the year, i.e., from May to the end of August, but not to block the access of solar radiation in the rest of the year. The internal overhang (I) is formed by part of the floor on the second floor being, at the same time, a part of the ceiling of the first floor (over the lower part of the buffer space, as can be seen in Figure 2). The internal overhang has been designed to allow direct solar radiation to enter fully into the interior space of the house in winter, exactly from November to the end of February, and to fully block the direct solar radiation penetration from May to the end of August. In the remaining months

of the year, solar radiation reaches the interior directly in the morning and afternoon. As has been mentioned, the buffer space has full access to solar energy from October to the end of April and partly (mornings and late afternoons) from May to the end of August.



Figure 4. Architectural solar passive system: (a) A view of the south glazed buffer space incorporated into the house; (b) and a cross-section of a house along the south–north direction with apparent shading planes.

To have planned such access to solar radiation, the size of the buffer space, the size and position of different partitions of the buffer space, including the size of the external and internal overhangs, have been determined on the basis of the astronomical relationship between position of the Sun and the different partitions of the buffer space (glazed and opaque) [20]. Calculations of solar energy availability have been conducted with a time step equal to one hour throughout the whole year. The anisotropic diffuse solar radiation HDKR (Hay – Davis – Klucher – Raindl) model has been applied to determine solar irradiation of surfaces of different inclination and orientation [21].

3.3. Northern Buffer Space

Analysis of solar energy availability in buildings also requires designers to pay attention to that part of the building envelope, which is not exposed to solar radiation, especially in winter. It is the northern part of the building enclosure which requires this thoughtful approach. In the considered climate, with cold winters and warm (or even hot) summers, a highly opaque insulated buffer zone should be created at the northern part of the building to reduce the effect of the severe climatic conditions in winter. The external north partitions must be characterized by very high thermal resistance (0.5 m thick walls, which include 0.25 m thick insulation) and no windows or any other transparent elements.

Figure 5 presents such a north façade, which is a façade of the considered low energy solar house.

The northern walls and roof are elements of the buffer space. Another important feature is to create usable spaces which do not require heating energy, because they are not for permanent residence of the inhabitants. The air temperature in that space can be, or even is required to be, lower than in the living space of the house. It is possible to plan a cold store, pantry, wardrobe, garage or boiler room there. Northern fully opaque and highly insulated buffer zones can significantly reduce the influence of severe climatic conditions in winter and have a positive impact on the energy balance of the building.

Planning cold and solar buffer spaces in a building allows introduction of temperature zones into the building in a natural way. Due to the architecture of the building, natural passive control of thermal comfort is created. In this way the following air temperature zones are designed:

- A cold northern zone with a seasonally variable indoor air temperature, daily changes of temperature are very small;

- A warm internal zone corresponding to the living space of residents with a requirement of relatively constant indoor air temperature (throughout the year), where a low temperature space heating system is applied;
- A southern solar zone with a variable air temperature on a daily scale (warm day/cold night) and on a seasonal basis depending on the intensity of solar radiation and the influence of the ambient air temperature.



Figure 5. A view of the northern buffer space of the house.

Thus, the architecture of the building creates a smart concept for building structure focused on the planned use of the environment to reduce the need for heating and cooling energy for the living spaces. The temperature zones go from the north, always with the lowest indoor air temperature, to the south, with most variable indoor air temperature during daylight hours, the highest in summer, high or moderate in spring and autumn and high or low in winter. The thermal state of the southern buffer space is directly impacted by the solar radiation and by ambient air temperature. However, the radiation is the dominant component. In such a way a smart solar low energy concept of a house can be created. When the energy needs of a house are accomplished through the smart and energy efficient design of a building then highly energy efficient devices and installations can be introduced.

4. Building Energy Needs and Final and Primary Energy Consumption

4.1. Space Heating Energy Needs of the Considered House

Usually, to reduce building energy consumption, two main measures are applied. The first is focused on improvement of the thermal performance of the building envelope by adding insulation and reducing infiltration rates, and the second is on improvement of energy efficiency of the devices and installations used in buildings, including lighting, heating, ventilation and air-conditioning [22]. However, to reduce the energy consumption significantly the design of the building cannot be based only on reduction of heat and mass flow through the building envelope (through improvement of insulation and reduction of infiltration). The architecture of a building is crucial and it should take into account specific climatic and environmental conditions with a focus on solar energy availability specific for the given climate and location of the building. The single family house presented in this paper was designed using this wide holistic approach to reduce energy needs, as has been described in the previous section. In this section the results of calculations of the energy balance of the building and the final and primary energy consumption are presented. Simulation studies have been performed using our own simulation code. The availability of solar radiation and its impact on the energy needs of the building have been determined. Modeling of the space heating and DHW needs have been based on the methodology on determination of energy performance of buildings [23].

The floor area of the heated space of the house is 350 m². In addition to two floors, the building has an unheated attic (there is no basement). The roof directed to the south and north is inclined at 30 degrees. The northern slope is larger than the southern one, required by the specially designed north unheated buffer space. The south façade of the building is transparent in 70% of its total surface area, which in turn is related to the design of the south solar buffer space. There are two types of windows. Large windows form the main part of the façade and their heat transfer coefficient U is equal to 1.2 W/(m²K). The U value of the other regular windows and internal windows of the south buffer space is 1.4 W/(m²K). The main idea of the building design was to use standard construction materials, typical nowadays for such a climate, to make the building envelope energy efficient and reduce heat transfer with ambient surroundings. External walls are 0.5 m thick (two layers: mineral wool from outside and bricks from inside). The heat transfer coefficient U is equal to 0.14 W/(m²K). The U value for the ceiling over the second floor, under the unheated attic, is lower and accounts for 0.12 W/(m²K), but the heat transfer coefficient for the floor on the ground is larger and is equal to 0.17 W/(m²K).

The energy balance of the building was formulated and space heating energy needs were calculated. The results are shown in Figure 6. This figure presents monthly space heating energy demand with all components of the energy balance of the building. Thus all heat losses through the building envelope and ventilation (positive values), as well as heat gains: internal and solar (negative values), are presented. It can be noticed that ventilation and heat losses through windows dominate among all others, but it is also evident how large the solar gains are and their impact on the energy balance of the building.

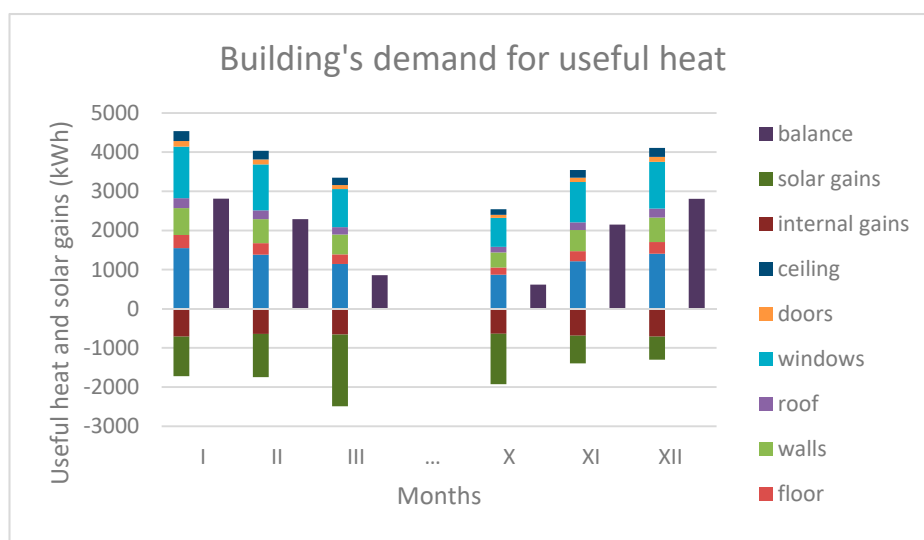


Figure 6. Monthly space heating demands with energy balance components: heat losses and gains.

The main observations on heat losses from Figure 6 are confirmed by the diagrams in Figure 7 which presents the seasonal share of different heat loss components in the total heat loss of the building. As could be expected for a low energy house, the largest losses occur through ventilation and then through windows, and they account for 34% and 29% of the total losses, respectively. In the third place there are heat losses through walls (15%) and all the others take nearly the same share (6–7%) (heat losses through doors are lower at 3%).

It can be noticed that the heat energy demand for the ventilation system results from the natural necessity to exchange air in the building, including exchange for hygienic purposes in rooms such as kitchens and bathrooms. In the building under consideration, the heat demand is significantly reduced due to the use of heat recuperation. In the calculations of energy demand the use of a recuperative unit was taken into account when determining the final energy consumption. Heat recuperation requires a forced ventilation system to be used. The design of the forced ventilation system is usually taken into

account at the design stage of the building and its interior, and this was the case with the building under consideration. Ventilation ducts supplying fresh air, which is preheated in a recovery unit, as well as ducts discharging used air outside through the recovery unit, were planned at the time of creating the architectural design of the building. It can be mentioned that the heat recovery ventilation unit is not used all the time, but only when inhabitants are at home. For the remaining months outside the heating season only short-term morning and evening ventilation is used.

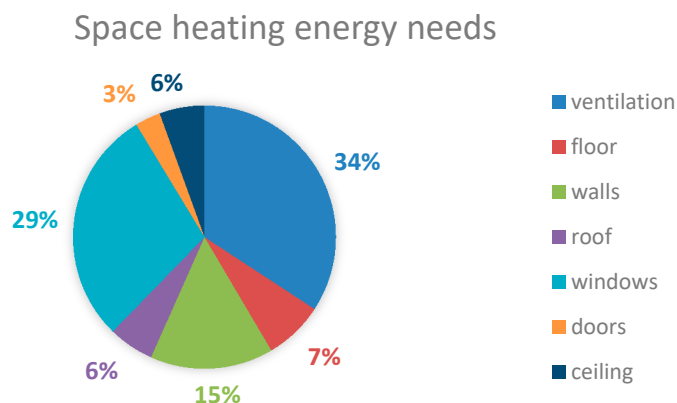


Figure 7. The seasonal share of heat losses in the total amount of heat losses of the building.

The calculated index of the annual space heating energy needs amounts to 36.16 kWh/m^2 of the heated floor area. The low space heating energy demand results from the architectural concept of the building, the introduction of temperature zones resulting from the existence of buffer spaces at the northern and southern sides of the building, including the passive use of solar radiation energy. Low energy demand also results from the use of appropriate building materials of high thermal insulation and thermal capacity. The high thermal capacity is demonstrated by a building time constant, equal to 222 h.

According to existing regulations [23], when the energy performance of a residential building is calculated the energy consumption for domestic hot water (DHW) heating is also taken into account. For the considered house, the annual total heat demand index (for DHW and space heating, which is only seasonal) is equal to 45.6 kWh/m^2 . The annual DHW head demand is equal to 3011 kWh (heat demand index for DHW is equal to 9.44 kWh/m^2). Up to now there have not been any official regulations introduced to limit these energy-need indices of buildings; this is a problem which does not help in significantly reducing the energy consumption of buildings, as the authors try to present in this paper. There are limits only for the heat loss coefficients of walls, e.g., for walls U was equal to $0.3 \text{ W/(m}^2\text{K)}$, now it is $0.25 \text{ W/(m}^2\text{K)}$. It can be mentioned, that 10 years ago when the house was constructed according to the obligatory regulations, buildings (of similar compact shape) required a maximum of 90 kWh/m^2 of final energy and 69 kWh/m^2 of primary energy consumption (regulation [10], before amendments in 2013). Nowadays, these indices are even higher, because the official limits stated for primary energy consumption for a single family house is equal to 95 kWh/m^2 . Since the beginning of the 2021, even if a new house is to be called “nearly zero energy” the index for primary energy consumption will be at a level of 69 kWh/m^2 .

4.2. Final Heating Energy Consumption of the Building

In order to determine the final energy consumption, it is necessary to take into account the energy efficiency and effectiveness of energy devices and installations used to cover heating needs, as well as their time of operation. In addition, the work of auxiliary devices necessary for the operation of heating systems, such as circulation pumps in liquid circuits and fans in air circuits also have to be taken into account.

Operation of heating systems in the low energy house is of course based on using energy efficient devices and installations. Heating demand is met by a ground source heat pump with vertical heat exchangers coupled to a solar thermal systems with flat plate solar collectors via a buffer storage tank. The buffer storage tank has a smaller DHW tank inside. In this way water in the main volume of the buffer tank not only serves as a storage medium, but also as thermal insulation for the water in the internal DHW tank. DHW is preliminarily heated in the internal tank and then it flows to another DHW tank with an auxiliary heat source (electric heater). Solar collectors are integrated into part of the south roof surface. A low temperature underfloor space heating system is used. The flow is forced by a pump into every loop of the system. As has been mentioned, the heat recuperation unit is also applied. Fans are used to force the flow of fresh and used air through the ventilation ducts. The main characteristics of the heating system are presented in Table 1.

Table 1. Main (elements) devices of the heating system of the house and their main parameters.

Devices and Their Parameters	Value	Units
Ground source heat pump		
Ground U-tube heat exchangers: number of boreholes	4	–
Total length of boreholes	200	m
Heat pump heating capacity	8.1	kW
Seasonal COP (Coefficient of Performance)	4.9	–
Solar thermal flat plate collectors		
Gross / Aperture surface area	12/10.92	m ²
Annual average solar energy gains	380	kWh/m ²
Water storage system		
Buffer storage tank - total volume	700	kg
Internal DHW tank volume	100	kg
Auxiliary DHW tank	50	kg
Ventilation heat recovery unit		
Power of fans	280	W
Volumetric air flow	600	m ³ /h

The operation of the solar thermal collectors and the heat pump is not directly connected. Both devices operate in parallel. They can operate at different times of the day, but they can also supply heat at the same time. Flat plate solar collectors supply heat to the main buffer storage tank (via a heat exchanger). An antifreeze mixture circulates in a solar collector loop. There is another loop with an antifreeze mixture circulating in vertical ground heat exchangers, which are coupled with the evaporator of the heat pump. Heat can be sent to the buffer storage. It is also possible to supply heat directly from the heat pump to the underfloor heating system or DHW tank (without charging the storage tank). The buffer storage tank with water as a storage medium contains a small tank inside. The small tank is used as a buffer tank for the DHW system. Cold water is supplied to the small tank and when the water is heated up it flows out of the tank and is transferred to the other tank, which is the main DHW storage tank (50 l volume) equipped with an auxiliary electric heater. The ground source heat pump is used only during heating season. Domestic hot water out of the space heating system is accomplished via the solar thermal system operation, which operates very effectively in Polish conditions [18,24]. From May until the end of September the thermal solar energy system can cover all DHW heating demand. In March, April and October, solar energy provides about 60–70% of demand, in winter the share of solar energy is very small and it does not exceed 10% for the DHW and space heating. Figure 8 presents the print screen of a display showing the operation of the ground heat pump system coupled with the solar heating system for space heating and DHW heating.

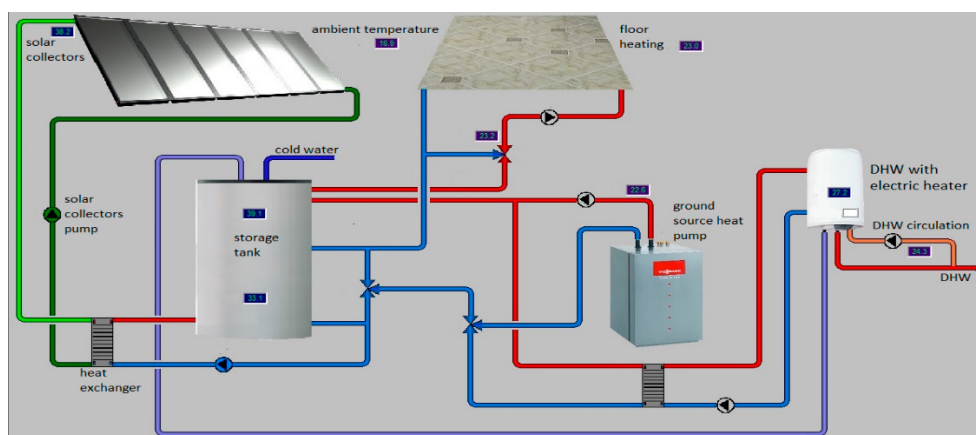


Figure 8. The print screen displaying the configuration and operation of the ground heat pump system coupled with solar heating system.

A micro-scale energy management system is used in the house. Operation of the heating systems is controlled by a central system that continuously monitors the operation of all heating devices and systems. Several variants of operation are possible depending on the availability of the given renewable energy source in time and its adherence with the energy demand in that time. The system is equipped with a number of sensors enabling on-line observation of the system's operation as well as its control. Through a dedicated computer application, it is possible to remotely change the temperature settings in the rooms. It is also possible to change the parameters of the system operation, mainly temperatures and flows, and even completely turn off the operation of individual devices or installations. Operation priorities are set according to the efficiency of energy conversion from a given energy source and the effectiveness of using that energy at a given time. The automatic control system helps in a smart way to ensure the highest energy efficiency in gaining the available renewable energy and consuming it in an effective way.

Figure 9 presents the distribution of monthly space heating final and primary energy consumption for comparing the distribution of monthly space heating needs. It can be noticed that monthly space heating needs are presented in two graphical forms. The highest bars show total energy demand with standard ventilation needs, as shown in Figure 4 (where ventilation is a dominant factor of energy demand). The lower bars (colored red) also show the total energy needs, but the demand is much reduced due to application of the heat recuperation ventilation system. The smallest bars represent final energy consumption. It is evident that final energy consumption is really very low thanks to the highly energy efficient energy systems and mainly because of using a heat pump that has been well selected for the given operating conditions and operates with high energy performance (SCOP (Seasonal Coefficient of Performance) nearly equal to 5 after nearly 10 years of operation).

The seasonal index of the final energy demand for space heating accounts for 4.61 kWh/m^2 , which is very low. As has been mentioned, determination of the energy performance of any residential building requires taking into account only the heat consumption of the building for space heating and DHW. The so called annual index of energy consumption includes the annual DHW heating and space heating, while the space heating takes place only during the heating season, and for the considered house it lasts only four months. Thus the final annual energy demand index for space heating and domestic hot water is 11.58 kWh/m^2 , which is still a very low value even if the electric energy consumption by the auxiliary devices of the heating loops (like pumps and fans) is included. It can be mentioned here, that in Poland a building can be classified as a low energy building, when its final annual energy consumption (for all heating needs) amounts to $30\text{--}60 \text{ kWh/m}^2$. Such a range of indices was proposed in 2007 [25] and is still used [26].

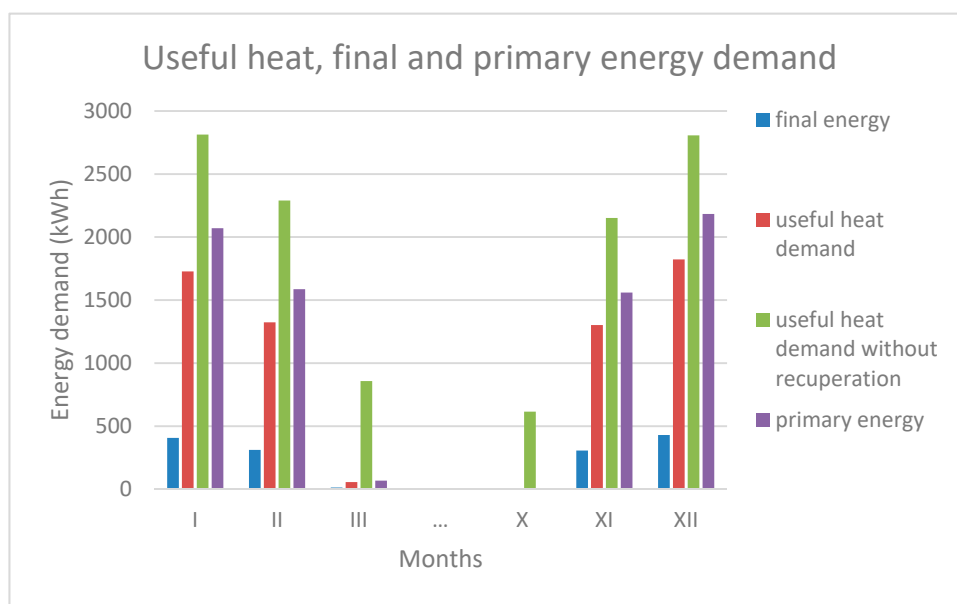


Figure 9. Monthly final and primary energy consumption and energy demand for space heating (bars for ventilation with heat recuperation and without are shown).

4.3. Primary Energy Consumption

The annual index of primary energy consumption for space heating and domestic hot water for the considered low energy solar house is equal to 25.77 kWh/m². The annual index for domestic hot water accounts for 4.11 kWh/m². These are really very small values, far below the existing and future (since 2021) limits for such indices required by the present regulations. The primary energy consumption is based on renewable energy sources: solar, solar thermal collectors and ground, ground source heat pump; on waste heat, i.e., recovery of heat from the ventilation system and on conventional electrical energy taken from the grid. In Poland, more than 90% of electricity is produced in power plants fired by coal (hard and brown). Thus, taking electricity from the grid means using primary energy based on fossil fuels. The calculated value of annual CO₂ emissions is equal to 596.8 kg per year. To estimate that value the official Polish energy mix with referred emissions for fossil fuel used was taken into account [27].

5. Conclusions

Carefully analyzing the results obtained it can be noted that the building under consideration is characterized by the final space heating energy consumption being lower than the space heating energy needs and lower than the primary energy consumption. At the same time, primary energy consumption is less than the heating energy needs (if heat recuperation from ventilation systems is included in the calculations of the final energy consumption). This low consumption of final energy results from the use of a heat pump for which a seasonal coefficient of thermal performance (SCOP) is used instead of standard efficiency or effectiveness of devices and systems. So the use of a heat pump should always be recommended to achieve a small final energy consumption.

In standard buildings with standard thermal energy systems supplied by fossil fuels the primary energy consumption is always the highest, then the final energy (which is lower than primary energy) and the lowest being the energy heating needs (in this case for the space heating). In energy efficient buildings the application of a heat pump reduces the final energy consumption, which is lower than energy needs (what is also the case in the energy system described in this paper). Such a lowering of final energy can be also achieved and fostered through application of a ventilation heat recovery system (real operational effectiveness of the recuperative heat exchangers is 70% in the considered system, theoretical one accounts for 85%). However, it can be noted why the heat recovery of the

ventilation system should be considered as final energy consumption, when the decision to use such a system is made during elaboration of the architectural concept of the building (ventilation ducts for forced airflow must be considered at this stage). So when the space heating of the low energy solar house is considered in this paper and if we assume the heat recovery of the ventilation system at the stage of determining the space heating energy needs, then comparing all three forms of energy, i.e., energy needs, final and primary energy consumption, the final energy consumption is the lowest, and the energy needs are lower than the primary energy consumption. Next, when application of renewables is taken into account then the primary energy consumption is reduced. How much this energy is reduced depends on the share of renewable energy sources used to fulfill the energy requirements. All these considerations show how difficult it is to determine the energy performance of a building. The problem is that in the official requirements for determination of energy performance of a building there are no limits (indices) for the heating energy needs of the building, so perhaps if a heat pump and the heat recovery ventilation system are to be applied, then the space heating energy consumption can just be at the limit of official regulated indices, even if not much has been done to reduce the energy needs.

Another problem is connected to official national regulations, which do not require (or even do not allow) inclusion of the electricity use by electrical lighting and appliances, when determining the energy performance of a residential building. Consequently, when any renewable energy system, like photovoltaic or wind energy, is used, then it can be considered if such a system supplies energy to drive the heating device, like a heat pump or electric heater. This means that any energy produced by such renewable energy systems for electrical appliances during the whole year cannot be included in calculations for determination of the energy performance of buildings. Thus the air heat pump used all year round to supply heat for DHW and seasonally for space heating can turn out to be a much better solution than using solar collectors for heating energy demand, mainly for DHW demand. This paper describes a ground source heat pump operated during the space heating season. Such a heat pump operates in a very efficient way, because out of heating season the ground can recover and come back to its natural thermal state very quickly. As a result the thermal conditions of using the ground source throughout the space heating season are very good (SCOP is quite high). In a case of an air heat pump the SCOP is much lower, because of using an ambient air source during winter.

It turns out, that determination of the energy performance of a solar low energy house based on official regulation does not allow for showing how energy efficient and smart the building really is. The main problem is that there are no limits on the energy demand of the building.

The basis for ensuring the energy efficiency of the building is primarily ensuring significantly reduced energy needs for the energy used in the building, i.e., the heating energy (energy for DHW, for space heating or cooling) and electricity. The biggest energy saving is the lack of demand for it. In buildings, significant savings can be obtained through the appropriate architectural concept of the building, designing the compact shape of the building, opening the southern side of the building to the impact of solar radiation and closing it tightly from the north to limit the impact of the external environment, especially in winter. A suitable concept for the interior of the building, e.g., as described in this paper, is the concept of using buffer zones, including the introduction of a southern buffer zone into the interior of the building, allowing the use of energy from the environment, including primarily solar radiation, and thus significantly reducing heat demand for heating. The architectural concept should ensure a natural temperature zoning of the interior of the building, including high thermal living comfort zones for permanent residence of people, zones for periodic residence (e.g., in transition seasons like spring and autumn) and non-residential zones (e.g., for cold or hot auxiliary facilities). Such natural zoning ensures a significant reduction in final energy consumption, and determines the smartness of the building. One could say it is an innate, inborn intelligence because the smartness is achieved naturally, passively, and not through the use of complex energy management systems in the building.

As has been presented in this paper, a low energy solar building is smart through its architecture, construction, energy efficient devices and systems applied, and through the well managed operation of all components based on utilization of renewable energies. It can therefore be concluded that the building should have the built-in (embodied) smartness of reducing energy demand and consumption, achieved naturally, passively, as well as through the use of energy-efficient devices and installations, planning appropriate operating priorities and the use of efficient low-carbon energy sources, preferably renewables.

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References

1. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings; The Energy Performance of Buildings Directive (EPBD), 2010. Available online: <https://eur-lex.europa.eu/eli/dir/2010/31/oj> (accessed on 10 May 2020).
2. Directive 2018/844 of The European Parliament and of The Council of 30 May 2018 Amending Directive 2010/31/EU on The Energy Performance of Buildings and Directive 2012/27/EU on Energy Efficiency; The Energy Performance of Buildings Directive (EPBD), 2012. Available online: <http://data.europa.eu/eli/dir/2018/844/oj> (accessed on 10 May 2020).
3. The Energy Efficiency Directive (2012/27/EU) of the European Parliament and of the Council of 25 October 2012 on Energy Efficiency, 2012. Available online: <http://data.europa.eu/eli/dir/2012/27/oj> (accessed on 10 May 2020).
4. Marszal, A.J.; Heiselberg, P.; Bourrelle, J.S.; Musall, E.; Voss, K.; Sartori, N.A. Zero Energy Building—A review of definitions and calculation methodologies. *Energy Build.* **2011**, *43*, 971–979. [CrossRef]
5. Available online: <https://ec.europa.eu/eurostat/web/environmental-data-centre-on-natural-resources/resource-efficiency-indicators/resource-efficiency-scoreboard/thematic-indicators/key-areas/improving-buildings> (accessed on 10 May 2020).
6. Bragança, L.; Wetzel, C.; Buhagiar, V.; Verhoef, L.G.W. (Eds.) *Cost C16 Improving the Quality of Existing Urban Building Envelopes; Facades and Roofs*, Research Architectural Engineering Series; IOS Press BV: Amsterdam, The Netherlands, 2007; Volume 5.
7. Available online: https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en (accessed on 10 May 2020).
8. Chwieduk, D. Impact of solar energy on the energy balance of attic rooms in high latitude countries. *Appl. Therm. Eng.* **2018**, *136*, 548–559. [CrossRef]
9. Chwieduk, D. Cooling demand: A challenging issue for new buildings in moderate climates. In Proceedings of the ICR 2019 IIR the 25th International Congress of Refrigeration, Montreal, QC, Canada, 24–30 August 2019; Refrigeration Science and Technology Proceedings: 2019. pp. 3948–3956, ISBN 978-2-36215-035-7.
10. Rozporządzenie Ministra Infrastruktury w Sprawie Warunków Technicznych, Jakim Powinny Odpowiadać Budynki i ich Usytuowanie Warszawa. National Regulation on Technical Conditions for Buildings and Their Location with Amendments. *Dziennik Ustaw*, Dnia 13 Sierpnia 2013, r. Poz. 926. (In Polish). Available online: <https://sip.lex.pl/akty-prawne/dzu-dziennik-ustaw/warunki-techniczne-jakim-powinny-odpowiadac-budynki-i-ich-usytuowanie-16964625> (accessed on 10 May 2020).
11. Drury, B.; Crawley, D.B.; Hand, J.W.; Kummert, M.; Griffith, B.T. Contrasting the capabilities of building energy performance simulation programs. *Build. Environ.* **2008**, *43*, 661–673.
12. Kivimaa, P.; Martiskainen, M. Innovation, low energy buildings and intermediaries in Europe: Systematic case study review. *Energy Effici.* **2018**, *11*, 31–51. [CrossRef]

13. Available online: <https://www.rcrwireless.com/20160725/business/smart-building-tag31-tag99> (accessed on 10 May 2020).
14. Wang, S.; Xie, J. Integrating Building Management System and facilities Management on the Internet. *Autom. Constr.* **2002**, *11*, 707–715. [CrossRef]
15. Masoso, O.T.; Grobler, L.J. The dark side of occupants' behavior on building energy use. *Energy Build.* **2010**, *42*, 173–177. [CrossRef]
16. Anderson, B. *Solar Energy: Fundamentals in Building Design*; Total Environmental Action, Inc.: Harrisville, NH, USA, 1975.
17. Kolokotsa, D.; Santamouris, A.; Karlessi, T. Passive Solar Architecture. In *Comprehensive Renewable Energy*; Kalogirou, S.A., Saigh, A., Eds.; Elsevier: Amsterdam, The Netherlands, 2014; Volume 3, pp. 637–665.
18. Chwieduk, D. Solar energy use for thermal application in Poland. *Pol. J. Environ. Stud.* **2010**, *19*, 473–477.
19. Chwieduk, D. Achievement of Low-Energy Buildings in High-Latitude Countries Through Passive Solar Systems. In *Renewable Energy and Sustainable Buildings*; Sayigh, A., Ed.; Innovative Renewable Energy; Springer: Berlin/Heidelberg, Germany, 2019; pp. 955–961.
20. Duffie, J.A.; Beckman, W. *Solar Engineering of Thermal Processes*, 4th ed.; John Wiley and Sons: Hoboken, NJ, USA, 2013.
21. Reindl, D.T.; Beckman, W.A.; Duffie, J.A. Evaluation of Hourly Tilted Surface Radiation Models. *Sol. Energy* **1990**, *45*, 9–17.
22. Ahmad, N.; Ghiaus, C.H.; Thiery, T. Influence of Initial and Boundary Conditions on the Accuracy of the QUB Method to Determine the Overall Heat Loss Coefficient of a Building. *Energies* **2020**, *13*, 284. [CrossRef]
23. Rozporządzenie Ministra Infrastruktury i Rozwoju z dnia 27 lutego 2015 r. w Sprawie Metodologii Wyznaczania Charakterystyki Energetycznej Budynku oraz świadectw Charakterystyki Energetycznej. National Regulation on Methodology of Determination on Energy Performance of Buildings and Energy Performance Certificates. *Dziennik Ustaw*, 2015, poz. 376. (In Polish). Available online: <http://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20170000022> (accessed on 10 May 2020).
24. Sawicka-Chudy, P.; Rybak-Wilusz, E.; Cholewa, M. Thermal efficiency of a solar power system in a collective residential structure based on performance tests. *J. Renew. Sustain. Energy* **2016**, *8*. [CrossRef]
25. Stachowicz, A.; Fedorczyk, C.M. Low energy buildings—Analysis of energy consumption of the all life cycle building. *Czasopismo Techniczne* **2007**, *Z-1B*, 133–141. (In Polish)
26. Matuszko, L.; Parzych, J.; Hozer, J. The low-Energy building—New trends of the construction industry. *Studia i Prace WNEiZ US* **2018**, *54*, 21–31. (In Polish) [CrossRef]
27. Available online: www.kobize.pl (accessed on 10 May 2020).



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