AIP | Journal of Renewable and Sustainable Energy

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Citation: J. Renewable Sustainable Energy **5**, 041819 (2013); doi: 10.1063/1.4817809
View online: http://dx.doi.org/10.1063/1.4817809
View Table of Contents: http://jrse.aip.org/resource/1/JRSEBH/v5/i4
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JOURNAL OF RENEWABLE AND SUSTAINABLE ENERGY **5**, 041819 (2013)

Optimization of photovoltaics panels area at Serbian zero-net energy building

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(Received 7 February 2013; accepted 23 July 2013; published online 8 August 2013)

In this study, the possibilities to decrease energy consumption of a residential building in Serbian conditions are analyzed. The building uses electricity for space heating system, heating of domestic hot water, lighting, and for other electric equipment. The electrical energy is generated by photovoltaics (PV) system and it may be consumed by the building or may be fed-in to the electricity grid. The major aim of the optimization of PV area is to determine the avoided electricity from the grid (avoided exergy), and to minimize the consumption of primary energy. The residential buildings with variable thermal insulation thickness, hot water consumption, life time, and PV's embodied energy are investigated, in order to achieve zero-net energy building or positive-net energy building. The buildings are presented by a mathematical model, in EnergyPlus environment. Open Studio plug-in in Google SketchUp was used for building virtual design, Hooke-Jeeves algorithm for optimization, and GENOPT software for software execution control. For the different areas of photovoltaics, the investigations gave the results for their optimal values. In that way, the fossil energy consumption and CO_2 emission are also minimized. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4817809]

I. INTRODUCTION

Nowadays, the research and development of renewable energy resources and the use of renewable energy is essential, because the renewable energy systems have a significant impact on the environment. The reserves of oil and gas, at current rates of consumption, would be adequate for another 40 and 60 yr, respectively, and the reserves for coal could be adequate for at least the next 250 yr.[1] Also, the problem is the global warming and increasing problem of greenhouse gases and air pollution. The "TRIPLE 20" goal for 2020, in the EU countries aims to reduce greenhouse gas emissions and energy consumption by 20% and simultaneously incorporate 20% renewable energy into energy consumption.

Photovoltaic (PV) energy conversion is one of the more promising renewable energy technologies which contribute significantly to a sustainable energy supply and which may help to mitigate greenhouse gas emissions.[2] PV energy conversion represents the direct conversion of sunlight into electricity. A PV generation system consists of multiple components such as PV cells, mechanical and electrical connections and mountings. Commercial PV materials commonly used for photovoltaic systems include solar cells of multi-crystalline-silicon (mc-Si), single-crystalline-silicon (sc-Si), amorphous-silicon (a-Si), cadmium-telluride (CdTe), copper-indium-diselenide (CIS) and of other thin layer materials.[3–5] The PV systems are still an expensive option for producing electricity compared to other energy sources. But many countries support this technology. Over the last five years, the global PV industry has grown more than 40% each year.[6]

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Kapsalaki[7] says that a radical approach for the mitigation of the energy demand is the concept of the zero-net energy building (ZNEB). By definition, ZNEB produces all energy it consumes during year, i.e., yearly electrical energy supplied to the electricity grid balances the amount received from the electricity grid. Positive-net energy building (PNEB) produces more energy than it consumes during year, i.e., yearly electrical energy supplied to the electricity grid is higher than the amount received from the electricity grid. Negative-net energy building (NNEB) produces less energy than it consumes during year—yearly electrical energy supplied to the electricity grid is lower than the amount received from the grid.[8,9]

In this paper, the energy consumption is analyzed for a residential building located in Kragujevac, Serbia. The building is designed with PV panels installed on the roof—Figure 1. Electricity generated by the PV array is limited by the size of PV array.

In buildings, energy is used for space heating and cooling, domestic hot water (DHW) heating, lighting, and electric equipment. The analyzed building has an electrical space heating system. The PV system can generate more or less electricity than the amount of electricity needed for the entire building. When the PV system would not directly satisfy the building needs for electrical energy, then the rest of electricity will be used from the electricity grid. When the PV system would satisfy the building needs for electrical energy, then the rest of the PV generated electricity will be fed-in the electricity grid. For water heating in the DHW system, the electrical energy produced by the PV modules will be used.

The major aim of this investigation is to determine the portion of PV panels on the roof in order to minimize the consumption of primary energy. The primary energy refers to energy required to generate and deliver the electricity by grid to the site.

In this paper, the EnergyPlus, Open Studio plug-in in Google SketchUp, Hooke-Jeeves algorithm, and Genopt were used. To calculate the total primary energy, the imported and exported energy is multiplied by the appropriate site-to-source conversion multipliers. For the presented building, the energy consumption and electricity generation will be discussed in this paper.

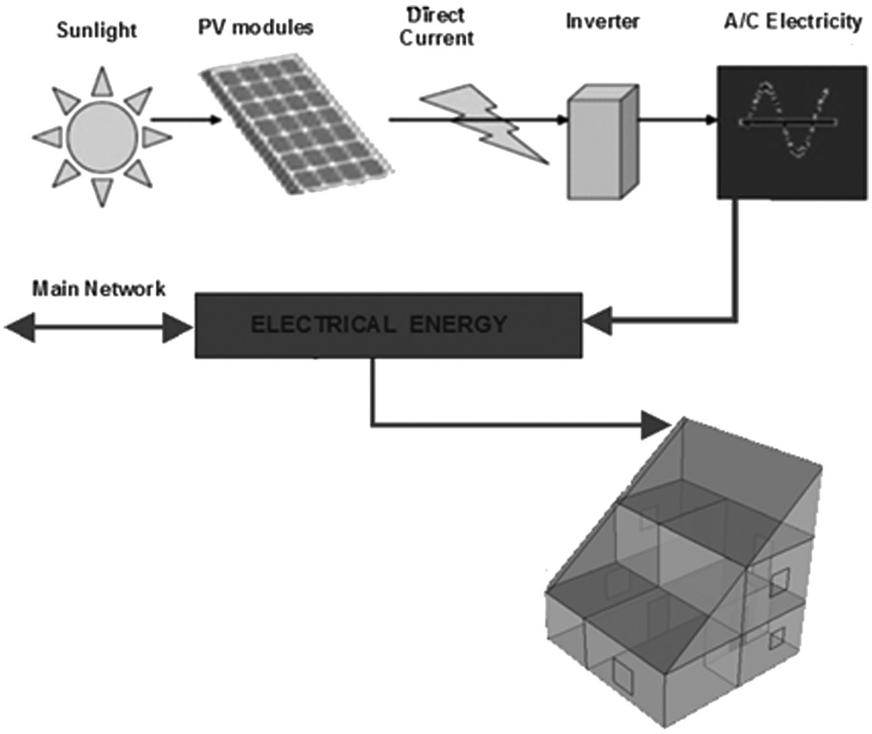

FIG. 1. Positive-net energy building with PV module.

II. SIMULATION SOFTWARES AND CLIMATE

In this paper, simulations and optimizations are performed by three softwares. The EnergyPlus software is used for simulations, OpenStudio plug-in in Google SketchUp for the building virtual design, and GenOpt software with the Hooke-Jeeves algorithm for the optimization.

A. Simulation software—EnergyPlus

The EnergyPlus software may be used for simulation of heating, cooling, ventilating, lighting, and other energy and mass flows in the buildings.[10] Also, EnergyPlus can simulate the energy use in a building and energy behavior of the building for defined period. In this study, the building energy simulation software EnergyPlus (version 7.0.0) was used. EnergyPlus is made available by the Lawrence Berkley Laboratory in USA.[11] EnergyPlus has its roots in BLAST (Building Loads Analysis and System Thermodynamics) and DOE-2 programs. Both of these packages, BLAST and DOE-2, were developed and released in the late seventies and early eighties of the twentieth century, as tools for thermal and energy simulations. This software simulates the building energy behavior and use of renewable energy in buildings. The renewable energy simulation capabilities include solar and photovoltaic simulation. Other simulation features of EnergyPlus are the user defined input and output data structures, the user-configurable modular systems and the variable time steps. The software is intensively validated and has been tested using the IEA HVAC BESTEST E100-E200 series of tests.[12] For PV electricity generation, software EnergyPlus uses the different component, such as PV array and inverter.[13]

B. Open studio plug-in in Google SketchUp software

Google SketchUp is a free 3D software tool that combines a tool-set with an intelligent drawing system.[14] The software enables to place models using real world coordinates. Most people get rolling with SketchUp in just a few minutes. There are dozens of video tutorials, an extensive Help Centre and a worldwide user community.

The OpenStudio is free plug-in that adds the building energy simulation capabilities of EnergyPlus to the 3D SketchUp environment. The software allows to the user to create, edit, and view EnergyPlus input files within SketchUp. The plug-in uses the standard tools provided by SketchUp. The software adds as much extra detail as the user needs to zones and surfaces. The plug-in allows the easily creation a building geometry from scratch: add zones, draw heat transfer surfaces, draw windows and doors, draw shading surfaces, etc. The users can save what they have drawn as an EnergyPlus input file. The plug-in also allows users to launch EnergyPlus simulations and view the results from within SketchUp.

C. Simulation software—GenOpt

GenOpt is an optimization program for the minimization of a cost function evaluated by an external simulation program.[15] GenOpt serves for optimization problems where the cost function is computationally expensive and its derivatives are not available or may not even exist. GenOpt can be coupled to any simulation program that reads its input from text files and writes its output to text files. The independent variables can be continuous variables (possibly with lower and upper bounds), discrete variables, or both, continuous and discrete variables. Constraints on dependent variables can be implemented using penalty or barrier functions. GenOpt is written in Java so that it is platform independent. GenOpt is applicable to a wide range of optimization problems. GenOpt has a library with adaptive Hooke-Jeeves algorithm.

D. Optimization Hooke–Jeeves algorithm

Hooke- Jeeves algorithm is used for the optimization. It is direct search and derivative free optimization algorithm.[16–18] In Hooke Jeeves algorithm, only the objective functions and the constraint values are used to guide the search strategy. In this research, the adaptive precision

Hooke Jeeves algorithm is used. Compared to the fixed precision Hooke Jeeves algorithm, the adaptive precision Hooke Jeeves algorithms have a test that controls the precision of the approximating cost functions. The test causes the optimization algorithms to use coarse approximations to the cost function in the early iterations and too progressively increase the precision of the approximating cost functions as the sequence of iterates approaches a stationary point. Another difference between the adaptive Hooke and Jeeves algorithms and the fixed precision Hooke Jeeves algorithms is that the adaptive algorithms can be parameterized so that they only accept iterates that reduce the cost sufficiently. The main advantage of adaptive precision control algorithm is reducing the computation time.

E. Climate

In this paper, the building is analyzed that is located in Kragujevac, Serbia. The latitude of Kragujevac is 44.1 °N, and the longitude is 20.55°E. The time zone is GMT + 1.0 h. The citizens of Kragujevac have worm and humid summers with temperatures as high as 37 °C. The winters are cool, with snow and with temperatures as low as −19 °C.[8] Figure 2 represents some Energyplus weather data for Kragujevac.

The EnergyPlus software uses weather data from its own data base with weather files. In EnergyPlus, the input object includes parameters that allow EnergyPlus to calculate the solar position (using Latitude, Longitude, and Timezone) for any day of the year as well as supply the standard barometric pressure (using elevation). Weather files have hourly or sub-hourly data for each of the critical elements needed during the calculations (i.e., Dry-Bulb Temperature, Dew-Point Temperature, Relative Humidity, Barometric Pressure, Direct Normal Radiation, Diffuse Horizontal Radiation, Total & Opaque Sky Cover, Wind Direction, Wind Speed) as well as some auxiliary data such as Rain or Snow.

III. MATHEMATICAL MODEL

The mathematical model for the simulation of electric energy generation by PV arrays and energy behavior of the modeled building is developed inside EnergyPlus's environment.

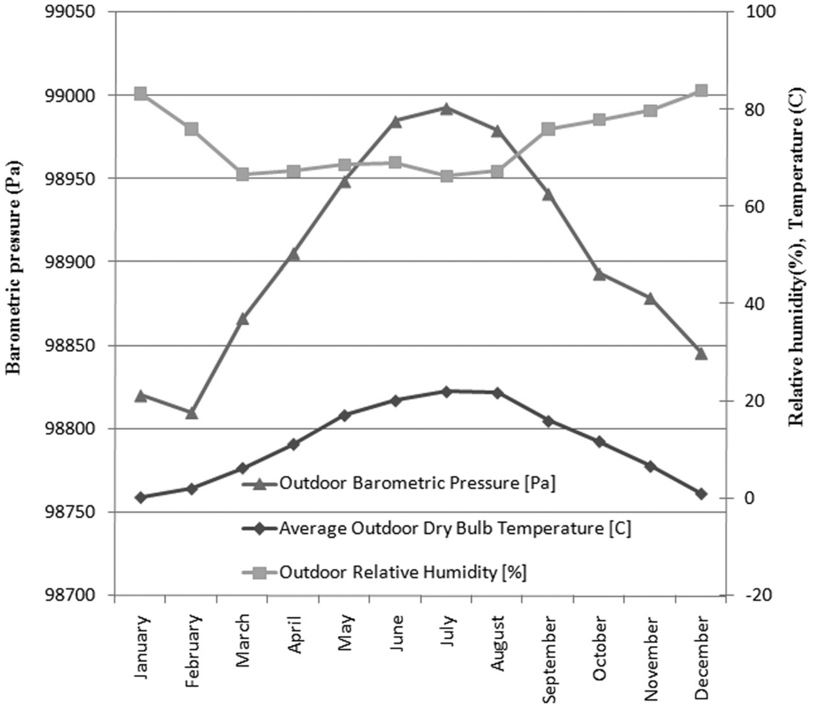

FIG. 2. Barometric pressure, relative humidity and outdoor dry bulb temperature for Kragujevac, Serbia, from weather file.

A. EnergyPlus model for the residential building

The investigated building is shown in Figure 3. The building has the south-oriented roof with the slope of 37.5°. This is not a typical, common house in the Eastern Europe, but it is chosen because it was found that the optimal value of the roof angle (and PV panel slope) is 37.5°.[19] On the roof, the PV array is installed. The building has two floors. On the first floor, there are a large living room, bedroom, and bathroom, while on the second floor, there are two bedrooms. Also, there are two attic zones. It is assumed that the building accommodates a family of four members. It is also assumed that the house is not surrounded with any object. The entire building has 5 conditioned (heated) zones.

The modeled house has the total floor area of $160\,\mathrm{m}^2$ and the total volume of conditioned zones of $264.64\,\mathrm{m}^3$. The roof has the total area $80.6\,\mathrm{m}^2$. The windows are double glazed, with the total area of $12.44\,\mathrm{m}^2$ and U-value $= 2.72\,\mathrm{W/(m^2K)}$. The concrete building envelope is insulated by stiropore. The U-values for the building envelope are in the range from $0.132\,\mathrm{W/(m^2K)}$ to $1.862\,\mathrm{W/(m^2K)}$. In the investigations presented in this paper, the thermal insulation thickness is varied in order to vary the building energy consumptions.

The operation period of the space heating systems is from October 15th to April 14th (07:00–21:00 h). The air temperatures in the heated rooms are set to 20 °C at from 07:00 to 09:00 and from 16:00 to 21:00. From 09:00 to 16:00 (when the occupants is not at the building), the air temperatures in the rooms are put to 15 °C. The simulation time step is 15 min. The amount of infiltration is 1.5 ach^{-1}. The building has a monthly hot water consumption of $10\,\mathrm{m}^3$.

B. Electrical energy consumption

The largest amount of electrical energy is consumed by electrical space heating in the building. The second amount is consumed for DHW system, and the other two parts of electrical energy are related to the lighting and electrical appliances in building such as refrigerator, freezer, dishwasher, cloth washer, toaster, vacuum cleaner, TV, hair dryer, and computer.

The total electrical energy consumption $E_{\mathrm{T,Y}}$ is electrical energy that is annually consumed to satisfy energy needs of the occupants. $E_{\mathrm{T,Y}}$ is divided into three parts regarding a mode of electricity consumption: (1) the electrical energy for space heating of the house $E_{\mathrm{T,H,Y}}$, (2) the electrical energy for DHW heating $E_{\mathrm{T,HW,Y}}$, (3) the electrical energy for lighting of the house $E_{\mathrm{T,L,Y}}$, and (4) the electrical energy for other electrical equipment $E_{\mathrm{T,O,Y}}$

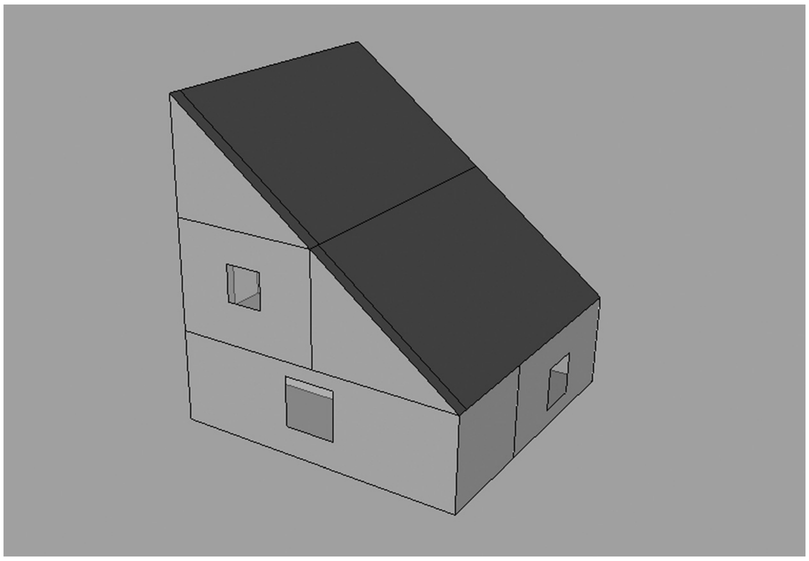

FIG. 3. Modeled residential building.

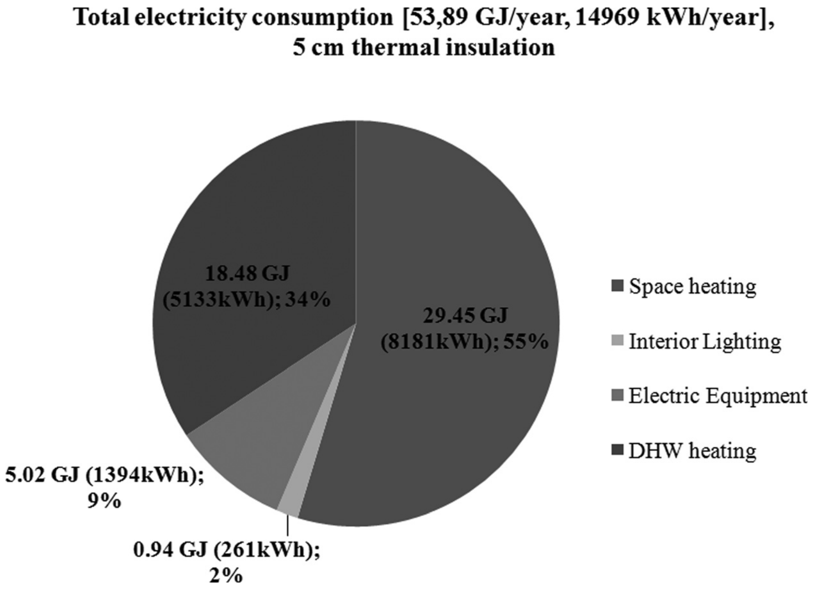

FIG. 4. Total energy consumption for the building with 5 cm thermal insulation thickness.

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

The pies with the total energy consumption for the buildings with 5 cm, 10 cm, and 15 cm thermal insulation thickness are given in Figures 4–6.

C. Mathematical modeling of PV system

The PV system consists of a PV array and an inverter. The operations of the PV array and the heating system are together simulated by using EnergyPlus. The system would run during entire year. The life time of PV array is set to 20 yr and the embodied energy of PV panels is set to 3.75 GJ/m^2.[2,4]

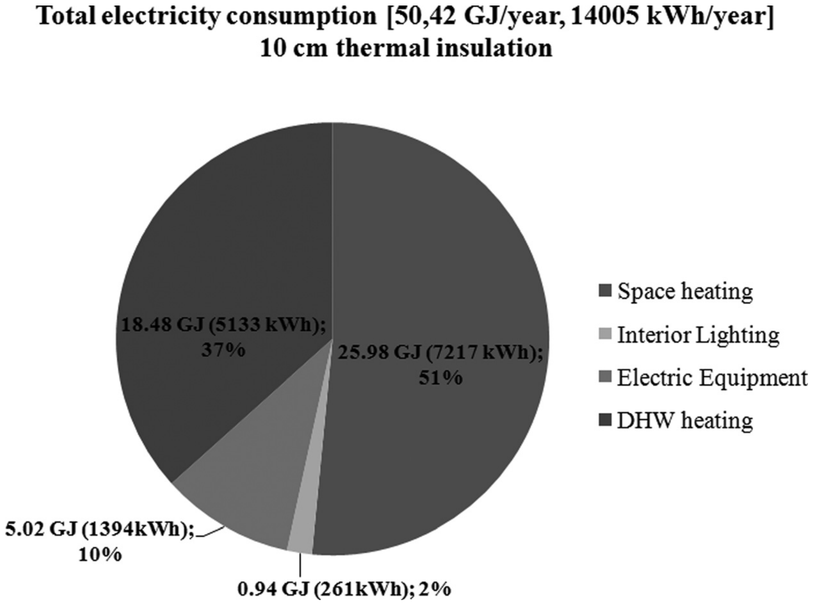

FIG. 5. Total energy consumption for the building with 10 cm thermal insulation thickness.

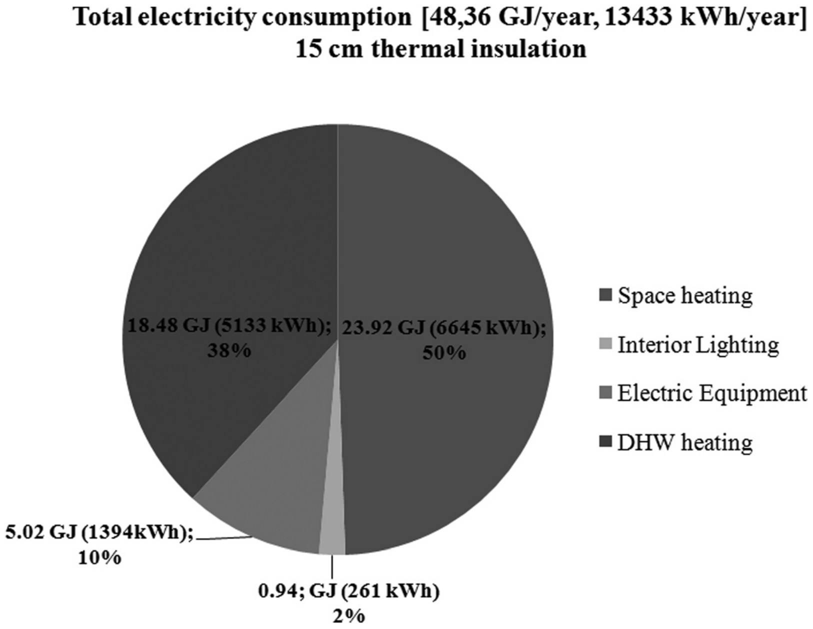

FIG. 6. Total energy consumption for the building with 15 cm thermal insulation thickness.

The PV array panels are put at the south direction roof under the slope of 37.5°. The main assumption is that when the PV system operates, all generated electrical energy will be immediately consumed.

EnergyPlus offers different options for predicting the amount of electricity produced by solar PV panels. In this paper, the operation of PV panel is represented by the mathematical model of Photovoltaic:Simple from EnergyPlus,[11] which allows the user to input an arbitrary efficiency. The PhotovoltaicPerformance:Simple object describes a simple model of photovoltaic that may be useful for early phase design analysis. The generator is connected to an Electric Load Center. The PV models refer to surface objects defined elsewhere in the input file. This PV object describes an PV array that is "attached" to a surface object in order to describe its orientation and to access results of the solar insolation calculations. This will define the orientation of the solar panel for the detailed models and also the area for the simple model. The exposure of that surface to the incident solar radiation is calculated using the full set of models in EnergyPlus, which are used to account for solar thermal loads arising from building windows and walls. Therefore, the incident solar radiation is calculated to include the effects of shading and reflections from other surfaces declared in the input file. In addition to the output variables associated with PV models, there are numerous related output variables available for the surfaces.

The electricity production is metered based on the output of the inverter.

Output results are available before and after the inverter. One assumption is that the PV array is assumed to be always operating at the maximum power point. The energy production is based on the assumption that the quasi-steady power prediction is constant and continuous over the simulation timestep.

The model predictions are closely related to the solar radiation data in the EnergyPlus weather file.

The Generator:PV:Simple object represents the simplest model to predict photovoltaic energy production. In this model, the user specifies the efficiency with which the PV array converts the incident solar radiation to electricity. (In the other models, this efficiency is an output of the model.) The full geometric model for solar radiation is used, including sky models, shading, and reflections, to determine the incident solar resource. The model accepts arbitrary conversion efficiencies and does not require actual production units be tested to obtain empirical performance coefficients. This model is intended to be useful for design purposes to quickly get an idea of the levels for annual production and peak power.

The usable electrical power produced by a PV surface is calculated as

$$P = A_{\mathrm{surf}} \cdot f_{\mathrm{activ}} \cdot G_{\mathrm{T}} \cdot \eta_{\mathrm{cell}} \cdot \eta_{\mathrm{invert}}, \tag{2}$$

where G_{T} represents the total solar radiation incident on PV array (W/m^2).

On the right-hand side of this equation, only G_{T} is calculated by EnergyPlus and the rest are user inputs. The power levels are assumed constant over the timestep to arrive at energy production.

To determine the temperature of the PV panel, the "decoupled" method was used. The model of the PV panel is developed under the assumption that it operates at its maximum power. The inverter is selected with maximum efficiency.

The outputs of EnergyPlus for PV are the total electrical energy consumption of the building ($E_{\mathrm{T,Y}}$), the electrical energy generated by the PV panel (E_{PV}), electrical energy generated by the PV array and fed in the electricity grid ($E_{\mathrm{PV,S}}$), the electrical energy purchased by the building from the grid (E_{P}), the electrical energy purchased by the building from the grid without electrical energy generated by the PV array and fed in the electricity grid ($E_{\mathrm{P,NET}}$), and the electrical energy generated by the PV array and immediately used by the building ($E_{\mathrm{PV,B}}$) (Figure 7). All these values are computed for one year, so the index Y is put. They also can be calculated for each day or month, during the entire year.

EnergyPlus calculates the electrical energy generated by the PV - E_{PV}. As the electricity is the pure exergy, it can be said that EnergyPlus calculates the avoided exergy consumption E_{AE} by using the PV array. This is the avoided electricity (avoided exergy), i.e., $E_{\mathrm{AE}} = E_{\mathrm{PV}}$. This means that buildings needs for electricity (exergy) may be covered by using the electricity (avoided exergy) generated by the PV array, based on the fact that exergy is replaced by the solar-origin electricity.

IV. SIMULATION AND OPTIMIZATION

A. Optimization procedure

In this investigation, the optimization was performed with the aim to determine the optimal value of the PV array area, according to the buildings energy needs. In this way, the total

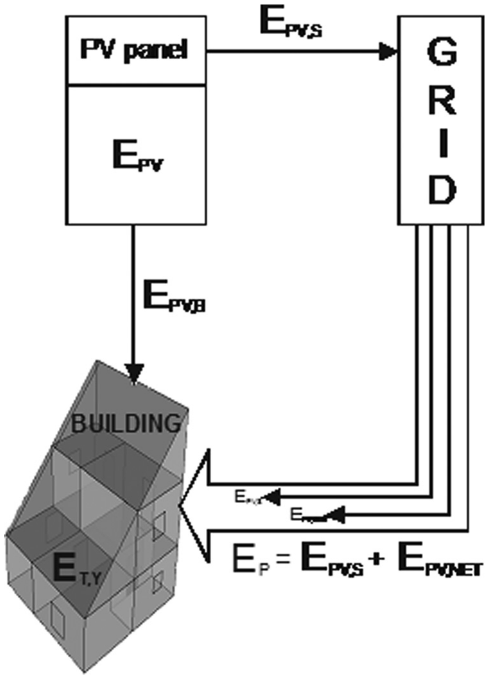

FIG. 7. PV produced electricity, electricity consumption, and purchased electricity.

energy consumption of the building, i.e., the primary energy consumption, can be minimized. The value of the PV panel portion in the roof is marked by *y*. With this optimization, also, the primary energy saving of the PV panels is maximized. The objective function in optimization process is the yearly primary energy saving ($E_{\text{S-final,PV}}$).[20] The value of the primary energy saving is divided into two parts: the energy generated by PVs (E_{PV}) and the embodied energy of PV panels ($E_{\text{em,PV}}$).

The primary energy refers to the primary energy required to generate and deliver the energy to the site. To calculate the total primary energy, the imported energy and the exported energy are multiplied by the appropriate site-to-source conversion multiplier (P_{PV}). For this calculation, 3.04 was used for the fossil energy equivalent for electrical energy.[20,21]

The following equation is used as the objective function:

$$E_{S-final,PV} = p_{PV}E_{PV} - C_m E_{em,PV}, \tag{3}$$

where $C_{\text{m}} = 1/LC$ and LC is life time, in years.

B. Embodied energy and life cycle of PV panels

Alsema *et al.*,[2,4] report that the earlier investigations for the energy requirement of present-day crystalline silicon modules vary considerably: between 2400 and 7600 MJ/m^2 for mc-Si technology and between 5300 and 16 500 MJ/m^2 for sc-Si technology. The efficiencies are 13% for mc-Si modules and 14%, respectively, for sc-Si modules.

Sanchez[22] also reports that the total energy requirements of a frameless a-Si module are in the range from 710 to 1980 MJ/m^2, while their module efficiency is 7%.

Based upon the Alsemas investigations, Bankier and Gale[23] give the literature review for energy requirements and efficiencies of PV panels. The results are given for a frameless module and a module with Al frame, supports and inverter - Table I.

Alsema[4] reports that the average life time of the PV modules is 30 years. Bankier and Gale[22] showed that the PV panels have the life time of 25 - 30 years.

V. RESULTS AND DISCUSSION

The residential building in Kragujevac, Serbia, is investigated. The building has the PV array on its roof. As we can see in Figures 4–6, the most part of energy requirement is for electrical space heating and for the heating of DHW. The electrical energy for electrical equipment and lighting in the house is consumed during entire year according to their own schedules.

The simulation results are the 15 min values for the electricity consumed by the building, the electricity purchased by the building, the electricity produced by the PV array, the electricity generated by the PV array and used by the building, and the electricity generated by the PV array and fed in the electricity grid. These values are obtained and recorded during entire year and they depend on value y—a part of PV panel area on the roof.

Based on these results, we analyze the total yearly building generated energy and yearly building energy requirements, in order to achieve ZNEB or PNEB.

TABLE I. Embodied energy and module efficiency of PV modules found by Alsema.

Module type	Embodied energy of PV module (MJ/m^2)	Embodied energy of PV module with frame (Al), supports, and inverter (MJ/m^2)	Module efficiency (%)
mc-Si	4200	5400	13
Sc-Si	5700	6900	14
Thin Film	1200	2400	7

TABLE II. Energy consumption, generated electrical energy by PV, and generated thermal energy by solar collectors with different thermal insulation thickness (yearly values).

Thermal insulation thickness	0.05 m	0.1 m	0.15 m
Total electricity consumption	53.89 GJ (14969 kWh)	50.42 GJ (14006 kWh)	48.36GJ (13433 kWh)
Total generated electricity	48.48GJ (13467 kWh)	48.48 GJ (13467 kWh)	48.48 GJ (13467 kWh)
Portion of PV panels on the roof	0.92	0.92	0.92
$E_{S\text{-final}}$ – primary energy saving	35.69 GJ (9913 kWh)	35.69 GJ (9913 kWh)	35.69 GJ (9913 kWh)

A. Different thermal insulation thickness and optimization of PV panel area

The building operation is simulated during the entire year. The thermal insulation thickness is varied in order to achieve ZNEB. The presented results are the total yearly energy consumption of the building, the yearly generated PV electricity (avoided exergy), the portion of PV panels on the roof (in percents) and total primary energy saving.

The first case is the building with 0.05 m thermal insulation thickness. The second case is the building with 0.10 m thermal insulation thickness and the third case is the building with 0.15 m thermal insulation thickness. Results are in Table II.

Graphical presentation of total electricity consumption and total generated electricity is given in Figure 8. This figure show that the building with 0.15 m thermal insulation thickness is very close to ZNEB, but it is PNEB. All energy requirements of this building are covered from the PV array (which is at 92% of the roof, i.e., 74.15 m^2). This PV array provides more electricity than that is needed by the entire house. In that case, the PV array can sell the electricity to the grid.

The portion of PV panel is the same for all three analyzed cases ($y = 0.92$).

The total electrical energy consumption decreases when the thermal insulation thickness increases—the space heating energy decreases because of smaller heat losses through the building walls. The yearly primary energy saving $E_{S\text{-final}}$ is the same in all cases, because the portions of PV panel is the same 0.92, and the yearly total generated electrical energy (avoided exergy) is the same, 48.48 GJ.

If the thermal insulation thickness is lower than 0.15 m, the building will be NNEB, because its energy consumption can't be satisfied by the electricity generated by the PV panels. In that case, the building has to buy the electricity from the grid.

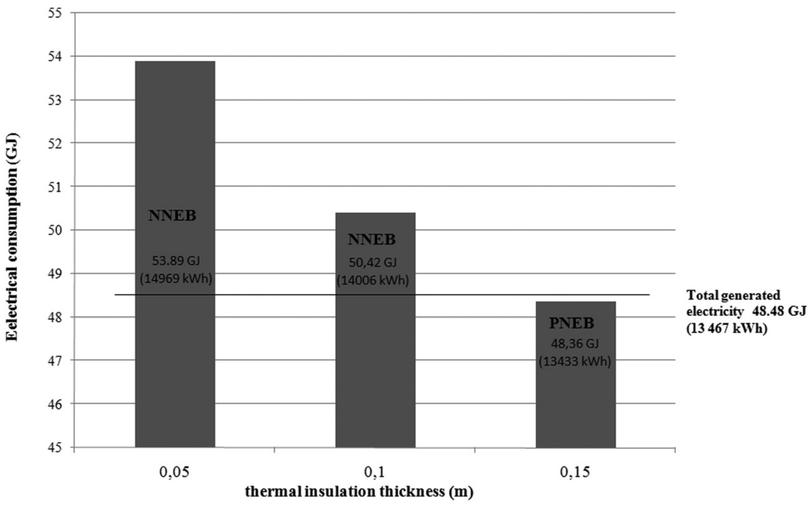

FIG. 8. Electrical energy consumption and total generated energy by PV panels (yearly values), for different thermal insulation thickness.

TABLE III. Energy consumption, generated electrical energy by PV array, portion of PV panels and primary energy saving with different hot water consumption (Yearly values).

Hot water consumption	7.5 m^3	10 m^3	15 m^3	20 m^3
Total electric energy consumption	46.29 GJ (12858 kWh)	48.36 GJ (13433 kWh)	52.13 GJ (14481 kWh)	54.86 GJ (15239 kWh)
Total generated PV electricity	47.33GJ (13147 kWh)	48.48 GJ (13467 kWh)	50.27 GJ (13964 kWh)	52.7 GJ (14639 kWh)
Portion of PV panel (-)	0.9	0.92	0.954	1
Primary energy saving	37.36 GJ (10378 kWh) PNEB	35.69 GJ (9913 kWh) PNEB	34.56 GJ (9600 kWh) NNEB	32.87 GJ (9131 kWh) NNEB

B. Different hot water consumption and optimization of PV panel area

In the next investigation the building operation is simulated changing the hot water consumption. The PNEB is investigated, so the thermal insulation thickness is 0.15 m. The previous monthly hot water consumption is 10 m^3. The hot water consumption is changed, and analyzed cases are with monthly hot water consumptions of 7.5 m^3, 15 m^3, and 20 m^3. The presented results are the following: the total yearly building energy consumption, the yearly generated PV electricity (avoided exergy), the portion of PV panels (in percents), and total primary energy saving, and they are shown in Table III.

From Figure 9, it can be seen that the buildings with the lower hot water consumption (7.5 and 10 m^3) are PNEBs. In that cases, PV array generates total electrical energy (avoided exergy) of 47.33 GJ (13147 kWh) and 48.48 GJ (13467 kWh), respectively. That is more than energy requirements of these buildings of 46.29 GJ (12858 kWh) and 48.36 GJ (13433 kWh), respectively. The surplus of produced energy is sold by the PV array to the grid. In this case, portions of PV panel on the roof are 90% and 92%, respectively (see Figure 10).

The building with hot water consumption of 10 m^3 is approximately the ZNEB. All energy requirements of this building are covered from the PV array (which has 92% of the roof, i.e., 74.15 m^2).

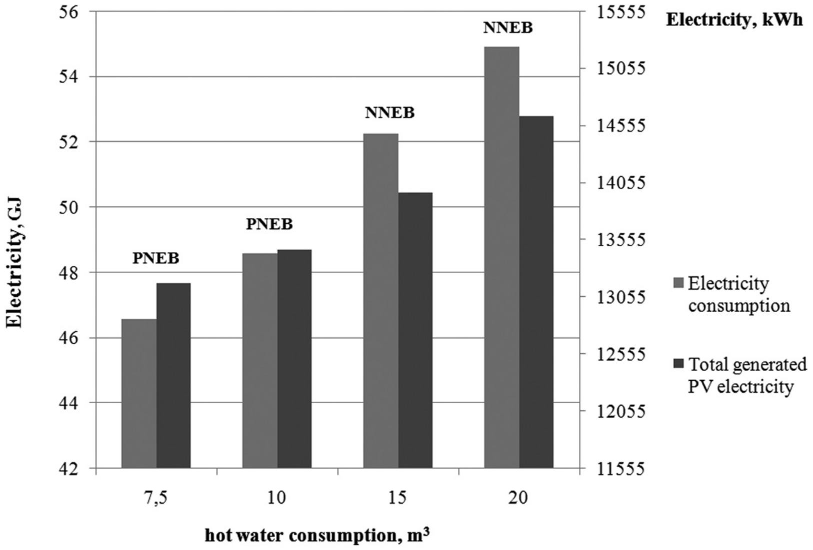

FIG. 9. Electricity consumption and total generated electricity by PV arrays (yearly values), for different hot water consumption.

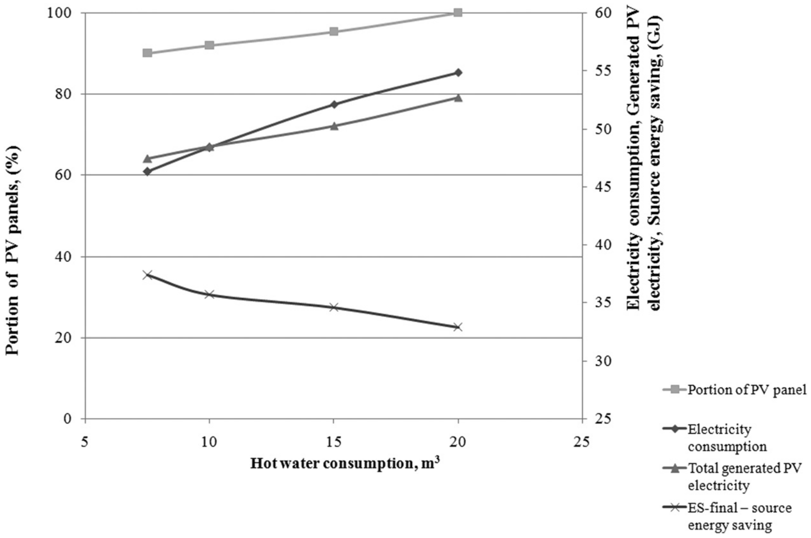

FIG. 10. Electrical energy consumption, total generated PV electricity and PV panel portion for different hot water consumption.

When the hot water consumptions of the building are 15 m^3 and 20 m^3, the investigated building would be NNEB. The total energy consumption of these buildings can't be satisfied by the PV panel electricity generation and the building has to buy electricity from the grid. In these cases, the portion of PV panel is smaller.

It can be concluded that in all cases, with the increase of hot water consumption, the portion of PV panels and the total energy consumption enlarge also. With the increase in hot water consumption, the yearly primary energy saving reduces, because of the increase in the portion of PV panels.

As it can be seen, with the changing of hot water consumption, from 7.5 m^3 to 20 m^3, the portion of PV panels on the roof has changed from 0.9 to 1, and the yearly primary energy saving would decline. The values of the yearly primary energy saving in these cases are 37.36 GJ (10378 kWh) and 32.87 GJ (9131 kWh), respectively. These results confirm the validity of the presented optimization procedure and the objective function.

C. Different life time of PV array

All previous analyses were with the same life time of PV panels of 20 yr. A change in the life time will give the same portion of PV panels, but different values of yearly primary energy saving. For PNEB with thermal insulation thickness of 0.15 m and hot water consumption of 10 m^3, from previous investigation, Table IV and Figure 11 represent some results for different life time.

TABLE IV. Energy consumption, generated electrical energy by PV array, portion of PV panels and primary energy savings with different life time of PV array (yearly values).

PV life time	15 yr	20 yr	25 yr	30 yr
Total energy consumption	48.36 GJ (13433 kWh)	48.36 GJ (13433 kWh)	48.36 GJ (13433 kWh)	48.36 GJ (13433 kWh)
Total generated energy	48.48 GJ (13467 kWh)	48.48 GJ (13467 kWh)	48.48 GJ (13467 kWh)	48.48 GJ (13467 kWh)
Portion of PV panel (-)	0.92	0.92	0.92	0.92
Primary energy saving	29.67 GJ (8242 kWh)	35.69 GJ (9913 kWh)	37.37 GJ (10381 kWh)	39.22 GJ (10894 kWh)

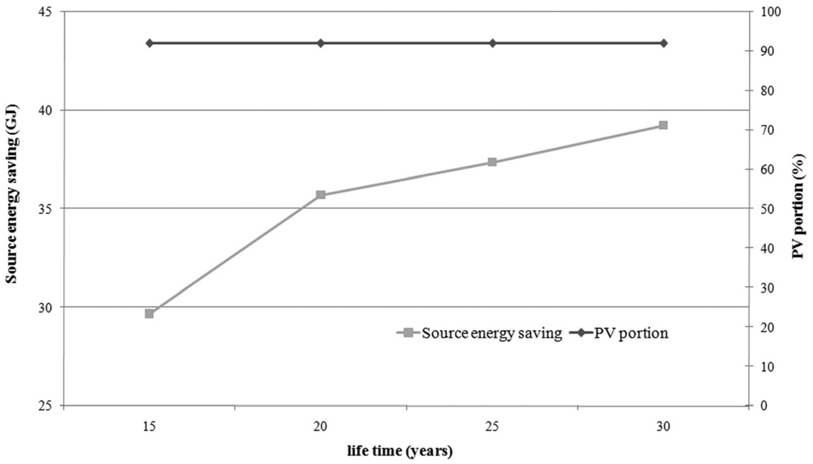

FIG. 11. Primary energy saving (yearly values), and portion of PV panel for different life time of PV array.

The obtained results show that with increasing the life time of the PV array, the primary energy saving increases too.

D. Different embodied energy for different types of PV array

The embodied energy of the PV arrays in all the previous analyses was 3.75 GJ/m^2. This value is chosen, because it is the mean value of embodied energy of a thin-film PV module and a mc-Si PV module.[2,4] The embodied energy for mc-Si PV module with support, frame, and inverter is 5.4 GJ/m^2. The embodied energy for sc-Si PV module with support, frame, and inverter is 6.9 GJ/m^2, and for a-Si module it is about 2.4 GJ/m^2.

PNEB is analysed with the thermal insulation thickness of 0.15 m, the PV modules life time of 20 years, and the hot water consumption of 10 m^3 (from previous investigation). Table V, and Figures 12 and 13 represent the results for different embodied energy of PV arrays.

As it can be seen, when the embodied energy of PV array increases, the primary energy saving decreases, and the portion of PV panels on the roof also decreases lightly.

The major objective of this investigation is to maximize the primary energy saving. In these cases, when the embodied energy in PV is larger than 3.75 GJ/m^2, for the investigated buildings, the PV array can't generate the electricity to cover the whole building needs, so that buildings are NNEBs.

E. Different electricity consumption in building

To confirm the validity of the presented model, additional investigations are made. In these tests, the buildings electricity consumption, as one of the main parameters of the study, is varied (Figure 14).

TABLE V. Yearly energy consumption, generated electrical energy by PV and portion of PV panels with different PV embodied energy (yearly values).

PV embodied energy	2.4 GJ/m^2	3.75 GJ/m^2	5.4 GJ/m^2	6.9 GJ/m^2
Total energy consumption	48.36 GJ	48.36 GJ	48.36 GJ	48.36 GJ
	(13433 kWh)	(13433 kWh)	(13433 kWh)	(13433 kWh)
Total generated energy	48.48 GJ	48.48 GJ	48.27 GJ	48.06 GJ
	(13467 kWh)	(13467 kWh)	(13467 kWh)	(13467 kWh)
	0.92	0.92	0.916	0.912
Portion of PV panel	39,28 GJ	35,69 GJ	28,34 GJ	22,78 GJ
Primary energy saving	(10911 kWh)	(9913 kWh)	(7872 kWh)	(6328 kWh)

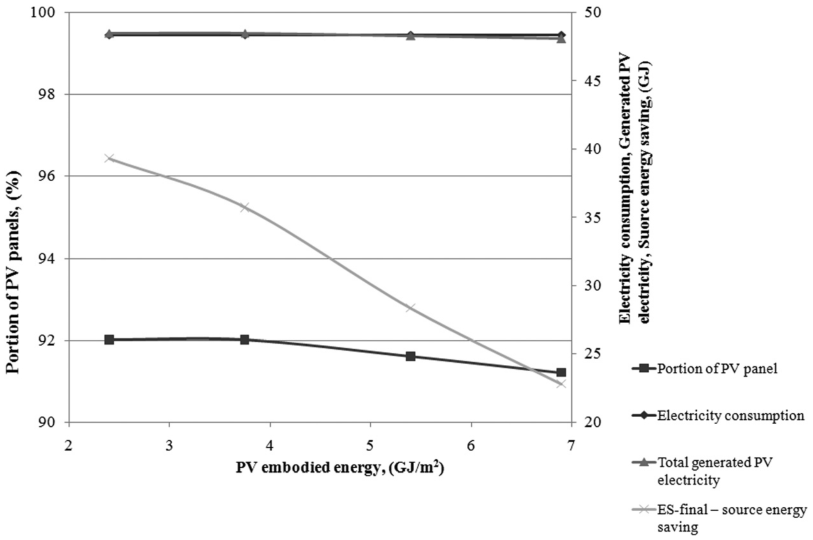

FIG. 12. Electricity consumption, generated PV electricity, primary energy saving (yearly values in GJ) and portion of PV panel for different PV embodied energy.

In case 1, the considered building has the thermal insulation of 0.15 m thickness, the hot water consumption of 10 m^3/month, and the total yearly electricity consumption of 48.36 GJ (13433 kWh) (see Figure 6). Then, the distribution of the yearly electricity consumption is the following: water system 18.48 GJ (5133 kWh), space heating system 23.92 GJ (6645 kWh), electric equipment 5.02 GJ (1394 kWh), and lighting 0.94 GJ (261 kWh). With the optimization procedure, the portion of PV panels on the roof was 0.92 and the yearly primary energy saving 35.69 GJ (9913 kWh) (see Table III).

In case 2, the considered building had the same insulation thickness and hot water consumption as that in case 1, but higher electricity consumption by electric equipment (7.4 GJ, i.e., 2056 kWh), and lighting (1.96 GJ, i.e., 544 kWh). Then, the yearly value of electricity consumption of this building was 51.76 GJ (14378 kWh).

The results for the both of cases are shown in Table VI.

The optimization procedure gave $y = 0.974$ as the optimal value for the portion of PV panels on the roof and the yearly primary energy saving of 33.78 GJ (9383 kWh). The both of

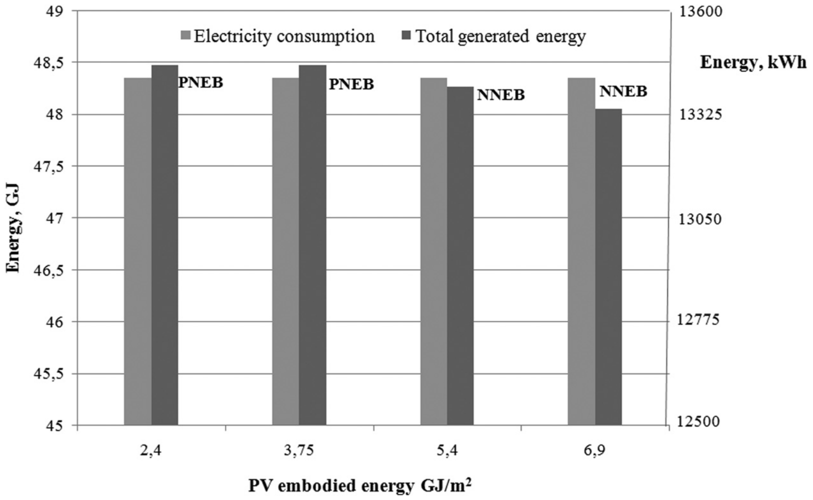

FIG. 13. Electricity consumption and total generated PV electricity (yearly values in GJ) for different PV embodied energy.

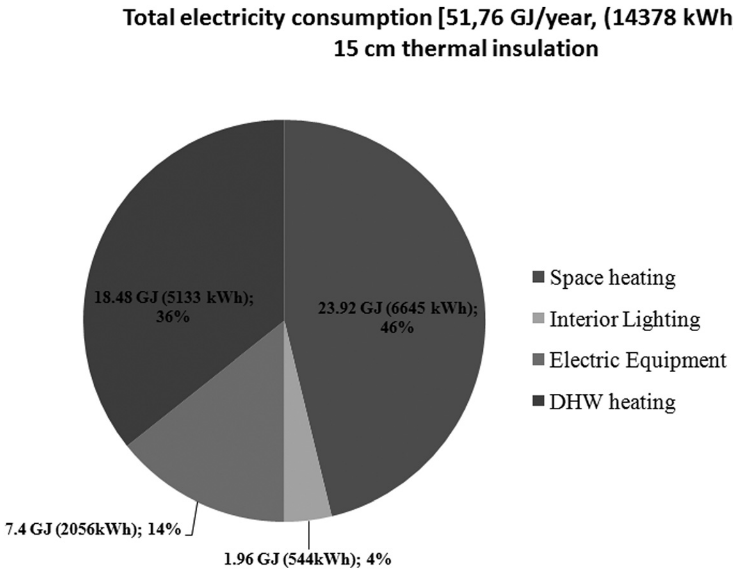

FIG. 14. Electricity consumption for the building with the higher yearly electricity consumption of electrical equipment and lighting.

TABLE VI. The results of energy consumption, generated electrical energy by PV array, portion of PV panels, and primary energy savings at the same building with different consumption of electricity (yearly values).

Case	1	2
Total electric energy consumption	48.36 GJ	51.76 GJ
	13433 kWh	14378 kWh
Total generated PV electricity	48.48 GJ	51.44 GJ
	13467 kWh	14289 kWh
Portion of PV panel (-)	0.92	0.974
Primary energy saving	35.69 GJ	33.78 GJ
	9913 kWh	9383 kWh
	PNEB	PNEB

buildings were PNEBs. With the obtained results, it can be concluded that the model and optimization routine are valid for further investigations.

VI. CONCLUSION

This paper reports the investigation in low energy Serbian house optimization. The major aim of the optimization procedure in this paper was to determine the optimal value of the PV array (installed on the roof which is south facing, with the slope at 37.5°) for electricity generation (avoided exergy consumption), and, at the same time, achieving the maximal primary energy saving. Also, the aim was to achieve the ZNEB or PNEB concept for this building.

The building was located in Kragujevac, Serbia. The PV array generated either lower or higher amount of electricity than that needed for the entire building. When the PV system would not directly satisfy the building needs for electrical energy, then the rest of electricity will be used from the electricity grid. When the PV system would satisfy the building needs for electrical energy, then the rest of PV generated electricity will be fed-in the electricity grid. In building, the energy is used for space heating, space cooling, DHW heating, lighting, and electric equipment. The analyzed building has an electrical space heating system.

Depending on the size of the PV array, the house will be either NNEB, or ZNEB, or PNEB. The investigation shows that if we change the thermal insulation thickness of the building, we can achieve ZNEB or PNEB. For the thermal insulation thickness of 0.15 m, the building is PNEB. Then, the PV array will provide more electricity than that needed for the entire house. If the thermal insulation thickness is lower than 0.15 m, the building will be NNEB.

Depending on the amount of the hot water consumption, different portion of the PV panel is needed. With an increase in the hot water consumption, the portion of PV panel would also increase. The results show that when the portion of PV panels increases, the primary energy saving would decrease. PNEB is the building with the hot water consumption of 10 m^3 and less. All energy requirements of this building are covered from the PV array. For the hot water consumption higher than 10 m^3, the building is NNEB.

With the increase in the life time of the PV modules, the portion of PV panels would remain the same, with different values of the yearly primary energy saving. The obtained results show, in that case, that the primary energy saving would increase.

The buildings with different types of PV array are investigated. They have different amounts of embodied energy in their PV arrays. Then, with an increase in the embodied energy of PV array, the primary energy saving would decrease, and the portion of PV panels on the roof would also slightly decrease. In the analyzed cases, when the PV's embodied energy is higher than 3.75 GJ/m^2, the PV array can't generate the electrical energy for the whole building needs, so these buildings are NNEBs.

Also, the same buildings with different electricity consumptions are investigated. They have had different amounts of electricity consumption of electrical equipment and lightening. The conclusion is that with the increases of electricity consumption, portion of PV panels is increasing too, and primary energy saving is decreasing.

Further investigation could be area optimization of PV panels and solar collectors for domestic hot water heating. Then, the primary energy saving will be greater than with the building with PV modules, only. Also, the economical benefit would be greater because the higher values of produced electricity which is not consumed in the building. That amount of produced electricity will be fed-in the electricity grid.

ACKNOWLEDGMENTS

This paper is a result of three projects: TR33015 supported by the Ministry of Science and Technological Development of Republic of Serbia, KNEP supported by the Center for Scientific Research of the Serbian Academy of Sciences and Arts and University of Kragujevac, and Cost action TU1205-BISTS supported by EU. The authors thank all institutions for their financial support.

NOMENCLATURE

P	Electrical power produced by PV (W)
A_{surf}	Net area of surface (m^2)
f_{activ}	Fraction of surface area with active solar cells (-)
η_{cell}	Module conversion efficiency (-)
η_{invert}	DC to AC conversion efficiency (-)
$E_{\mathrm{S\text{-}final,\ PV}}$	Yearly primary energy saving, by PV array (J)
P_{PV}	Site-to-source conversion multipliers (J of fossil energy/ J of electricity)
E_{PV}	Yearly electrical energy generated by PV array (J)
$E_{\mathrm{em,PV}}$	PV array embodied energy (J)
C_{m}	Life time constant ($C_m=1/LC$)
LC	Life time (yr)
y	Ratio between PV panel area and roof area (-)
$E_{\mathrm{T,Y}}$	Total yearly electrical energy consumption (J)
$E_{\mathrm{T,H,Y}}$	Yearly amount of electrical energy for space heating (J)
$E_{\mathrm{T,HW,Y}}$	Yearly amount of electrical energy for DHW heating (J)

$E_{T,LY}$	Yearly amount of electrical energy for lighting (J)
$E_{T,O,Y}$	Yearly amount of electrical energy for other electrical equipment (J)
E_{AE}	Avoided exergy consumption (J)
$E_{PV,S}$	Electrical energy generated by PV array and fed in the electricity grid (J)
E_P	Electrical energy purchased by the building from the grid (J)
$E_{P,NET}$	Electrical energy purchased by the building from the grid without electrical energy generated by the PV array and fed in the electricity grid (J)
$E_{PV,B}$	Electricity generated by the PV array and immediately used by the building, (J)

Indices

PV	photovoltaic array
surf	surface
active	active solar cells
T	total
cell	solar cells
invert	inverter
y	yearly
em	embodied energy
s-final	primary energy
AE	avoided exergy
NET	net
B	building
H	heating
L	lighting
O	other electric equipment

Abbreviations

PV	photovoltaic
PNEB	Positive-Net Energy Building
ZNEB	Zero-Net Energy Building
NNEB	Negative-Net Energy Building
DHW	Domestic hot water
mc-Si	multi-crystalline Silicium
sc-Si	single-crystalline Silicium
a-Si	amorphous Silicium

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