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Toward a positive-net-energy residential building in Serbian conditions

Milorad Bojić *, Novak Nikolić, Danijela Nikolić, Jasmina Skerlić, Ivan Miletić

Faculty of Mechanical Engineering at Kragujevac, University of Kragujevac, Sestre Janjic 6, 34000 Kragujevac, Serbia

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ABSTRACT

This article reports investigations of a residential building in Serbian conditions energized by electricity from photovoltaics (PVs), and the electricity grid. The building uses electricity to run its space heating system, lighting and appliances, and to heat domestic hot water (DHW). The space heating system comprises floor heaters, a water-to-water heat pump, and a ground heat exchanger. The PV system generates electricity that either may be consumed by the building or may be fed-in the electricity grid. The electricity grid is used as electricity storage. Three residential buildings are investigated. The first residential building has PVs that yearly produce smaller amount of electricity than the heating system requires. This is a negative-net energy building (NNEB). The second building has the PVs that produce the exact amount of electricity that the entire building annually needs. This is a zero-net energy building (ZNEB). The third building has PVs that entirely cover the south-facing roof of the building. This is a positive-net energy building (PNEB). These buildings are presented by a mathematical model, partially in an EnergyPlus environment. For all buildings, simulations by using EnergyPlus software would give the generated, consumed, and purchased energy with time step, and monthly and yearly values. For sure, these buildings would decrease demand for electricity during summer, however they will increase this demand during winter when there is no sun and start of space heating is required. Depending on the size of PV array this building will be either NNEB, or ZNEB, or PNEB. However it is crucial for such a building to be connected to the electricity grid. The smaller payback for investment in the PV array is obtained for buildings with larger size of PV array. The feed-in tariff for the generation of electricity in Serbia should be under the constant watch to be corrected accordingly for larger penetration of this technology in the Serbian market.

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1. Introduction

In Serbia the built environment consumes around 50% of the primary energy. Participation of households in the total electricity consumption is 56% [1]. The energy mix for electricity production consists of around 72% of electricity produced by fossil fuel (mainly coal, and some natural gas or oil) power plants and 28% of electricity produced by hydroelectric power plants [1]. This energy mix means that 1 J of electricity is generated by 2.154 J of the primary energy. These data reveal that 1 J of electricity spent in buildings would generate 2.154 J of the primary energy consumption that has large impact to the environment.

On 24 September 2007, Serbia ratified Kyoto protocol which regulates reduction in greenhouse gas emissions. On the other side, an intention of our country to become a member of EU obliges us to reduce energy consumption by 20% and to obtain 20% of total energy from renewable energy sources by 2020 [2]. To achieve these goals, some advanced energy concepts for built environment should be applied such as ZNEB and PNEB. In addition, the feed-in tariffs should be used that are recently established in Serbia. Currently, the feed-in tariff for electricity production by solar power plants is 0.23 €/kW h [3].

From renewable energy, the building may usually produce electrical energy by the PV array on its roof. If the building is also connected to the national electricity grid, the building may consume electrical energy either from the PV array or from the electricity grid. The generated electrical energy may feed either the building or the electricity grid. The building supplies the electricity grid with electrical energy when there is the electrical energy surplus in the building. When there is electrical energy shortage in the building, the electricity grid supplies the building with electrical energy. By definition, ZNEB produces all energy it consumes during year, PNEH produces more energy than it consumes during year, and NNEB produces less energy than it consumes during year. The "zero-net" concept means that yearly the excess electrical energy supplied to the electricity grid balances the amount received from the electricity grid. The "positive-net" concept means that yearly the excess electrical energy supplied to the electricity grid is higher than the amount received from the electricity

* Corresponding author. Tel.: +381 64 8449694; fax: +381 34 360 905.
E-mail address: bojic@kg.ac.rs (M. Bojić).

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Nomenclature

C_G (€/kW h) price of electricity from the electricity grid
C_{PV} (€/kW h) price of electricity from the PV system.
$C_{inverter}$ (€/W$_p$) average price for inverter
C_{array} (€/W$_p$) price for PV array
$C_{mounting}$ (–) costs for mounting the PV system relative to I_o
D (€) yearly profit when applying the PV system.
$E_{PV,Y}$ (J/year) electrical energy generated by the PV array
$E_{PV,G,Y}$ (J/year) electrical energy generated by the PV array that is feed in the electricity grid (not used by the house)
$E_{PV,G,G,Y}$ (J/year) $E_{PV,G,Y}$ that is equal to the amount of the electrical energy purchased from the electricity grid (when the PV electricity is not available).
$E_{PV,G,S,Y}$ (J/year) $E_{PV,G,Y}$ that is the true surplus of the PV-origin electrical energy
$E_{PV1,Y}$ (J/year) electrical energy generated by the PV panel sized at 1 m^2
$E_{PV,B,Y}$ (J/year) electrical energy generated by the PV array and consumed by the house
$E_{G,Y}$ (J/year) electrical energy purchased from the electricity grid (and used in the house)
$E_{T,Y}$ (J/year) total electrical energy consumption of the house
$E_{T,H,Y}$ (J/year) electrical energy consumption of the house for heating
$E_{T,L,Y}$ (J/year) electrical energy consumption of the houses for lighting
$E_{T,O,Y}$ (J/year) electrical energy consumption of the houses for other needs
F_I (m^2) area of the PV array in design 1
F_{II} (m^2) area of the PV array in design 2
F_{III} (m^2) area of the PV array of design 3
F_{array} (m^2) area of the PV array,
I_{array} (€) investment cost for the PV array
$I_{inverter}$ (€) investment cost for the inverter
I_o (€) investment to supply and install the PV system
PB (years) investment return
R_o (€/year) expenses to support the operation and maintenance of the PV array
$R_{PV,B,Y}$ (€/year) financial savings due to direct use of the PV-origin electricity
$R_{PV,G,Y}$ (€/year) yearly revenue from the PV-origin electricity sold to the electricity grid
$R_{PV,G,G,Y}$ (€/year) yearly revenue that would cover the expenses of the houses for the purchased electricity from the electricity grid
$R_{PV,G,S,Y}$ (€/year) net revenue of the houses due to the installed PV array
$S_{G,Y}$ (€/year) expenses to purchase the electrical energy from the electricity grid
S_{panels} (W/m^2) maximum power of PV panels per m^2
$S_{T,Y}$ (€/year) expenses for consumed electricity when the house does not have the PV array

Indices
i particular month
j particular time step
Y year

Abbreviations
GCHP ground-coupled heat pump
NNEB negative-net energy building
PNEB positive-net energy building
PV photovoltaic
ZNEB zero-net energy building

grid. The "negative-net" concept means that yearly the excess electrical energy supplied to the electricity grid is lower than the amount received from the electricity grid. Namely, the ZNEB, PNEB, and NNEB use the national power grid as an electrical storage battery.

The research toward ZNEBs drew worldwide interest such as in Europe [4–9], North America [10–13], and Asia [14,15]. In addition, the interest toward PNEB started to accelerate [16–18]. For ZNEBs in Europe, Ref. [4] reported theoretical research on first and second law analysis of a solar assisted heat pump based heating system in Romania. Ref. [5] reported on performance and costs of a roof-sized PV/thermal array combined with a ground coupled heat pump that is used in ZNEB in the Netherlands. Ref. [6] reported on energy and environmental comparison of three variants of a family house during its whole life span in Switzerland. The best performances were obtained for the house with the highest use of renewable energy. Ref. [7] reported on ZNEBs in Netherlands considering a heat pump for space heating with ventilation air as a heat source. Ref. [8] reported on design and performance of energy-efficient solar residential house in Andorra. Ref. [9] reported on the low energy residential settlement Borgo Solare in Italy. During its design, the main concern was the thermal mass and embodied energy of envelope for residential building in this settlement.

For ZNEB in North America, Ref. [10] reported on design of a solar home with a BIPV-thermal system and a ground source heat pump in Canada. Ref. [11] reported research on achieving total domestic hot water production with renewable energy in ZNEB in Canada. Here, space heating and cooling was provided by a water-to-air heat pump. It is found that the best alternative is using solar collectors with electrical energy as back-up system. Electrical energy is obtained by using PV array. Ref. [12] reported research on life cycle cost and energy analysis of a net zero energy house with solar combisystem with solar collectors and PV modules in Canada taking into account embodied energy in the house. Ref. [13] reported research on affordable ZNEB in cold climate in Colorado, USA. This house uses PV for electrical energy production; however they use fossil fuel for heating.

For ZNEB in Japan, Ref. [14] reported research on field performance on a Japanese low energy home relaying on renewable energy. This house used GSHP, super insulation, air tightness, direct solar gain, ventilation with exhaust stack, PV array, wind power, and solar collectors to satisfy space heating, space cooling and DHW use. The house produced 80% of necessary energy by the PV array, solar collectors, underground and exhaust heat. Ref. [15] reported thermal performance and embodied energy analysis of a zero energy green home – the mud-house as an energy efficient and eco-friendly habitat for achieving natural thermal comfort for rural population of India since they cannot afford for window air conditioner or air heater in harsh summer and winter climatic conditions in India.

Except development of ZNEB, the development of PNEB can be noticed where examples are an office building in design by Bouygues Immobilier in Paris, France [16], an archives building in design by Bouygues Construction in Lille, France [17], and Masdar Headquarters in design by Adrian Smith and Gordon Gill in Abu Dhabi [18].

In ZNEBs and PNEBs, energy may be used for space heating, space cooling, DHW heating, lighting, and appliances. However, the amount of energy generated by the PV array and solar collectors located on the building roof is limited as there is a shortage in surface (space) needed for energy generation. Consequently, the rule of thumb for design of these buildings is to minimize the energy consumption in the building. This would minimize the required energy generation and the surface area required for the energy generation. In such buildings, their envelope should minimize heat transfer. In cold climate, the building envelope has to be super insulated and air tight. Special double glazed windows may be used at that are filled with argon and have low heat emissivity film coating.

In ZNEB and PNEB, space heating, space cooling, DHW heating, lighting, and appliance use should be energy efficient. In this direction, space heating is usually provided by ground-coupled heat pumps (GCHPs). They may give around three times greater amount of heat energy than that of electrical energy with which they run. The GCHPs may be also used for space cooling when the direction of refrigeration fluid is reversed. For space heating, a GCHP with hydronic floor heating or air heating is used the most often in these buildings. DHW may be heated by solar collectors, by electrical energy produced by the PV array, by the heat pump driven by electrical energy, or by resistance heat only obtained by using solar electricity. Lighting and appliances should be energy efficient to minimize use of electrical energy that has to be generated by the building.

Energy generation should use the smallest surface area on the roof as this is possible. Technologies for energy generation are generation of heat energy by solar collectors, electrical energy by the PV array and wind power, and heat and electrical energy by the hybrid PVT array. When there is energy generation with the PV array and solar collectors, the ratio between areas of the PV array and of solar collectors should be determined.

Energy saving and producing technologies should be cost effective. That means minimum construction costs for these houses and their fastest penetration into practice. The highest cost is the cost of its GCHP heating system and the PV array. To minimize these costs, the designer has to minimize heating and cooling loads to these homes. For designer, the most interesting questions are that of area of the PV array and financial attractiveness of their installation. As these technologies are still relatively expensive, the government enhanced financial attractiveness of the investment in such devices usually by different credit schemes, and feed-in tariffs system for the excess electricity that is sold to the electricity grid.

This article reports investigations of energy consumption in three residential houses. These two-story houses are identical, except of the size of PV array installed at their roof. Then, when their PV system would not directly satisfy the building needs for electrical energy, then the rest of electricity will be used from the electricity grid (storage). When their PV system would satisfy the building needs for electrical energy, then the rest of PV generated electricity will be fed-in the electricity grid.

The houses are located in Kragujevac, Serbia. In each house, the electricity is used to satisfy energy needs for space heating, lighting, appliances, and DHW heating. Each house uses the electricity grid network for the electricity storage. The building has a space heating system that uses a GCHP with a vertical ground heat exchanger and floor heaters. The compressor of the GCHP is a main component of the GCHP powered by electricity.

The first house has the PV system that would yearly produce the exact amount of electricity only needed to run the heating system. The second house has the PV system that would yearly produce the exact amount of electricity needed for entire building. The third house has the PV system that would yearly produce more electricity than needed for the entire building. For these buildings, the article will comment on consumption, generation, and purchase of electrical energy by the building. This will be reported for each time step during one winter and one summer day, for each month during entire year and for the entire year. In addition, the article will report the payback time for use of PV array as a function of the feed-in tariff of generated electricity, size of PV array, and price of the PV panel. This article will comment if current Serbian policy is attractive enough to disseminate these buildings in Serbia.

2. Model of the building, space heating, and PV system

Energy modelling of residential building, space heating, and PV system was done in EnergyPlus environment. Modelling of economical performances of these energy systems was performed by using mathematical models given in the paper.

2.1. Simulation software – EnergyPlus

In this study, the simulation software EnergyPlus (Version 5.0) was partially used [19]. EnergyPlus is made available by the Lawrence Berkeley Laboratory in USA [20]. Its development began in 1996 on the basis of two widely used programs: DOE-2 and BLAST. The software serves to simulate building energy behavior and use of renewable energy in buildings. The renewable energy capabilities include solar thermal and photovoltaic simulation. Other simulation features of EnergyPlus include: variable time steps, user-configurable modular systems, and user defined input and output data structures. For Europe and different parts of the world, the software has been tested against analytical solutions, empirical results, and results of other software. The software has been tested using the IEA HVAC BESTEST series of tests [21]. The software has been verified for the building is located in Ravenna when data on real energy consumption and EnergyPlus simulations are compared. Ravenna is located in the North-East of Italy, near the Adriatic sea with latitude of 44.42°N that is almost equal to that of Kragujevac [22]. Next, the software gives results in good agreement to the series of experimental results of solar gain modeling in building energy codes by test cell constructed in Duebendorf, Switzerland [23]. To model, the space heating system and PV electricity generation in EnergyPlus environment, models of different components embedded in EnergyPlus are used such as that of heat pump, vertical ground heat exchanger, floor heater, and PV array [24,25].

2.2. Climate

The investigated residential house is located in the city of Kragujevac. Kragujevac lays in Balkan Peninsula in state of Serbia, around 120 km south of its capital city of Belgrade. Its average height above sea-level is 209 m. Its latitude is 44°1′N, longitude 20°55′E, and time zone GMT + 1.0 h. The EnergyPlus weather file used in the EnergyPlus simulation is generated by Meteonorm software [26]. To familiarize with the Kragujevac climate, Figs. 2 and 3 are given by using monthly statistics for Kragujevac from Meteonorm weather file. For each month during entire year, Fig. 2 gives the dry bulb temperature (minimum, daily average, and maximum) and relative humidity. For each month during entire year, Fig. 3 shows direct, diffuse and global average solar radiation, and daily average wind speed. These figures show that the city has a moderate continental climate with a gradual transition between the four distinct seasons (winter, spring, summer, and autumn). The summers are worm and humid, with temperatures as high as 37 °C. The winters are cool, and snowy, with temperatures as low as −12 °C. In these simulations, it is taken that the heating devices may operate from 15 October to 14 April next year that is

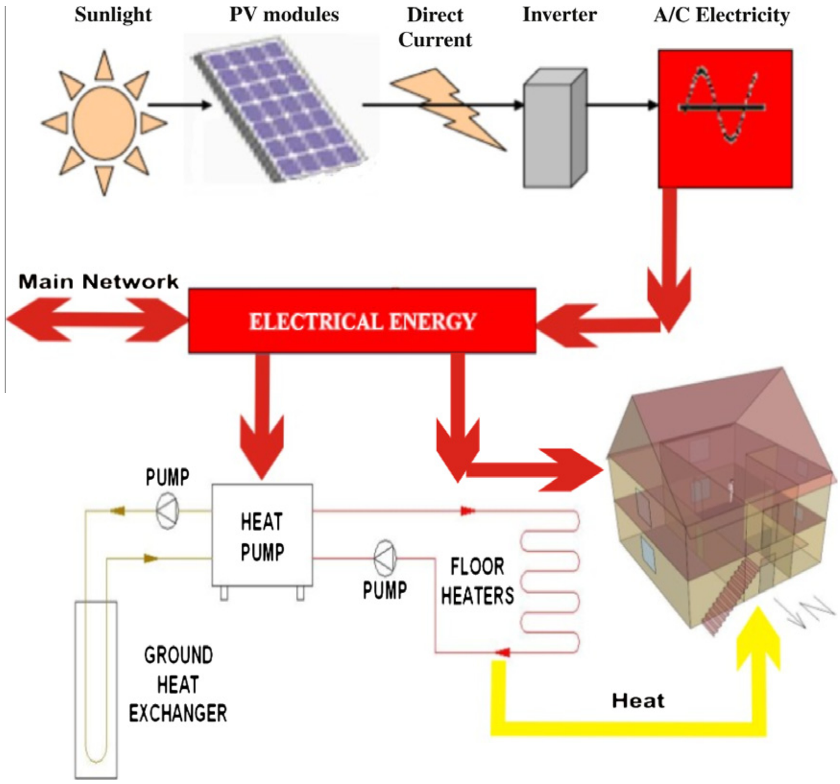

Fig. 1. The house, its heating system, and PV system under investigation (the PV array is located at the house roof facing south).

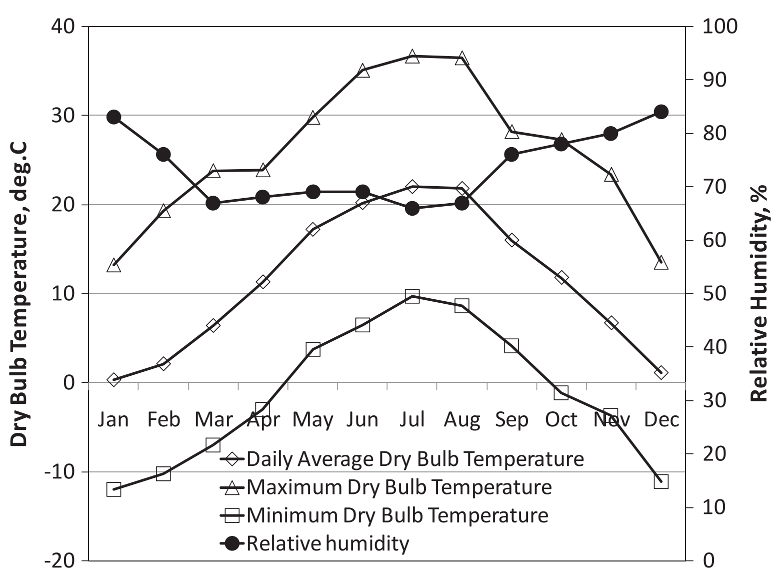

Fig. 2. Relative humidity and dry bulb temperature (minimum, daily average and maximum) from the monthly statistics for Kragujevac, Serbia from Meteonorm weather file.

valid in practice for entire Serbia. In these simulations, it is also taken that the cooling devices may operate from 15 April to 14 October.

2.3. Residential building

The investigated residential building is described to be designed in order to minimize amount of energy required for its space heating during winter. In addition, the special case should be devoted to efficient lighting and efficient use of appliances.

2.3.1. Thermal description

The investigated house has the total floor area of 130.6 m^2 (Fig. 1). It has a footprint of 65.3 m^2. The house dimensions are provided in details in Table 1. It has two stories with two identical apartments, each on one story. It is assumed that each apartment accommodates a family of four. Each apartment consists of three rooms: living room, bedroom and bathroom. The physical characteristics of the house (R-values of differently oriented walls, window specifications, roof's materials) demonstrate that the house is designed as an efficient passive house.

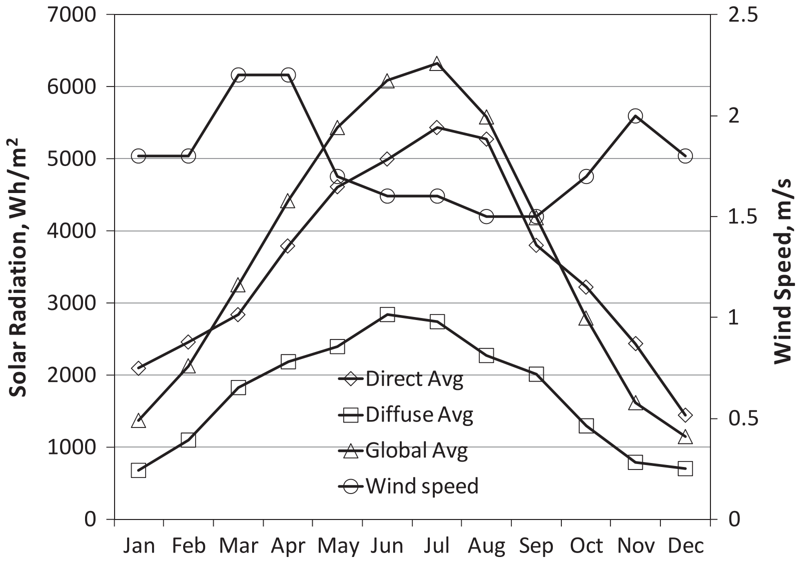

Fig. 3. Direct, diffuse, and global average solar radiation, and daily average wind speed from the monthly statistics for Kragujevac, Serbia from Meteonorm weather file.

Table 1
House characteristics (dimensions).

Conditioned area	131 m^2 (8 m × 8.16 m × 2 floors)
Conditioned volume	339 m^3(8 m × 8.16 m × 2.6 m × 2 floors)
Roof area (south/north)	46.2 m^2/46.2 m^2 with 45° slope
Attic volume	130 m^3
Window area	9.12 m^2
East/south/west/north	3.92/3.92/1.28/0 m^2

It is also assumed that the house is not surrounded with any object. The constructions (walls, ceilings, floors, doors, and windows) are made by material layers with characteristics given in [19]. The characteristics of the house envelope are provided in Table 2. The amount of infiltration is between 0.75 and 1.25 ach^{-1}.

2.3.2. Electrical energy consumption

In the building, total electrical energy consumption $E_{T,Y}$ is the electrical energy is annually consumed to satisfy energy needs for house occupants. The same amount of energy is needed for the buildings with PV and buildings without PV. $E_{T,Y}$ is divided into three groups regarding mode of electricity consumption: (1) electrical energy for space heating of the house $E_{T,H,Y}$, (2) electrical energy for lighting the house $E_{T,L,Y}$, and (3) electrical energy for other electrical equipment $E_{T,O,Y}$:

$$E_{T,Y} = E_{T,H,Y} + E_{T,L,Y} + E_{T,O,Y}. \tag{1}$$

The space heating uses heat pumps and floor heating. The electrical energy for space heating is used to run the compressor of the heat pump and to run the variable speed water pump for hot water inside the floor heating pipes. The electrical energy for other electrical equipment is used to heat domestic hot water (DHW), and run appliances. In typical Serbian residences, the DHW is heated by electrical energy in DHW storage tanks. The used appliances are refrigerators, freezers, dishwashers, cloth washers, electric range, toaster, vacuum cleaner, TV, hair dryer, and computer.

Table 2
Envelop.

Window	Double pane (3 mm), air, U = 3.19 W/m^2 K, SHGC = 0.762
Conditioned space wall	102 mm brick, 12.7 mm air layer
R = 4.74 m^2 °C/W	150 mm mineral wool
	12.7 mm gypsum board
Conditioned space floor	150 mm conc. (2400 kg/m^3)
R = 3.77 m^2 °C/W	125 mm mineral wool
Conditioned space ceiling	19 mm gypsum board
R = 8.92 m^2 °C/W	
	310 mm mineral wool
Basement wall	12.7 mm gypsum plaster
R = 3.57 m^2 °C/W	200 mm conc. (2400 kg/m^3)
Roof	115 mm mineral wool
R = 0.3 m^2 °C/W	6 mm shingles
	12.7 mm plywood
	PV arrays on the south tilted at 45°

2.4. Heating system

The heating system consists of the water-to-water heat pump, the ground circuit, and the heating circuit (Fig. 1). The compressor of the heat pump consumes either PV-origin electricity or the grid-origin electricity. The heat pump transfers heat from the ground circuit to the heating circuit inside the building. The heating circuit heats the building rooms.

The ground circuit consists of the ground heat exchanger and variable speed pump. The ground heat exchanger is vertical U-tube buried in the ground. The pump transports water between ground heat exchanger and the evaporator of the heat pump. Within the ground circuit, the water circulates between evaporating side of the heat pump and vertical ground heat exchangers. It is heated by ground at the ground heat exchanger and then cooled at the evaporator of the heat pump, and sent to the ground heat exchanger again.

The heating circuit consists of flow heaters and variable speed pump. The pump transports water between the condenser of the heat pump and the floor heaters. Within the heating circuit, heating fluid, in this design water, after transferring heat to the rooms by using the floor heaters, is directed to condenser of the heat pump. There, it would be heated again to necessary temperature. Then, it would be directed to floor heaters again.

2.4.1. Water-to-water heat pump

The heat pump is a main part of the system. It is water-to-water type with refrigerant R22, nominal COP = 3.5, and heating capacity

Table 3
The values of parameters of the PV panel of Shell S115 type [27].

Panel characteristics	Value	Panel characteristics	Value
Short circuit current, A	4.7	Open circuit voltage, V	32.8
Current at maximum power, A	4.2	Number of cells in series	54
Voltage at maximum power, V	26.8	Panel area, m^2	1.037
Temperature coefficient of open circuit voltage, V/K	−0.115	Panel heat capacity, J/m^2 K	50,000
Temperature coefficient of short circuit current, A/K	0.002	Panel heat loss coefficient, W/m^2 K	30

of 50 kW. Its main parts are the compressor, evaporator, and condenser. The compressor is driven by electricity. The evaporator transfers heat from the ground circuit to the refrigerant R22 of the heat pump. The condenser transfers heat from the refrigerant R22 of the heat pump to the heating circuit. Within software EnergyPlus, the model of the heat pump uses physical parameters generated from the heat pump manual.

2.4.2. Vertical ground heat exchanger

Vertical ground heat exchanger is the U-tube with outside diameter of 0.0267 m and thickness of 0.00241 m. U-tube is mounted in the borehole which is fulfilled with material of great thermal conductivity (from tube side). The borehole is deep 76.2 m with radius of 0.064. Inside the borehole, U-tube pipe is placed. Borehole is surrounded with soil or stones. The model of this exchanger, taken from data list within software EnergyPlus, simulates its operating under different thermal loads.

2.4.3. Floor heaters

For floor heaters, it is necessary to define where they are located inside a floor construction. Inside the floor construction on the first story, they are put after 7th material layer (gypsum tile) and on the second story, after 4th material layer (gypsum tile), looking from outside to inside of the room. Floor heater had different lengths for different rooms were they are located such as 220 m for living room, 60 m for bathroom and 165 m for bedroom. Tube spacing is 0.1524, and tube inside diameter 0.012 m.

Control of these heaters is accomplished by the variable water flow rate inside the flow heaters. This flow rate is achieved by using a variable speed water pump. The flow rate from 6 h to 22 h is governed by using two quantities with their values set at the room thermostat: the air temperature in the room 19 °C, (air temperature of 23 °C in the bathroom) and air temperature range for the temperature control of 2 °C. For example, at the thermostat, the air temperature is set at 19 °C and the temperature range is set at 2 °C. Then, the water flow rate inside the floor heaters will be zero when the air temperature inside the room is at or above 20 °C. On the other side, the water flow rate inside the floor heaters will have its maximum value when the air temperature is at or below 18 °C. The water flow rate will linearly vary between its maximum and minimum (zero) value when the values of the air temperature are between 18 °C and 20 °C [19].

2.5. PV system

The PV system would produce electrical energy to satisfy needs for electrical energy of the house. The PV system consists of PV array, and an inverter. The system would run during entire year. The operations the PV and heating system are together simulated by using EnergyPlus. The investigation analyses use of three PV systems of different design. Their designs have different sizes of PV arrays: 14.5 m^2, 29 m^2, and 45.6 m^2. A PV array consists of PV panels. The array panels are put at the south direction roof under the slope of 45°. The inverter is selected with maximum efficiency. The PV system operates under assumption that all generated electrical energy will be immediately consumed.

2.5.1. PV panels

The used PV panels are made from polycrystalline silicon (type Shell S115) [27]. Their characteristics are shown in Table 3. The PV panel is represented by the mathematical model of equivalent one-diode circuit from EnergyPlus. This model consists of mathematical models for a DC current source, diode and either one or two resistors. The model simulates the operation of the PV system under real conditions using empirical mathematical equations [22]. To determine the temperature of the PV panel, the "Decoupled" method was used [22]. The model of the PV panel is developed under the assumption that it operates at its maximum power. That may not be a case when the PV system operates under the real conditions.

2.5.2. PV array – the first house

The first house has the PV array sized to produce the exact amount of electrical energy that the heating system would consume during year ($E_{PV,Y} = E_{T,H,Y}$). This array does not cover other electricity consumption of this building such as that of the lighting and miscellaneous electric loads. The total area of PV array is obtained as

$$F_I = E_{T,H,Y}/E_{PV1,Y} = 14.5\ m^2. \tag{2}$$

Here, $E_{PV1,Y}$ stands for the electrical energy generation of one PV panel.

2.5.3. PV array – the second house

The second house has the PV array sized to produce enough electricity to satisfy the building needs for the electrical energy during the entire year ($E_{PV,Y} = E_{T,Y}$). There is

$$F_{II} = E_{T,Y}/E_{PV1,Y} = 29\ m^2 \tag{3}$$

2.5.4. PV array – the third house

The third house has the PV array covering entire roof area facing south at slope of 45°. The area size is 45.6 m^2. It produces more energy than it is necessary to cover the annual electricity consumption of the entire house. Here,

$$E_{PV,Y} = F_{III}E_{PV1,Y}. \tag{4}$$

3. Operation of the building energy system – energy balance

In this case, the building energy system consists of an electrical energy consumption part and an electrical energy generation part. The PV system is electrical energy generation part. It may entirely or partially cover consumption of electrical energy in the building. Each time during year, different amounts of electrical energy may be produced by the PV array and consumed by the building. To match differences in the electricity production and consumption, the storage of electricity is provided by the grid electricity network. The energy consumption and production is governed by two balance equations: that of the energy balance of the electrical energy consumed by building and that of electrical energy generated by building.

3.1. The energy outputs of EnergyPlus

The outputs of EnergyPlus are amounts of energy recorded during entire year at time steps of 15 min. These outputs are the following: the electrical energy consumed by building ($E_{T,j}$), the electrical energy purchased by the building ($E_{G,j}$), the electrical energy generated by the PV panel sized at 1.037 m^2 ($E_{PV1,j}$), the electrical energy generated by the PV array ($E_{PV,j}$), the electrical energy generated by the PV array and used by the building ($E_{PV,B,j}$), and electrical energy generated by the PV array and fed in the electricity grid ($E_{PV,G,j}$). The index j stands for the specific time step. The monthly and yearly amounts are obtained as the sums of the time step amounts. Energy with subscript i instead of j would be the monthly amount and with Y instead of j the yearly amount. Index i designates the specific month. For instance, the monthly amounts, of these energies will be designated as $E_{T,i}$, $E_{G,i}$, $E_{PV1,i}$, $E_{PV,i}$, $E_{PV,B,i}$, and $E_{PV,G,i}$. Their yearly amounts are $E_{T,Y}$, $E_{G,Y}$, $E_{PV1,Y}$, $E_{PV,Y}$, $E_{PV,B,Y}$, and $E_{PV,G,Y}$.

3.2. The electrical energy annually consumed by the building

The building may consume energy from different sources: the PV array and the electricity grid:

$$E_{T,Y} = E_{PV,B,Y} + E_{G,Y} \tag{5}$$

Here, $E_{PV,B,Y}$ stands for the electrical energy generated by the PV array and consumed by the building, and $E_{G,Y}$ stands for the electrical energy imported from the electricity grid and consumed by the building. The both $E_{PV,B,Y}$ and $E_{G,Y}$ are yearly amounts.

As generation of electrical energy by the PV array and the consumption of electrical energy by building do not simultaneously happen in the same amounts, However, during a day, different amounts of electrical energy are consumed by the building and generated by the PV array. Sometimes, during daylight, the PV array generates more electrical energy than the building needs. Then, the unused PV electrical energy will be put (sold) into the electricity grid. The electricity grid will behave as storage of the electrical energy.

During a year, month, day, and time step, there is imbalance in amounts of electrical energy consumed by the building and generated by the PV array. Practically, there are three situations. Sometimes, during daylight, the PV array generates more electrical energy than the building needs. Then, the unused PV electrical energy will be put (sold) into the electricity grid. The electricity grid will behave as storage of the electrical energy. Sometimes, during daylight, the PV array may generate less energy than that the building requires. The rest of the electrical energy needed by the building will be imported from the electricity grid (storage). Then, during night, the solar electricity is not produced by the PV array. The electrical energy will be imported to the building from the electricity grid.

3.3. The electrical energy generated annually by the PV array

The electrical energy annually generated by the PV array is designated as $E_{PV,Y}$. In practical application, $E_{PV,Y}$ may be used directly by the building ($E_{PV,B,Y}$) and sold (fed in) to the electricity grid ($E_{PV,G,Y}$):

$$E_{PV,Y} = E_{PV,B,Y} + E_{PV,G,Y}. \tag{6}$$

Actually, $E_{PV,G,Y}$ is the electrical energy generated by the PV array that is not used by the building. This energy consists of two parts. The first part $E_{PV,G,G,Y}$ actually compensates for (equals to) the amount of the electrical energy purchased from the electricity grid (when the PV electricity is not available). The second part $E_{PV,G,S,Y}$ is the true surplus of the PV-origin electrical energy. This electrical energy is only available in PNEB. There is

$$E_{PV,G,Y} = E_{PV,G,G,Y} + E_{PV,G,S,Y}. \tag{7}$$

Finally, the total PV-origin electrical energy is given as

$$E_{PV} = E_{PV,B} + E_{PV,G,G} + E_{PV,G,S}. \tag{8}$$

When annually $E_{PV,G} < E_G$; $E_{PV,G,S} = 0$, this is a NNEB. Then, during the entire year in the case of ZNEB, an amount of energy is exported to the electricity grid and the same amount is consumed from the electricity grid when the electricity production by the PV array is available ($E_{PV,G} = E_G$; $E_{PV,G,S} = 0$). When annually $E_{PV,G} > E_G$; $E_{PV,G,S} > 0$, this is a PNEB.

4. Operation of the building energy system – application economy

The operation of the building energy system is investigated by analysis of the economy of the application of this system. In this direction, we investigated yearly revenue, expenses, profit and investment return for the application of the proposed system in Serbian residential building

4.1. Yearly income due to energy production

When the building has the PV array, its yearly expenses to purchase the electrical energy from the electricity grid are

$$S_{G,Y} = C_G E_{G,Y}. \tag{9}$$

In addition, there are the yearly expenses R_o to support the operation and maintenance of the PV array. It is assumed that these expenses are 1% of I_o ($R_o = 0.01 I_o$).

When the house does not have the PV array, the yearly expenses for consumed electricity are given as

$$S_{T,Y} = C_G E_{T,Y} \tag{10}$$

Yearly revenue from the PV-origin electricity sold to the electricity grid is given as

$$R_{PV,G,Y} = C_{PV} E_{PV,G,Y} = R_{PV,G,G,Y} + R_{PV,G,S,Y}. \tag{11}$$

Here, C_{PV} stands for the price of the PV-origin electricity sold to the electricity grid. The first term in this equation $R_{PV,G,G,Y}$ is the yearly revenue that would cover the expenses of the building for the purchased electricity from the electricity grid:

$$R_{PV,G,G,Y} = C_G E_{G,Y}. \tag{12}$$

C_G stands for the price of electricity purchased from the electricity grid assumed to be 0.11 €/kW h. The second term in this equation $R_{PV,G,S,Y}$ would be the net revenue of the building due to the installed PV array.

The yearly income is calculated for the case of the existing building when the PV system is additionally installed. The yearly income by the building is given as

$$D = (S_{T,Y} - S_{G,Y}) + R_{PV,G,Y} - R_o \tag{13}$$

4.2. Investment in PV system

The investment cost is given as

$$I_o = (1 + C_{mounting})(I_{array} + I_{inverter}) \tag{14}$$

Here, I_{array} stands for the investment cost for the PV array, $I_{inverter}$ stands for the investment cost for the inverter, and $C_{mounting}$ stands for the percentage addition to the investment cost to mount the PV array and the inverter at the site. The investment cost for the PV array is

$$I_{array} = F_{array} S_{array} C_{array} \tag{15}$$

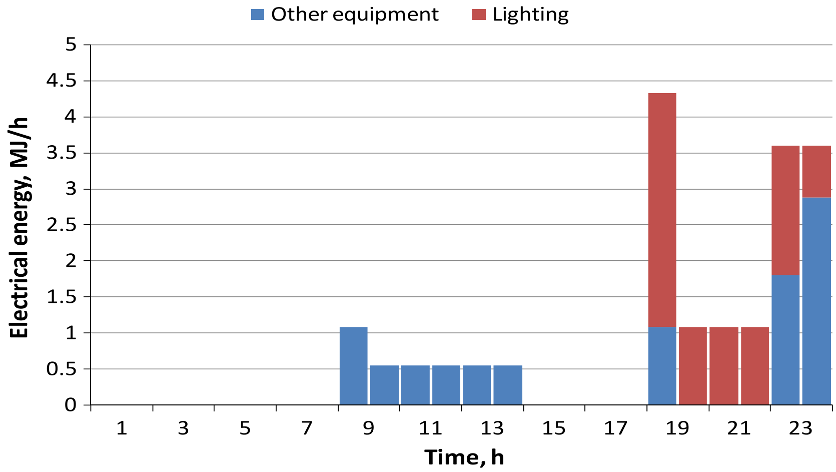

Fig. 4. Electrical energy consumed in the houses for lighting and other equipment (excluding heating): its daily distribution.

Here, F_{array} represents the total array area, S_{array} = 113 W_p/m^2 represents the array rated power per m^2, and C_{array} = 4.44 €/W_p represents the average price of the array per the unit of its rated power [28]. The investment cost for the inverter is given as [29]

$$I_{inverter} = 1.1 F_{array} S_{array} C_{inverter} \tag{16}$$

where $C_{inverter}$ = 0.512 €/W_p represents the average price for the inverter per the unit of the rated power [30]. The costs for mounting the PV system are assumed to be 10% of the total investment costs for the PV system, $C_{mounting}$ = 0.1. Hence,

$$I_o = 1.1(F_{array} S_{array} C_{array} + 1.1 F_{array} S_{array} C_{inverter}) \tag{17}$$

4.3. Investment return of the PV system application

The investment return of application of the PV system to some existing building is estimated by

$$PB = I_o/D \tag{18}$$

where I_o stands for the investment cost to supply and install the PV system, and D stands for the yearly income when operating the PV system.

5. Results and discussion

The three houses are investigated. The simulation is carried out during entire year. These houses are in Kragujevac, Serbia. They only differ in the size of PV array. The first house has the PV-array size of 14.5 m^2 that can supply enough electrical energy for space heating. The second house has the PV-array size of 29 m^2 that can supply enough electrical energy to cover all electricity consumption in the house. The third house has the PV array that covers the entire area of the house roof facing south of 45.6 m^2.

The space heating operates every day from 15th October to 15 April. Daily, it functions from 6:00 to 22:00 h. The electrical energy for lighting of the house and all other electrical equipment is consumed during entire year according to the schedule shown in Fig. 4.

For the each house (1–3), the simulation results are the 15 min values for the electricity consumed by the building, electricity purchased by the building, electricity produced by the PV array, electricity generated by the PV array and used by the building, and electricity generated by the PV array and fed in the electricity grid. These values are obtained and recorded during entire year. Based on these results, we establish the monthly energy values, the yearly energy values, and the yearly income by the building from PV electricity. In addition we calculated the investment in the PV system. Furthermore, we discussed the daily energy distribution, the yearly energy distribution per different months, the yearly energy balance, and the investment return.

5.1. The daily energy distribution

The simulation results for the third house are presented for January 21st and July 21st in Figs. 5 and 6, respectively. The presented results are the outdoor temperature, the purchased electricity, the generated PV electricity, and the PV electricity sent to the electricity grid for each 15 min during each day.

Fig. 3 shows for January 21st (the day with space heating) that the highest 15-min amount of the purchased electricity is at 6:15 am when space heating starts to operate. This 15-min amount is even higher than any 15-min amount of electrical energy generated by the PV array. Naturally, the energy consumption is not covered by the PV-origin electricity between 6:00 am and 7:30 am as the sun did not generate any electrical energy. The PV electricity starts to be generated from 7:30 am to 4:15 pm. When the electricity is generated from the sun, it easily covers the building energy consumption. After 4:15 pm the energy consumption is not covered as the PV electricity is not generated. Then, all electricity is purchased from the electricity grid.

Fig. 4 shows for July 1st (the day without space heating). The PV electricity starts to be generated from 5:00 to 19:00 h. Then, the PV-origin electricity easily covers the building energy consumption. After 18:00 h the energy consumption is not covered as the PV electricity is not generated.

In conclusion, these figures clearly show that the grid electricity helps to overcome parts of day without solar energy (PV electricity). In addition, it is clear that part of the day when the space heating starts to operate is critical part of the day for the electricity grid as there is the highest electricity demand and no solar electricity is available. Solar energy can help to the electricity grid during time when the sun is shining which is very important during summer when air conditioning is on due to intense heat.

5.2. The yearly energy distribution per different months

The monthly values for different types of electrical energy in the house are calculated and shown in Figs. 7–9. Fig. 7 shows the monthly values for different types of consumed and generated electrical energy in the third house with PV array. Fig. 8 shows

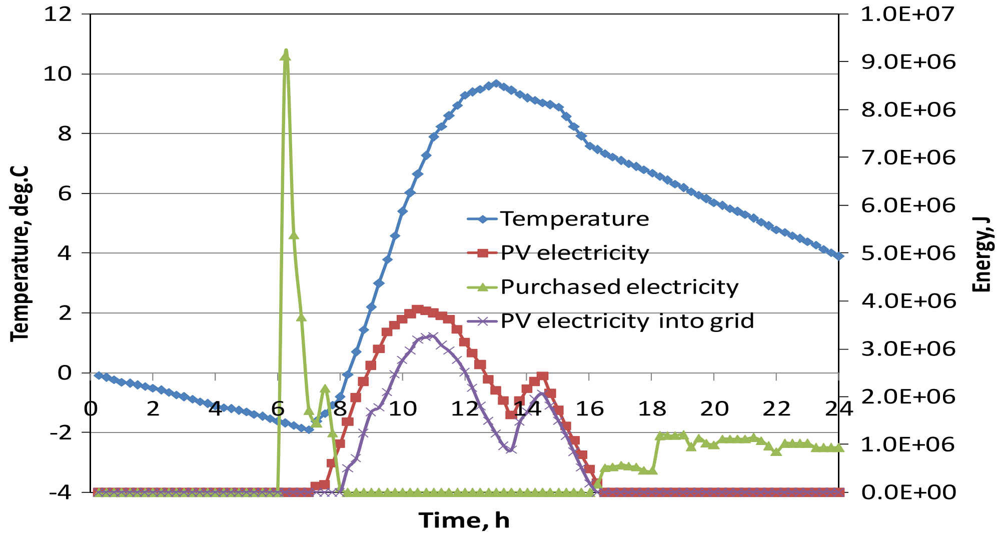

Fig. 5. Different types of electrical energy as a function of time for the third house. Simulation values are given for each 15 min on January 21st.

the monthly values of generated PV electrical energy for all three houses. Fig. 9 shows the monthly values for the electricity consumption covered by PV-origin electricity for all three investigated houses.

Fig. 7 shows the monthly values for different types of consumed and generated electrical energy. The consumed electrical energy shown are the total consumed energy by the house, electricity purchased by the building, and the electrical energy generated by the PV array, and the consumed electrical energy with PV-origin. This figure shows that high amount of energy is generated during summer that can be not entirely be used by the building. It can be sold to the electricity grid and used to satisfy energy consumption for lighting, and other needs in other buildings, where it will replace electrical energy obtained by power plants. However, the monthly amount of energy that is generated during winter months is almost two times smaller than that generated during summer months. The highest amount of electricity is generated in July and August. The lowest amount of electricity is generated in December when there is the highest monthly amount of electricity consumed by the house. In conclusion, the lowest amount of PV electricity is generated when there is the highest need for the electricity by building. The highest amount of electricity is generated when there is the lowest need for electricity by the building. Then, it is important that the electricity grid has other needs that need to be satisfied and consume the electricity generated by PV.

Fig. 8 shows the monthly values for the generated electrical energy by all three houses. The monthly amounts of the total electrical energy required by the building are also given for comparison. This figure shows that the lowest amount of electrical energy is generated by the first house. This house can cover the electricity consumption in months from May to September. The second house can cover electricity consumption from April to October, while the third house can do this from March to October. This means that the winter energy consumption in all houses cannot be covered directly by solar energy.

Fig. 9 shows the monthly values for the electricity consumption covered by PV-origin electricity in all three houses. The monthly amounts of the total electrical energy required by the houses are also given for comparison. For each month and each building, the PV electricity consumption is lower than the total electricity consumption. This is consequence of the fact that the both electrical energy consumption and PV electrical energy generation does not happen at the same time. The figure shows that during days with heating, the house with the larger PV array will cover the higher amounts of energy consumption by the PV-origin electricity. During days without heating, the amount of energy consumption

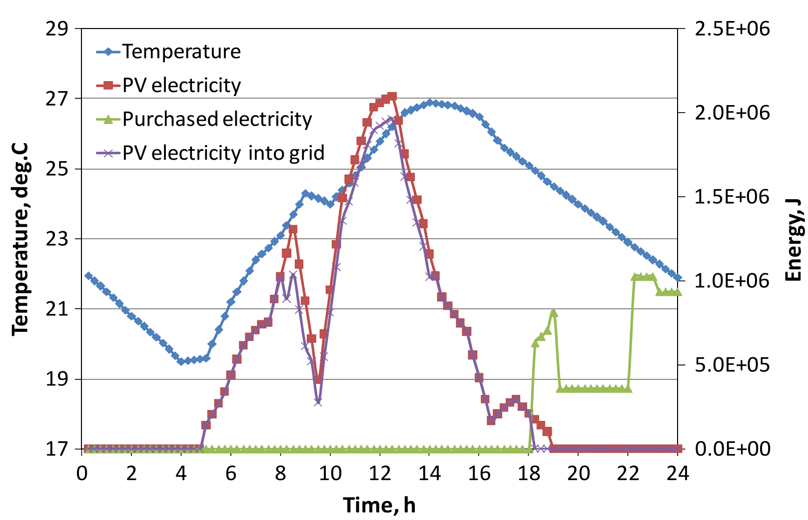

Fig. 6. Different types of electrical energy as a function of time for the third house. Simulation values are given for each 15 min on July 1st.

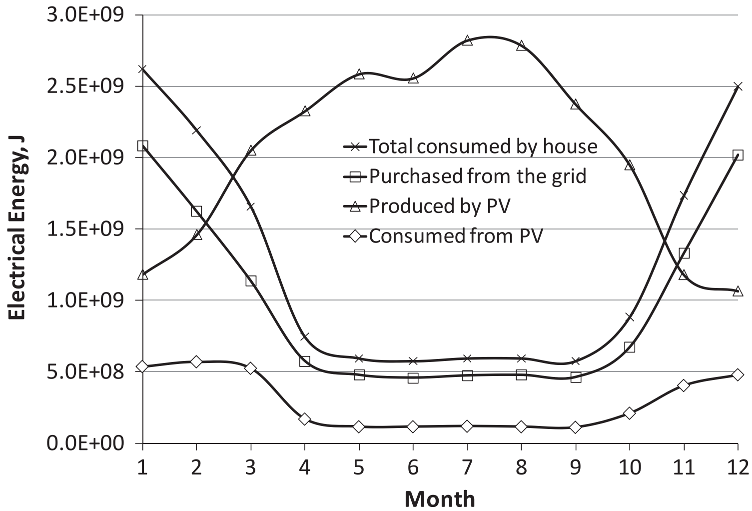

Fig. 7. Monthly values for different types of electrical energy for the third house.

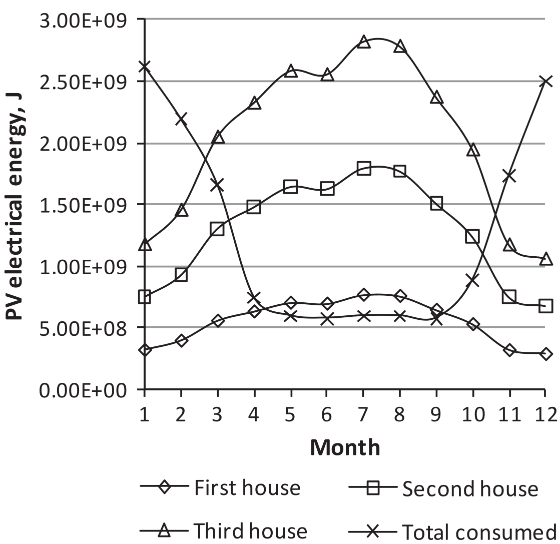

Fig. 8. Monthly values for the generated PV electrical energy by all three houses. The monthly values of the total electrical energy consumed by the houses are given for comparison.

covered by the PV-origin electricity does not depend on the size of the PV array.

5.3. Yearly energy balance

The total amount of electrical energy annually consumed by each house is $E_{T,Y} = 15.55$ GJ. The relative and absolute amounts of different types of this energy are shown in Fig. 10: for the space heating, for the lighting, and for other electrical equipment. The space heating consumes the largest amount of electrical energy of 54%. The lighting consumes somewhat around 23% of electrical energy. The other electrical equipment consumes around 23% of electrical energy. The other electrical equipment of this residence is appliances and DHW heating devices.

Different types of yearly electrical energy used in each house are shown in Fig. 11. The presented types of electrical energy are the following: the total electrical energy consumed by the house ($E_{T,Y} = 15.55$ GJ), the PV electrical energy consumed by the house ($E_{PV,B,Y}$), the PV electrical energy fed in the electricity grid that compensates the purchased electricity from the electricity grid ($E_{PV,G,G,Y}$), and the true surplus PV electrical energy fed in the

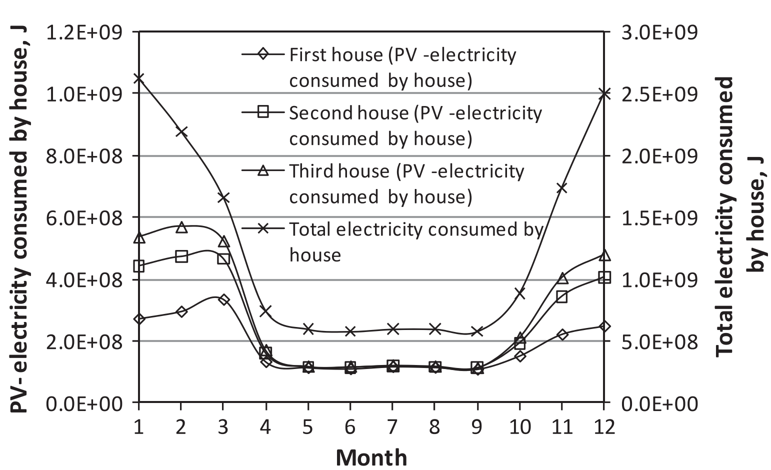

Fig. 9. Monthly values for the electricity consumption directly covered by PV-origin electricity by all three houses. The monthly amounts of the total electrical energy consumed by the houses are also given for comparison.

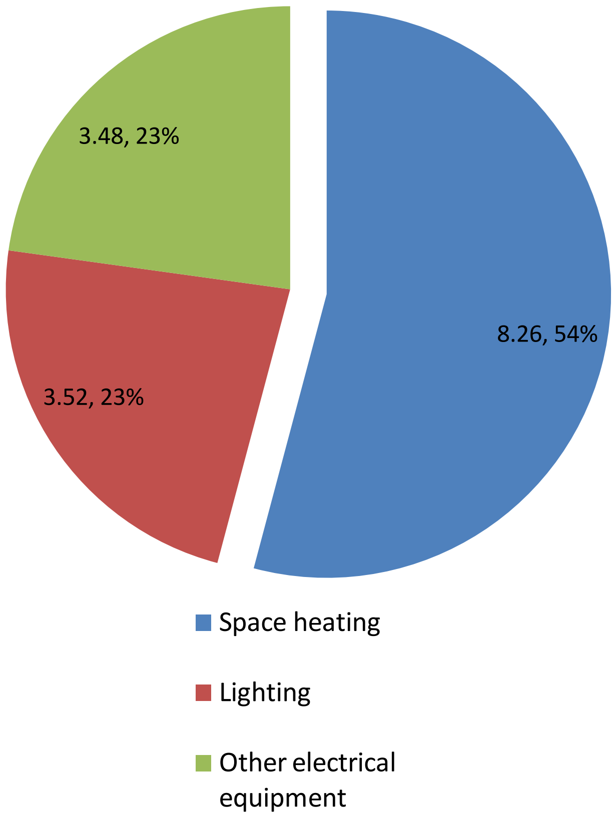

Fig. 10. Electrical energy (GJ/year) consumed in the houses: for space heating, for lighting, and by other electrical equipment. The other electrical equipment of this residence is appliances and DHW heating devices.

electricity grid ($E_{PV,G,S,Y}$). The total PV electrical energy generated by the house ($E_{PV,Y}$) is sum of $E_{PV,B,Y}$, $E_{PV,G,G,Y}$, and $E_{PV,G,S,Y}$.

The simulation results show that the first house (with the size of PV array of 14.5 m^2) is NNEB. The amount of the electrical energy generated by the PV system ($E_{PV,Y} = E_{PV,B,Y} + E_{PV,G,G,Y}$) is 7.5 GJ/year. This value is equivalent to the electrical energy consumed by the heat pump for space heating of the investigated house. Then, annually, $E_{PV,Y} < E_{T,Y}$. However, only around $E_{PV,B,Y}$ = 2.5 GJ/year of the electrical energy is consumed directly from the PV system by the heat pump. Around $E_{PV,G,Y}$ = 5 GJ/year of the PV-electricity is sold when there is an electricity surplus and then bought back to be consumed by the heat pump when there is an electricity shortage. $E_{PV,G,Y} = E_{PV,G,G,Y} < E_{G,Y}$, and $E_{PV,G,S,Y} = 0$.

For the second house (with the size of PV array of 29 m^2), the value for the PV generated energy is $E_{PV,B,Y} + E_{PV,G,G,Y}$ = 15.55 GJ/year. This value is equal to the energy consumption of the house ($E_{PV,Y} = E_{T,Y}$). This is ZNEB. Here, also around $E_{PV,B,Y}$ = 2.5 GJ/year is satisfied directly from the PV system, and additional energy of 13.05 GJ/year is generated by the PV system and sold to the electricity grid ($E_{PV,G,Y} = E_{G,Y}$, $E_{PV,G,G,Y} = E_{G,Y}$; $E_{PV,G,S,Y} = 0$).

For the third house (with the size of PV array of 45.6 m^2), the simulation results show that the PV array will provide more electricity than that needed for the entire house. This is PNEB. The PV generated energy is $E_{PV,B,Y} + E_{PV,G,G,Y} + E_{PV,G,S,Y}$ = 24 GJ/year – around 3.2 times more than that by the first house. Here, around 2.5 GJ/year is satisfied directly from the PV system, and additional energy of 21.5 GJ/year is generated by the PV system and sold to the electricity grid ($E_{PV,Y} > E_{T,Y}$, $E_{PV,G,G,Y} > E_{G,Y}$, and $E_{PV,G,G,Y} = E_{G,Y}$; $E_{PV,G,S,Y} > 0$).

To conclude, depending on the size of the PV array, the house will be either NNEB, or ZNEB or PNEB. The first house is NNEB. The second house is ZNEB. The third house is PNEB. This analysis show that the PV-origin electricity may annually consist of three parts: (1) PV electricity directly used by the house, (2) compensating electricity sold to the electricity grid (its amount is equal to that purchased by the house), and non-compensating electricity sold to the electricity grid. As the amount of solar electricity directly used by the house is always lower than the amount of electricity consumed by the building, it is crucial for such buildings to have access to the electricity grid or the storage battery.

5.4. Investment return

For three houses, the investment return PB is shown in Fig. 12 as a function of the feed-in price C_{PV} of produced PV electricity by the house, and the price of the PV array per unit of the rated power C_{array}. Here, the investigation is performed for two values of C_{array} for October 2010 taken from [28]. These values are the lowest

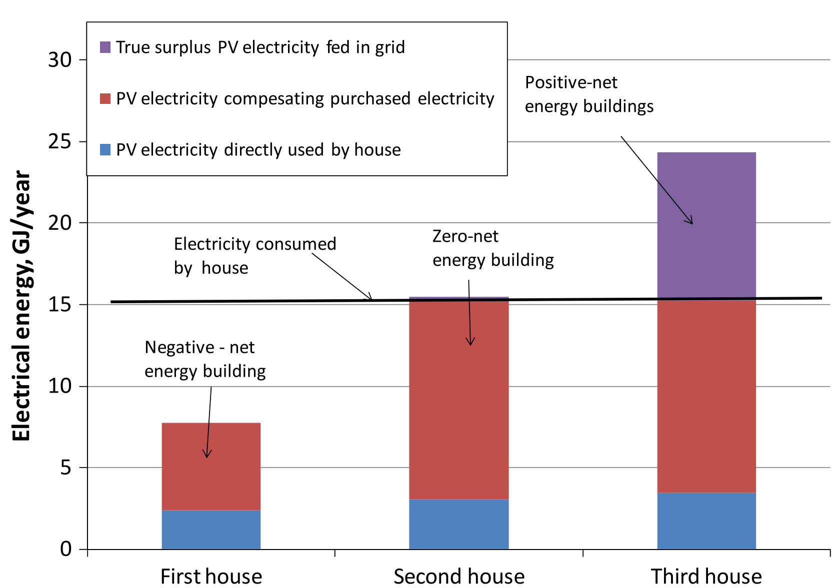

Fig. 11. Different types of electrical energy in the houses: the electrical energy consumed by the house, the PV electrical energy directly used in the house, the PV electrical energy compensating purchased electrical energy, and the true surplus PV electrical energy fed in the grid.

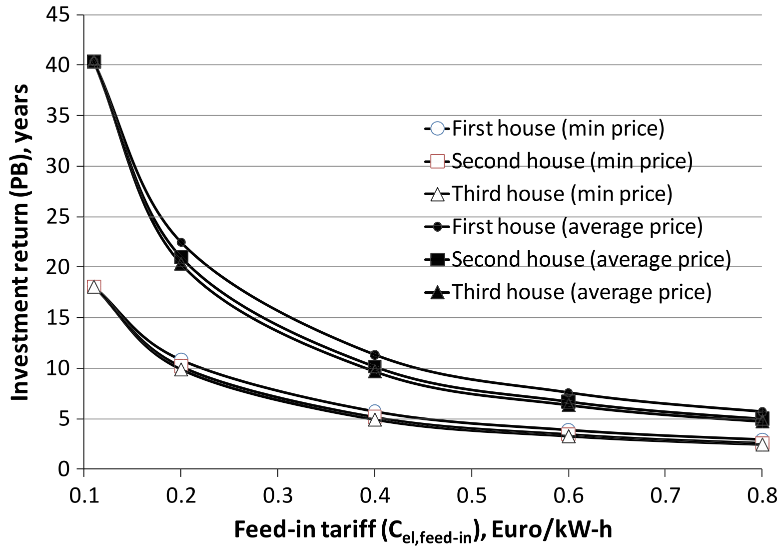

Fig. 12. The investment return of the PV system as a function of the produced electricity selling price.

C_{array} = 1.44 €/W_p and the average C_{array} = 3.2 €/W_p in the market. For the both cases, the average inverter price per the unit of the rated power ($C_{inverter}$ = 0.522 €/W_p) is used from [30].

This figure informs of the following: (1) When the investment return is equivalent to the life of the PV array of 30 years, the feed-in price for produced electricity has value around C_{PV} = 0.15 €/kW h for the average-priced array. When the array with minimum price is installed, PB is around 18 years without any feed-in tariff support. (2) For feed-in tariff in Serbia of C_{PV} = 0.23 €/kW h, the investment return is in the range of 9–20 years depending on the unit price of the PV array, which is not promising for penetration of such a technology in country. For the feed-in tariff of around C_{PV} = 0.6 €/kW h, PB is around 3–7 years. (3)The investment return depends also on the size of the PV array. The larger size of the PV array up to 15% may give the smaller PB for up to 15%. To conclude, the smaller PB will be obtained for higher feed-in tariff, and smaller unit price and larger size of the PV array. For better economy, it may be recommended for ZNEB to go toward PNEB. To achieve this, the energy consumption in such buildings has to be decreased to minimum and entire size of the roof should be used for installation of PV panels. The feed-in tariff for solar electricity in Serbia is not promising for penetration of this technology, however this might be completely changed according to the real market prices of PV array.

6. Conclusion

This article reports the simulation analyses of yearly operation of a low and solar energy house located in Kragujevac, Serbia. To drive its energy equipment and devices, the house uses electricity from its PV array with the electricity grid as the PV-electricity storage. Its heating system employs GCHP with the vertical ground heat exchanger and floor heaters. Three houses are investigated. In the first house, its PV system yearly produces only electricity needed by the heating system. The second house has the PV system that yearly produces all electricity that the house needs. The third house has the PV array that covers the entire south-facing roof area. Then, the PV system produces more electrical energy than the house consumes. By using the model of the system and software EnergyPlus, the investigations gave time step (15 min), monthly, yearly results on energy for these systems.

Daily energy distribution clearly showed that the grid electricity helps to overcome parts of day without solar energy (PV electricity). The part of the day when the space heating starts to operate is critical part of the day for the electricity grid as there is the highest demand for electricity and no solar electricity is available. The PV electricity can help to the electricity grid during time when the sun is shining which is very important during summer when air conditioning is on due to intense heat.

The monthly amounts of electrical energy generated by PV during winter are almost two times smaller than that during summer. During winter, the larger PV array will cover the higher amounts of the electrical energy consumption. During summer, the size of PV array will not influence the amount of energy consumption covered by the PV-origin electricity. The entire energy consumption in summer and winter cannot be directly covered by solar energy with any of the PV arrays that are investigated.

Depending on the size of the PV array, the house will be either NNEB, or ZNEB or PNEB. The first house is NNEB. The second house is ZNEB. The third house is PNEB. This analysis show that the PV-origin electricity may annually consist of three parts: (1) electricity directly used by the house, (2) compensating electricity sold to the electricity grid (its amount is equal to that purchased by the house), and non-compensating electricity sold to the electricity grid. As the amount of solar electricity directly used by the house is always lower than the amount of electricity consumed by the house, it is crucial for such houses to have access to the electricity grid or storage battery.

The smaller PB will be obtained for higher feed-in tariff, and smaller unit price and larger size of the PV array.

For better economy, it may be recommended for ZNEB to go toward PNEB. To achieve this, the energy consumption in such houses has to be decreased to minimum and entire size of the roof should be used for installation of PV panels. The feed-in tariff for solar electricity in Serbia is promising, however this might be completely changed according to the real market prices of PV array. The feed-in tariff for the generation of electricity in Serbia should be under the constant watch to be corrected accordingly for larger penetration of technology in the market.

References

[1] http://www.ssllink.com/mre/cms/mestoZaUploadFajlove/ENERGETSKI_BILANS_PLAN_ZA_2008.pdf [retrieved 18.05.09].

[2] http://www.biogasmax.eu/media/biogas_as_vehicle_fuel_ in_the_stockholm_region_master_thesis__ellen_martensso__096426600_1216_24092007.pdf [retrieved 04.07.09].

[3] Obradović D. Feed-in tariffs introduced in Serbia via regulation on promoting power generation from renewable. Energetika.net, 24th November; 2009. http://www.energetika.net/eu/iskanje?search=Dragan+Obradović,+Belgrade [retrieved 09.05.10].

[4] Badescu V. First and second law analysis of a solar assisted heat pump based heating system. Energy Convers Manage 2002;43:2539–52.

[5] Bakker M, Zondag HA, Elswijk MJ, Strootman KJ, Jong MJM. Performance and costs of a roof-sized PV/thermal array combined with a ground coupled heat pump. Sol Energy 2005;78:331–9.

[6] Citherlet S, Defaux T. Energy and environmental comparison of three variants of a family house during its whole life span. Build Environ 2007;42:591–8.

[7] Giljamse W. Zero energy houses in Netherlands. In: Beckman WA, Mitchell JW, editors. Proceedings of building simulation '95, the fourth conference at the international building performance simulation association. Madison, Wisconsin: IBPSA; 1995. p. 276–83.

[8] Llovera J, Potau X, Medrano M, Cabeza L. Design and performance of energy-efficient solar residential house in Andorra. Appl Energy 2010;88: 1343–53.

[9] Aste N, Adhikari R, Buzzetti M. Beyond the EPBD: the low energy residential settlement Borgo Solare. Appl Energy 2010;87(2):629–42. doi:10.1016/j.apenergy.2009.05.02. ISSN:0306-2619.

[10] Athienitis AK. Design of a solar home with BIPV-thermal system and ground source heat pump. In: 2nd Canadian solar buildings conference. Calgary; 2007.

[11] Biaou AL, Bernier MA. Achieving total domestic hot water production with renewable energy. Build Environ 2008;43:651–60.

[12] Leckner M, Zmeureanu R. Life cycle cost and energy analysis of a Net Zero Energy House with solar combisystem. Appl Energy 2011;88(1):232–41. doi:10.1016/j.apenergy.2010.07.03. ISSN:0306-2619.

[13] Norton P, Christensen C. A cold-climate case study for affordable zero energy homes. In: Solar 2006 conference, Denver, Colorado; July 9–13, 2006.

[14] Hamada Y, Nakamura M, Ochifuji K, Nagano K, Yokoyama S. Field performance on a Japanese low energy home relaying on renewable energy. Energy Build 2001;33:805–14.

[15] Chel A, Tiwari GN. Thermal performance and embodied energy analysis of a passive house – case study of vault roof mud-house in India. Appl Energy 2009;86(10):1956–69. doi:10.1016/j.apenergy.2008.12.03. ISSN:0306-2619.

[16] Immobilier Bouygues. Bouygues Immobilier launches first large positive-energy building. The Green Office project in Meudon; 25 October, 2007. <http://www.bouygues-immobilier.com/jahia/Jahia/lang/en/aboutus/espace_de_presse/pid/2407> [retrieved 02.09.10].

[17] Bouygues-construction, First positive-energy building; 2009. <http://www.bouygues-construction.com/667i/sustainable-development/news/first-positive-energy-building.html> [retrieved 02.09.10].

[18] Trotter C. Positive energy building in Masdar, Abu Dhabi. 03/06/08, <http://inhabitat.com/2008/03/06/world's-first-positive-energy-building-planned-for-masdar/retrived> [02.09.10].

[19] Bojić M, Nikolić N. Use of solar energy for operation of compressor heat pump. Report of center for heating, air conditioning, and solar energy. Faculty of Mechanical Engineering at Kragujevac, University of Kragujevac; 2009 ((in Serbian)).

[20] Crawley D, Lawrie L, Winkelmann F, Buhl W, Huang JY, Pedersen C, et al. EnergyPlus: creating a new-generation building energy simulation program. Energy Build 2001;33:443.

[21] Henninger R, Witte M, Crawley D. Analytical and comparative testing of EnergyPlus using IEA HVAC BESTEST E100–E200 test suite. Energy Build 2004;36:855–63.

[22] Tronchin L, Fabbri K. A round Robin test for buildings energy performance in Italy. Energy Build 2010;42:1862–∗1877.

[23] Manz H, Loutzenhiser P, Frank T, Strachan PA, Bundi R, Maxwell G. Series of experiment for empirical validation of solar gain modeling in building energy codes – experimental setup, test cell, characterization, specifications and uncertainty analyses. Build Environ 2006;41:1784–97.

[24] Lawrence Berkeley National Laboratory. EnergyPlus engineering document: the reference to EnergyPlus calculations. Bekeley: LBL; 2001.

[25] Lawrence Berkeley National Laboratory. EnergyPlus input output reference: the encyclopaedic reference to EnergyPlus input and output. Berkely: LBL; 2001.

[26] Meteonorm. Global meteorological database for engineers. Planners and education. <http://www.meteonorm.com> [retrieved 05.12.10].

[27] Shell Solar. Shell S115 photovoltaic solar module. <http://www.ameinders.nl/ShellSolarS115.pdf> [retrieved 01.10.10].

[28] http://www.solarbuzz.com/ModulePrices.htm [retrieved 01.10.10].

[29] Chel A, Tiwari GN, Chandra A. Simplified method of sizing and life cycle cost assessment of building integrated photovoltaic system. Energy Build 2009;41:1172–80.

[30] http://www.solarbuzz.com/Inverterprices.htm [retrieved 01.10.10].