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Exergy efficiency optimization of photovoltaic and solar collectors' area in buildings with different heating systems

D. Nikolic [a, *], J. Skerlic [b], J. Radulovic [a], A. Miskovic [c], R. Tamasauskas [d], J. Sadauskienė [e]

[a] University of Kragujevac, Faculty of Engineering, Sestre Janjic 6, 34 000, Kragujevac, Serbia
[b] Faculty of Technical Sciences, University of Pristina Temporarily Settled in Kosovska Mitrovica, Knjaza Milosa 7, 38220, Kosovska Mitrovica, Serbia
[c] Academy of Professional Studies Sumadija, Department in Kragujevac, Kosovska 8, 34000, Kragujevac, Serbia
[d] JSC "Planuotojai", Vasario 16-osios str. 8-6, LT-44250 Kaunas, Lithuania
[e] Kaunas University of Technology, Faculty of Civil Engineering and Architecture, Studentų st. 48, LT - 51367, Kaunas, Lithuania

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ABSTRACT

Exergy as a measure of useful work can be used in the design, simulation and performance evaluation of different energy systems. In this paper it is investigated the Serbian residential building with photovoltaics and solar collectors on the roof, and with three different heating systems: electrical heating, district heating and central heating with gas boiler. Exergy optimization was performed with the aim to determine the optimal area of the PV array and solar collectors on the roof (including embodied exergy). With these values, the maximum exergy efficiency of installed solar systems is obtained, and building primary energy consumption is minimized. The residential buildings with variable temperature in domestic hot water system, variable PV cell efficiency and variable hot water consumption are investigated in order to achieve positive-net energy building. The buildings were simulated in EnergyPlus software and Genopt was used for software execution control during optimization. The obtained results show that positive-net energy building with optimally sized photovoltaics and solar collectors', can be achieved in a case of gas heating system, and in the cases of PV cell efficiency of 14% and 16%. Also, an environmental and economic analysis of the most favourable solutions from exergetic optimization was performed. Total CO_2 emission (with embedded emissions of CO_2) increases with increasing amount of generated energy – for PV system of cell efficiency of 12%, 14% and 16%, total CO_2 emission of solar systems is 20.8 kg CO_2/m^2, 23.5 kg CO_2/m^2 and 26.2 kg CO_2/m^2, respectively. The emission payback time decreases with increasing PV cell efficiency from 1.11 to 1.04 years. With the increase of PV cell efficiency, there is an increase in the annual financial profit (from 1518 to 4305 €), while at the same time, the investment payback period decreases (from 16.9 to 6.1 years). Best results are obtained for the building with gas heating system.

1. Introduction

Energy performances of different systems are evaluated usually with the energy balance. But, in recent years, it has been concluded that energy analyses are insufficient for the evaluation of energy performance, so the exergy concept has gained considerable interest in the analysis of thermal processes. Exergy analysis, based on the Second law of thermodynamics, quantifies the loss of efficiency in a process, which is the result of the losses in quality of energy [1].

At the other side, at a time of growing energy needs in the world and the reduction of fossil fuel reserves, solar energy is the most acceptable alternative energy source, due to its inexhaustibility, low environmental pollution and developed and affordable technologies for its use - for electricity production and for water heating. As buildings are large energy consumers, where up to 50% of the total energy consumption refers to space heating [2] and about 20% to sanitary water heating [3], the simultaneous usage of photovoltaic systems and solar collectors represents a great opportunity for reducing energy consumption in the residential buildings. Proper dimensioning of solar systems is of great importance for achieving the highest possible exergy efficiency and minimizing the energy consumption.

* Corresponding author.
E-mail address: danijelan@kg.ac.rs (D. Nikolic).

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Nomenclature and abbreviations

BT	building type, [−]
BT_{EE}	building type with embodied energy, [−]
C_{inst}	coefficient of installation and maintenance of solar systems, [−]
C_{m1}	coefficient of the life cycle of thermal insulations, [1/year]
C_m	coefficient of life cycle of PV and solar collectors, [1/year]
C_{PV}	price of energy sold to the network, feed-in tariff, [€/kWh]
C_{NET}	price of energy purchased from the grid, [€/kWh]
DHW	domestic hot water
D	annual financial profit from installed solar systems, [€/year]
E_{COLL}	yearly thermal energy generated by solar collectors, [J]
E_{GEN}	generated finally energy, [J]
$E_{GEN,\ PRIM}$	generated primary energy, [J]
E_{EL}	total electricity consumption, [J]
$E_{EL,PRIM}$	primary energy consumption for electric heating, [J]
$E_{em,COLL}$	embodied energy of solar collectors, [J]
$E_{em,\ PV}$	embodied energy of PV array, [J]
$E_{em,\ ISO}$	embodied energy of insulation, [J]
$E_{em,\ SS,\ ins}$	embodied energy of solar systems, increased by the value of energy consumed on their installation and maintenance, [J]
$E_{em,\ ISO,\ ins}$	embodied energy of thermal insulation increased by the value of energy consumed on its installation and maintenance, [J]
$E_{P,\ NET}$	net-purchased electricity from the grid, [kWh]
$E_{PV,\ S}$	surplus electricity sold to the electricity grid, [kWh]
E_{PRIM}	avoided operative primary energy, [J]
$E_{PRIM,DH}$	primary energy consumption for district heating, [J]
$E_{PRIM,GH}$	primary energy consumption for gas heating, [J]
E_{PV}	yearly electrical energy generated by PV array, [J]
Ex_{CONS}	total consumer exergy, [J]
$E_{X,1}$	exergy after water mixing, [J]
$E_{X,COLD\ WAT}$	exergy of cold water, [J]
$E_{X,COLL}$	exergy of solar collector, [J]
$E_{X,CW}$	exergy of hot water for clothe-washer, [J]
$E_{X,DW}$	exergy of hot water for dish-washer, [J]
Ex_{PV}	exergy of PV panel, [J]
$Ex_{\ EE,\ COLL,\ PV}$	exergy obtained from solar systems, reduced by their embodied exergy, [J]
$Ex_{\ EE,\ PV}$	total exergy of PV array, [J]
$Ex_{\ EE,\ COLL}$	total exergy of solar collectors, [J]
$E_{X,SHOW}$	exergy of hot water for shower, [J]
$E_{X,SINK}$	exergy of hot water for sink, [J]
Ex_{SUN}	Sun exergy, [J]
Ex_{TANK}	tank's exergy, [J]
$Ex_{COLL,PV}$	exergy obtained by solar collectors and PV array, [J]
Ex_{PV}	exergy obtained by PV array, [J]
Ex_{COLL}	exergy obtained by solar collectors, [J]
EEx_{COLL}	embodied exergy of solar collectors, [J]
EEx_{PV}	embodied exergy of PV system, [J]
$EMPB$	emission payback time, [years]
e_x	ratio between required and obtained exergy, [−]
$e_{x,\ EE}$	ratio between required and obtained exergy with embodied exergy, [−]
I	mean annual insulation at the city of Kragujevac, [kWh/m^2]
I_0	investment of installed solar systems, [€]
LC	life cycle of PV and solar collectors, [years]
LC_{ISO}	is life cycle of thermal insulations, [years]
$NNEB$	negative net-energy building
PB	investment payback time, [years]
$PNEB$	Positive net-energy building
PV	photovoltaic
R_{EL}	primary conversion multiplier, [−]
R_{KOL}	annual expense of solar collectors, [€]
R_{PV}	annual expense of PV system, [€]
S_{CO2}	CO_2 emission from solar systems, [kg/GJ]
$S_{CO2,\ PV}$	CO_2 emission from PV, [kg/GJ]
$S_{CO2,\ COLL}$	CO_2 emission from solar collectors, [kg/GJ]
$S_{TOT,\ CO2}$	total emission of CO_2 from solar systems, [kg/GJ]
$S_{CO2,\ PV,\ emb}$	embedded emission of CO_2 of photovoltaics, [kg/GJ]
$S_{CO2,\ COLL,\ emb}$	embedded emission of CO_2 of solar collectors, [kg/GJ]
y	Fraction of PV panel on the roof, [−]
$ZNEB$	Zero net-energy building
η_x	exergy efficiency η_x without embodied exergy, [−]
$\eta_{x,\ EE}$	Exergy efficiency with embodied exergy, [−]

During the past 20 years many papers with various approaches for exergy calculation have been published. Paper written by Petela [4] represents the one of the pioneering works in the field of exergy calculation of solar radiation. He discussed exergy of solar radiation and he presented discussion of the dependence of substance exergy and solar radiation on temperature. Later work of Petela [5] evaluated solar radiation exergy and optimal temperature of absorbing surface. This paper was the basis for further investigation about solar radiation exergy. Candau [6] gave methodology for the calculation of solar radiation exergy based on classical thermodynamics. Park at al. in their paper [7] present the literature review on exergy analyses of typical renewable energy systems, among them for solar thermal and solar photovoltaic systems. Koroneos and Tsarouhis shown the exergy analysis which is coupled with Life-Cycle Assessment method due to performance analyzing of solar heating, cooling, and DHW systems, installed in a detached house in Thessaloniki, town in Macedonia region, north Greece [1]. The obtained exergy efficiency was in the range of 7% for DHW system. Hepbasli in his study [8] presented complete exergetic analysis and evaluation of different solar systems, among them the solar collector applications for water heating and a photovoltaic array. Exergy efficiency of the solar collector is defined as the ratio of the increased water exergy to the exergy of the solar radiation (as the ratio of the corresponding temperatures) by Singh at al [9]. and Sunil [10]. Farahat [11] and Ajam [12] in their papers investigated exergetic optimization of solar collectors. Exergy analysis of flat plate solar collectors was conducted by Chamoli [13], and his conclusion was that their exergy efficiency is at range of 0.5–4%. Saidur at al. present exergy analysis of different solar energy applications [14]. They report that exergy efficiency of flat plate solar collector has maximum value of 4%.

Exergetic evaluation of photovoltaics has been performed by Fujisa at al [15]. and Saitoh at al [16]. An exergetic optimization is developed to determine the optimal performance of solar photovoltaic array and the maximum exergy efficiency have been found by Sarhaddi at al [17]. Joshi et al. [18] studied energy and exergy performance of a photovoltaic system and they calculated the energy and exergy efficiencies under given experimental data. Evola at al. in their paper [19] gave a literature review which identifies methods used to carry out the exergy analysis of buildings and their solar systems.

This paper represents investigations on exergy optimization of solar systems with the aim to determine the optimal size of PV panels and solar collectors and, on that way, to achieve the maximum amount of exergy efficiency. With maximum values of exergy, it can be obtain the maximum of exergy efficiency of installed solar systems, and building energy consumption will be minimized. Investigated buildings is located in the city of Kragujevac, town in the central part of Serbia, which lies on the Balkan Peninsula in the southern-east part of Europe. Serbia has a moderate continental climate with cold winters, warm summers, and well-distributed rainfall. These conditions are characteristic for northern and central parts of the Balkan Peninsula. The building is designed with PV panels and solar collectors on the roof, and investigations are carried out for cases of electrical space heating (EH), district heating (DH) and central heating system with gas boiler (GH). Heating system operates from 15 October to 14 April next year. Generated thermal energy by solar collectors is used for DHW heating. Electricity generated by the PV array may be used for space heating, cooling, lighting, and electric equipment. Three important parameters, that can influence the exergy, were varied during these analyzes - hot water temperature in DHW system, hot water consumption in the building and PV cell efficiency. The results show the obtained values of final and primary building energy consumption with embodied energy and embodied exergy of solar systems, as well as the energy generated by solar systems. Based on these data, the building type was determined - zero-net energy building (ZNEB), negative-net energy building (NNEB) or positive-net energy building (PNEB), according to Kapsalaki [20]. Investigated building is designed in Open Studio plug-in in Google SketchUp, while EnergyPlus software was used for simulation of building energy behaviour. Hooke-Jeeves algorithm and Genopt software were used for simulation and exergy optimization.

The exergy efficiency obtained with numerical simulations and optimizations are within the frame of investigation results of the other authors who have conducted similar studies about exergy efficiency of PV array and exergy efficiency of solar system for domestic water heating, separately. The novelty of this study is exergy efficiency optimization of different solar systems installed on the building roof, and determination of the optimal area of PV system and solar collectors' at Serbian building with different heating systems. Investigations are realized with the aim to achieving zero-net energy building or positive-net energy building. There are no such studies in the available literature, neither for the Europe nor for the other parts of the world. The obtained results are not merely useful for the study of exergy calculations and calculations of exergy efficiency of different solar systems, but they could represent very useful results for similar investigation. As the buildings have the great energy consumption today, these analyses and investigations are important because of the possibility of reaching ZNEB or PNEB concept in the other regions that have the same or similar climate, weather conditions and topography.

2. Materials and methods

2.1. Modelled building and climate

In this research, the exergy optimization of solar systems is performed for residential building modelled in EnergyPlus software (Fig. 1). The building has two floors, with 6 conditioned zones, total floor area of 160 m^2 and total roof area of 80.6 m^2. The windows are double glazed with the air gap of 15 mm. The concrete building envelope, roof, and the floor are thermally insulated by polystyrene (thermal insulation thickness - 0.15 m). Air temperatures in the heated rooms are set to 20 °C from 07:00–09:00 and from 16:00–21:00, and to 15 °C from 09:00–16:00 and from 21:00–7:00 next day. The simulation time step is 15 min.

The building has the south-oriented roof with an optimal slope angle (for Kragujevac, optimal slope angle is 37.5^0 [21]), with PV array and flat plate solar collectors.

The PV system is an on-grid system. According to the investigations of Alsema [22,23], the life cycle of PV array is set to 20 years, the embodied energy of PV panels is set to 3.75 GJ/m^2 [22,23]. Embodied exergy of PV panels is set to 5 GJ/m^2, according to Colombo at al [24]. Ardente at al [25]. и [26] have analyzed Life Cycle Assesment of flat plate solar collectors. Kalogirou [27] has investigated solar system for domestic water heating, as Battisti and Corrado [28]. Following their research, it was adopted the life cycle of solar collectors of 20 years, the embodied energy of solar collectors of 2.75 GJ/m^2 and the embodied exergy of solar collectors of 3.8 GJ/m^2 [29]. Schematic representation of the analyzed building with installed solar systems is given in Fig. 2.

In the case of electrical space heating, the main part of exergy (i.e. electricity) obtained from PV array is consumed for building space heating. Electricity in building was also consumed for lighting, domestic hot water (DHW) system and appliances. Sun exergy is calculated based on the value of the mean annual insulation at the city of Kragujevac, Serbia (I = 1447.85 kWh/m^2) [30].

The investigated residential building is located in the city of Kragujevac, Central Serbia, with 209 m height above the sea, latitude of $44^0$10 N and longitude of $20^0$55 E. The time zone is GMT+1.0 h. Kragujevac has a moderate continental climate with four defined seasons (winter, spring, summer, autumn). Summers are very warm and humid, with temperatures as high as 37 °C. The winters are cool, and snowy, with temperatures as low as −12 °C. The EnergyPlus uses weather data from its own database file.

2.2. Optimization procedure

In order to better understand the principle of optimization, it will be present an explanation of the terms exergy and embodied exergy. Exergy is related to the quality of energy, and it is defined as energy that is available to be used. Also, exergy of a system can be defined as the maximum possible useful work during the process that brings the system into equilibrium with the environment. When the system is at equilibrium, it does not have the exergy, i.e. exergy is zero. Embodied exergy of some system is defined as the sum of the direct and indirect exergy, which is consumed in its production process. It is the sum of the system exergy and exergy previously used up to produce and provide the resource. Only exergy of non-renewable energy sources is accounted for. Embodied exergy in this paper refers to the exergy hidden in all the inputs of the construction of the PV system and solar collectors.

Total exergy of PV array can be defined as exergy obtained from PV array, reduced by its embodied exergy:

$$Ex_{EE,\,PV} = Ex_{PV} - EEx_{PV} \tag{1}$$

Total exergy of solar collectors can be defined as exergy obtained from solar collectors, reduced by their embodied exergy:

$$Ex_{EE,\,COLL} = Ex_{COLL} - EEx_{COLL} \tag{2}$$

Through procedure of exergy efficiency optimization with Genopt software, the maximum value of the exergy efficiency of the installed solar systems is determined. This value is achieved at the optimal size of PV array and solar collectors' area, and in the optimization routine it presents the roof area covered with PV array (y - fraction of PV panels on the roof). Fraction of PV panels y exists in

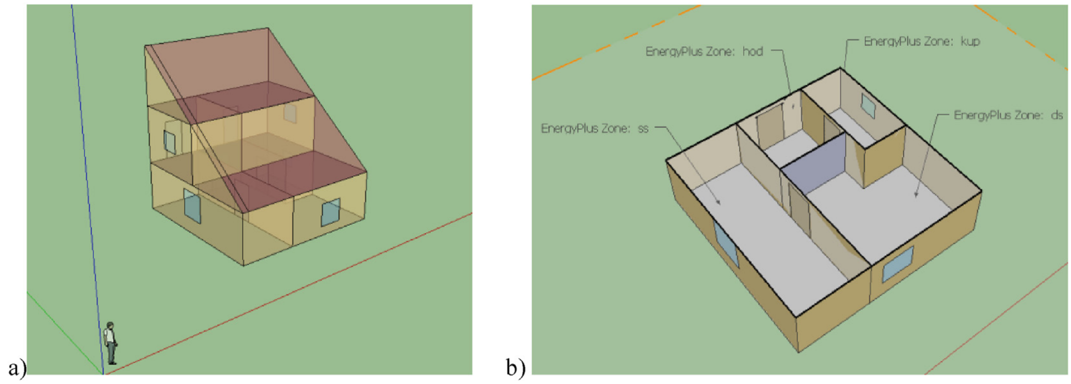

Fig. 1. (a) Modelled building; (b) Cross-section of the first building floor.

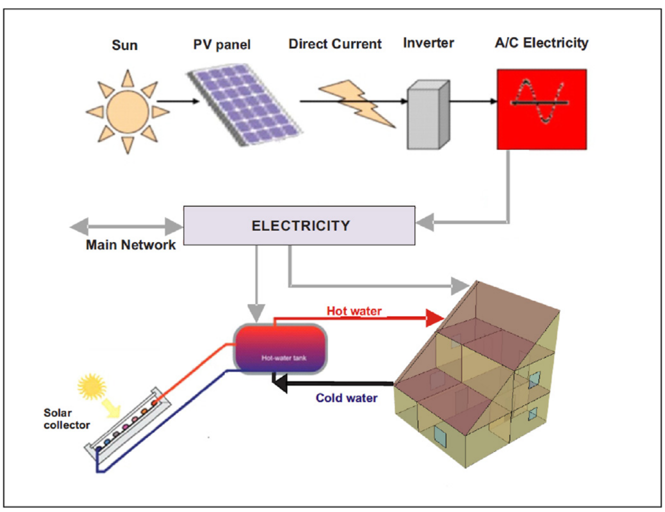

Fig. 2. Analyzed building with installed solar systems.

the calculated total exergy of PV system and solar collectors [29]. Fig. 3 shows exergy flow in solar collector, while Fig. 4 shows exergy flow in PV panel.

GenOpt is an optimization program for the minimization of defined objective function evaluated by an external simulation program. It can be coupled to any simulation program that reads its input from text files and writes its output to text files, and it has a library with adaptive Hooke-Jeeves algorithm. In this algorithm, only the objective functions and the constraint values are used to guide the search strategy. The main advantage of this algorithm is reducing the compute time.

Negative value of exergy efficiency is the objective function for Geonopt software. In that sense, the software varies the value of y until it gets its output - minimum value of exergy efficiency. For optimal y value, i.e. optimal size of PV array, we practically have the maximum value of the exergy efficiency of the installed solar systems. In that case, the largest amount of electricity is generated, which means the largest amount of the generated primary energy.

The objective function in the Genopt optimization procedure - exergy efficiency η_X without embodied exergy is:

$$\eta_X = \frac{Ex_{COLL,\ PV}}{Ex_{SUN}} \tag{3}$$

where:

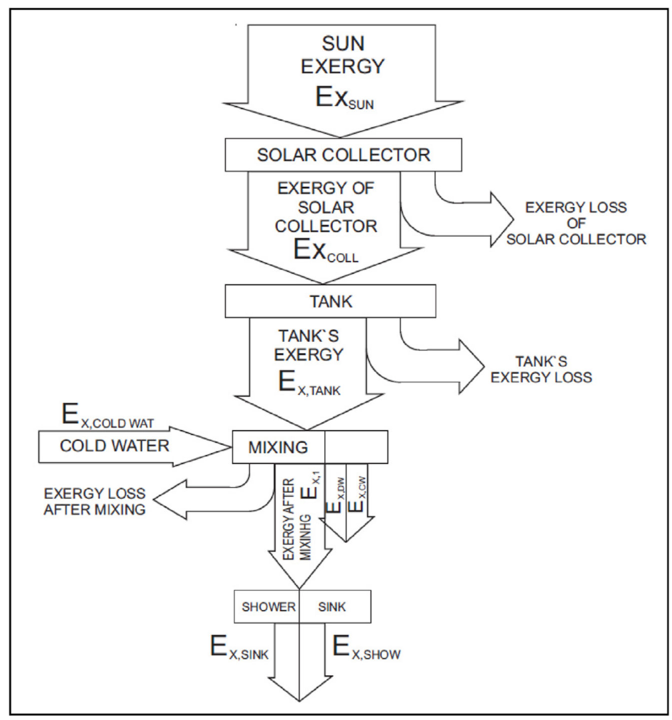

Fig. 3. Exergy flow in solar collector.

- Ex_{SUN} - Sun exergy, J;
- $Ex_{COLL,PV}$ - exergy obtained by solar collectors and PV array, J.

Exergy efficiency with embodied exergy, $\eta_{x,\ EE}$ is calculated as:

$$\eta_{X,EE} = \frac{Ex_{EE,\ COLL,\ PV}}{Ex_{SUN}} \tag{4}$$

where $Ex_{\ EE,\ COLL,\ PV}$ means exergy obtained from PV array and solar collectors, reduced by their embodied exergy (EEx_{PV} and EEx_{COLL}):

$$Ex_{EE,\ COLL,\ PV} = Ex_{COLL,PV} - EEx_{PV} - EEx_{COLL} \tag{5}$$

For exergy efficiency optimization, the significant ratios are between required and obtained exergy e_X and $e_{X,EE}$ (without and with embodied exergy):

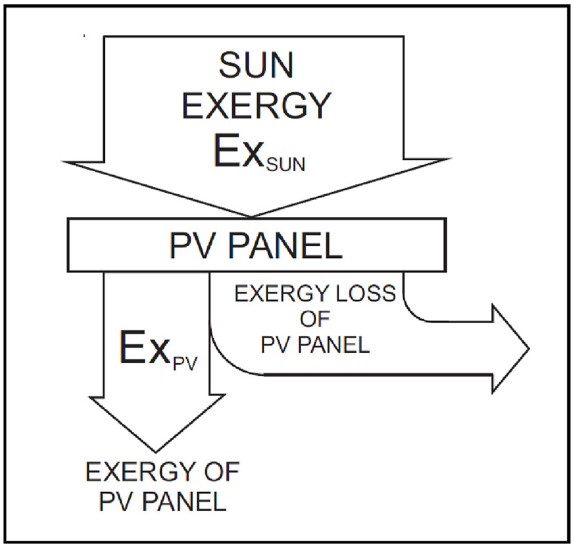

Fig. 4. Exergy flow in PV panel.

$$e_X = \frac{Ex_{CONS}}{Ex_{COLL,\ PV}} \tag{6}$$

$$e_{X,EE} = \frac{Ex_{CONS}}{Ex_{EE,\ COLL,\ PV}} \tag{7}$$

where Ex_{CONS} represents total consumer exergy (J) (sum of required exergy of all building consumers, yearly). Ratios of required and obtained exergy should be as small as possible [29].

In the process of exergy optimization, it is calculated total electricity consumption E_{EL}, primary energy consumption ($E_{EL,PRIM}$ for electric heating, $E_{PRIM,DH}$ for district heating and $E_{PRIM,GH}$ for gas heating), generated finally energy E_{GEN}, generated primary energy $E_{GEN,\ PRIM}$, and avoided operative primary energy E_{PRIM}.

Avoided operative primary energy consumption due to operation of the solar systems is [29]:

$$E_{PRIM} = R_{EL}(E_{PV} + E_{COLL}) - \left[C_m\left(E_{em,\ PV} + E_{em,\ COLL}\right)C_{inst}\right] - C_{m1}E_{em,ISO} \tag{8}$$

where:

- R_{EL} = 3.04 - primary conversion multiplier [2];
- E_{PV} – yearly electrical energy generated by PV array, J;
- E_{COLL} – yearly thermal energy generated by solar collectors, J;
- $E_{em,\ PV}$ – PV array embodied energy, J;
- $E_{em,COLL}$ – solar collectors embodied energy, J;
- Cm = 1/LC; where LC is life cycle of PV and solar collectors, years;
- Cm1 = 1/LC_{ISO}; where LC_{ISO} is life cycle of thermal insulations, years [29];
- $E_{em,\ ISO}$ – embodied energy of insulation, J [29];
- C_{inst} – coefficient of installation and maintenance of solar systems, during whole life cycle [31].

Defined avoided operative primary energy consumption due to operation of the solar systems, consists of three terms. First term refers to generated primary energy; the second term refers to the yearly value of embodied energy of solar systems, increased by the value of energy consumed on their installation and maintenance; the third term refers to the yearly value of embodied energy of thermal insulation increased by the value of energy consumed on its installation and maintenance. So, it can be concluded that

$$E_{PRIM} = E_{GEN,PRIM} - E_{em,\ SS,ins} - E_{em,ISO,ins} \tag{9}$$

At the end of the investigations, building type (NNEB, ZNEB or PNEB) without and with embodied energy is defined (BT and BT_{EE}). Building type compares generated primary energy ($E_{GEN,\ PRIM}$) and total building primary energy consumption ($E_{EL,\ PRIM}$, $E_{PRIM,\ DH}$ or $E_{PRIM,\ GH}$), for the approach without embodied energy. For the approach with embodied energy, building type compares generated primary energy ($E_{GEN,\ PRIM}$) and operative primary energy (E_{PRIM}).

2.3. Environmental analysys of installed solar systems

The installed solar systems, discussed in this paper, emit a certain amount of CO_2 into the atmosphere when generating electricity and thermal energy. Regardless of the fact that these are systems that have minimal harmful impact on the environment, their carbon dioxide emissions are calculated according to:

$$S_{CO_2} = S_{CO_2,PV} + S_{CO_2,COLL} \tag{10}$$

where:

- S_{CO2} – CO_2 emission from solar systems, kg/GJ;
- $S_{CO2,\ PV}$ – CO_2 emission from PV, kg/GJ;
- $S_{CO2,\ COLL}$ – CO_2 emission from solar collectors, kg/GJ.

CO_2 emission from photovoltaics is 50 g CO_2 per kWh of generated electricity [32], while CO_2 emission from solar collectors is 72 g CO_2 per kWh of generated thermal energy [33].

Total emission of CO_2 from solar systems presents the sum of CO_2 emissions of installed solar systems and embedded emission of CO_2 emitted during the production of analyzed solar systems

$$S_{TOT,CO_2} = S_{CO_2} + S_{CO_2,PV,emb} + S_{CO_2,COLL,emb} \tag{11}$$

where:

- $S_{CO2,\ PV,\ emb}$ - embedded emission of CO_2 of photovoltaics, kg/GJ;
- $S_{CO2,\ COLL,\ emb}$ – embedded emission of CO_2 of solar collectors, kg/GJ.

Total emission of CO_2 in this investigation is calculated per m^2 of installed solar systems.

The British Centre for Alternative Technology provides data on embedded emission of CO_2 [34], and for grid-connected PV systems in the region of southern Europe, embedded emission of CO_2 of photovoltaics is 35 g CO_2/kWh of generated electricity. Embedded emission of CO_2 for solar collectors of 300 kg CO_2/m^2 per year was adopted, according to the research data of Ardente at al [25,26]. and Kalogirou [27]. These data in calculations are convert in a proper values, in kg/GJ.

2.4. Economic analysys of installed solar systems

An economic analysis of the installed solar systems was conducted to determine the financial profit (D) and payback period of the investment (PB).

Financial profit is determined by the equation:

$$D = E_{PV,S}C_{PV} - E_{P,NET}C_{NET} - R_{PV} - R_{COLL} \tag{12}$$

where:

- D - annual financial profit from installed solar systems, €/year;
- $E_{PV,\,S}$ – surplus electricity sold to the electricity grid, kWh;
- $E_{P,\,NET}$ – net-purchased electricity from the grid, kWh;
- C_{PV} – price of energy sold to the network, feed-in tariff, €/kWh;
- C_{NET} – price of energy purchased from the grid, €/kWh;
- R_{PV} – annual expense of PV system, €;
- R_{COLL} – annual expense of solar collectors, €.

The annual consumption of photovoltaic systems and solar collectors is calculated according to the value of investment for these systems (I_0) and is given in Ref. [35].

Based on the calculated profit, the investment payback time is calculated as:

$$PB = \frac{I_0}{D} \tag{13}$$

When the PV system generates more electricity than building electricity needs, then the excess electricity is sold to the electricity distribution network at the feed-in tariff. The current value of the purchase price of electricity from renewable energy sources (feed-in tariff) in Serbia is 0.2066 €/kWh for systems up to 30 kW [36]. The average price of electricity in Serbia [37] purchased from the electricity distribution network is: for green tariff (<350 kWh) – 0.059 €/kWh, for blue tariff (351–1600 kWh) – 0.089 €/kWh and for red tariff (>1600 kWh) – 0.177 €/kWh.

3. Results and discussions

3.1. Different hot water temperature in DHW system

Exergy optimization was carried out for residential building with different heating systems and with variable water temperature in DHW system. It was analyzed the hot water temperature of 50 °C, 60 °C and 70 °C, respectively.

The obtained results (Table 1) show a small change in electricity consumption in all cases, which referred to the electricity for the operation of electrical appliances for water heating.

Table 1
–Exergetic optimization - residential building with variable hot water temperature in DHW system and different heating systems.

Heating system	Energy/Exergy	Hot water temperature (^{0}C)		
		50	60	70
EH	$Ex_{EE,\,COLL,\,PV}$, (GJ)	50.65	51.41	51.44
	$Ex_{COLL,\,PV}$, (GJ)	30.6	31.36	31.39
	E_{GEN}, (GJ)	55.68	55.68	55.68
	$E_{GEN,\,PRIM}$, (GJ)	169.3	169.3	169.3
	Ex_{CONS}, (GJ)	54.45	56.58	58.82
	E_{EL}, (GJ)	68.36	69	69.67
	$E_{EL,PRIM}$, (GJ)	207.8	209.8	211.8
	E_{PRIM}, (GJ)	149	149	149
	BT	NNEB	NNEB	NNEB
	BT_{EE}	NNEB	NNEB	NNEB
DH	Ex_{CONS}, (GJ)	16.92	19.03	19.73
	$E_{PRIM,\,DH}$, (GJ)	170.94	172.89	176.57
	BT, (–)	NNEB	NNEB	NNEB
	BT_{EE}, (–)	NNEB	NNEB	NNEB
GH	Ex_{CONS}, (GJ)	16.92	19.03	19.73
	$E_{PRIM,\,GH}$, (GJ)	134.96	136.91	140.58
	BT, (–)	PNEB	PNEB	PNEB
	BT_{EE}, (–)	PNEB	PNEB	PNEB

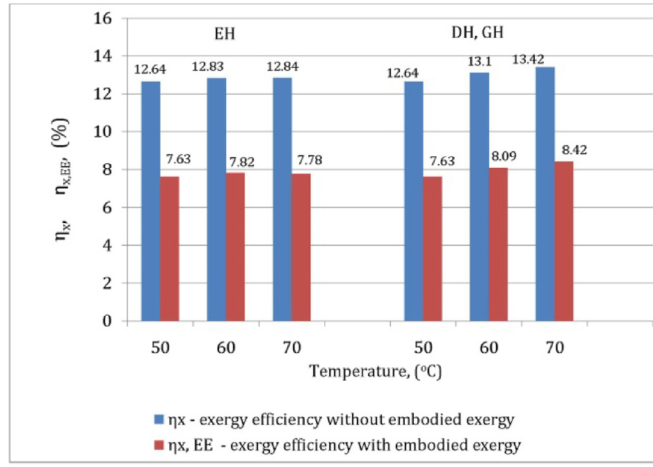

Fig. 5. Exergy efficiency in building with different hot water temperature in DHW system.

Exergy efficiencies (without and with embodied exergy) are given in Fig. 5.

It can be concluded that with the increasing of hot water temperature, there is an increase in both of the exergy efficiency (with and without embodied exergy). Exergy efficiency η_x for hot water temperature of 50 °C, 60 °C and 70 °C and building with electric heating is 12.64%, 12.83% and 12.84%, respectively, while the exergy efficiency $\eta_{x,EE}$ for the same values of hot water temperature is 7.63%, 7.82% and 7.83%, respectively. For building with district and gas heating, exergy efficiency η_x for hot water temperature of 50 °C, 60 °C and 70 °C is 12.64%, 13.1% and 13.42%, respectively, while the exergy efficiency $\eta_{x,EE}$ for the same values of hot water temperature are 7.63%, 8.09% and 8.42%, respectively.

Ratio between obtained and required exergy (with or without embodied exergy) for all heating systems and hot water temperatures are graphically shown in Fig. 6.

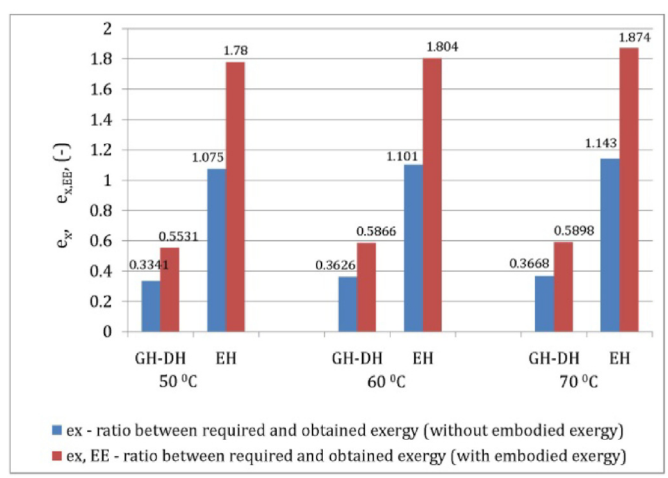

Fig. 6. Ratio between required and obtained exergy in building with different hot water temperature in DHW system.

Fraction of PV panels on the roof was the same in all cases – 98.75% (i.e. 79.6 m^2 of PV panels and 1 m^2 of solar collector). With these values of area, building generates 169.3 GJ of primary energy, while maximum avoided operative primary energy is 149 GJ. Only building with gas heating system is PNEB, with or without embodied energy.

3.2. Different PV cell efficiency

This part of investigations refers to residential building with different space heating systems and variable PV cell efficiency. The first case is the PV array with 12% of cell efficiency, and the other cases are the PV array with 14% and 16% of cell efficiency. Total annual finally energy consumption of the analyzed building is 68.36 GJ. That means that primary energy consumption in building with electric heating is 207.81 GJ, and for building with district heating and gas heating, this value is 170.94 GJ and 134.96 GJ, respectively. The results obtained by exergy optimization are in Table 2.

Fraction of PV panels on the roof was the same as in previous case, i.e. 98.75%. This is the optimal value for maximum generating of electrical energy with PV system installed on the roof. With the increasing of PV cell efficiency, there is a significant increase in generated electricity (Table 2). Different amount of electrical energy can be generated for PV cell efficiency of 12%, 14% and 16%, and it amounts 169.27 GJ, 195.85 GJ and 222.43 GJ, respectively.

By using the PV array with 12% and 14% of cell efficiency, building with electric heating will be NNEB (building type approach with and without embodied energy). By using the PV array with 16% of cell efficiency, it is possible to achieve the concept of positive-net energy building (PNEB, it generates 222.43 GJ of primary energy, which is more than the energy demands of 207.81 GJ) without embodied energy of installed solar systems and insulation. If it is taken into account, the building is negative-net energy building (NNEB).

Concept of PNEB can be achieved in building with district heating, by using the PV array with 14% and 16% of cell efficiency (with and without embodied energy). Primary energy conversion multiplayer for district heating in Serbia is 2.03 [2,38], so generated primary energy was 195.85 GJ and 222.43 GJ, respectively, while primary energy consumption is 170.94 GJ.

The most favourable case is a building with gas heating system, because of small primary energy consumption. For gas heating in Serbia, primary energy conversion multiplayer is 1.1 [2,28]. All these analyzed buildings were PNEB, because they have the lowest primary energy consumption (134.96 GJ), while minimum amount of generated primary energy is 169.27 GJ for PV cell efficiency of 12% (Table 2).

With the increasing of PV cell efficiency, there is a significant increase in the exergy efficiency (with and without embodied exergy). Exergy efficiency η_x for PV cell efficiency of 12%, 14% and 16%, for all space heating systems is 12.64%, 14.71% and 16.78%, respectively, while the exergy efficiency $\eta_{x,EE}$ is 7.63%, 9.71% and 11.78%, respectively. Preview of these two exergy efficiency is given in Fig. 7.

Ratios between required and obtained exergy e_x and $e_{x,EE}$, decreases with increasing PV cell efficiency. For PV cell efficiency of 12%, 14% and 16%, e_x in the building with electrical heating is 1.075, 0.9236 and 0.8095, respectively, while $e_{x,EE}$ is 1.78, 1.4 and 1.153, respectively. In the building with district/gas heating, e_x for PV cell efficiency of 12%, 14% and 16%, is 0.3341, 0.287 and 0.256, respectively, and $e_{x,EE}$ is 0.5531, 0.435 and 0.3584, respectively.

By implementation the PV module with 14% and 16% of cell efficiency, it can be achieved the ratio of required and obtained exergy which is less than 1 ($e_x < 1$). This means that installed solar system generates more exergy than required exergy of all consumers in the building. Graphical representation of the required and obtained exergy for different PV cell efficiency is shown in Fig. 8.

Table 2
Results obtained by exergetic optimization, for residential building with different PV cell efficiency and different heating systems.

Heating system	Energy/Exergy	PV cell efficiency (%) 12	14	16
	$Ex_{EE, COLL, PV}$, (GJ)	50.65	58.96	67.26
	$Ex_{COLL, PV}$, (GJ)	30.6	38.91	47.21
	E_{GEN}, (GJ)	55.68	64.42	73.17
	$E_{GEN, PRIM}$, (GJ)	169.3	195.85	222.43
EH	Ex_{CONS}, (GJ)	54.45	54.45	54.45
	E_{EL}, (GJ)	68.36	68.36	68.36
	$E_{EL,PRIM}$, (GJ)	207.8	207.8	207.8
	E_{PRIM}, (GJ)	149	175.6	202.18
	BT	NNEB	NNEB	PNEB
	BT_{EE}	NNEB	NNEB	NNEB
DH	Ex_{CONS}, (GJ)	16.92	16.92	16.92
	$E_{PRIM, DH}$, (GJ)	170.94	170.94	170.94
	BT, (−)	NNEB	PNEB	PNEB
	BT_{EE}, (−)	NNEB	PNEB	PNEB
GH	Ex_{CONS}, (GJ)	16.92	16.92	16.92
	$E_{PRIM, GH}$, (GJ)	134.96	134.96	134.96
	BT, (−)	PNEB	PNEB	PNEB
	BT_{EE}, (−)	PNEB	PNEB	PNEB

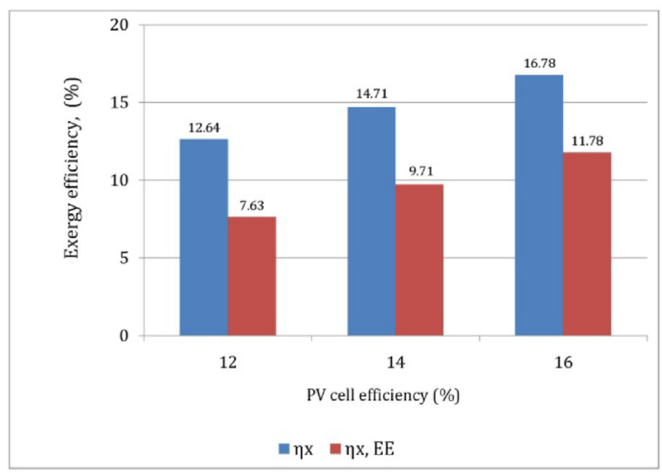

Fig. 7. Exergy efficiency in building with different PV cell efficiency.

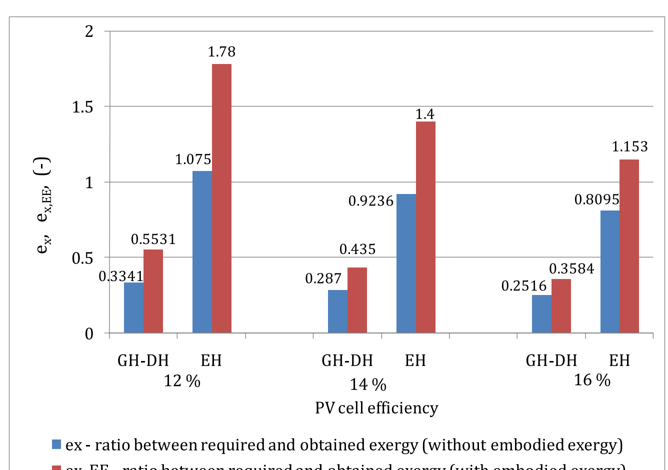

Fig. 8. Ratio between required and obtained exergy in building with different PV cell efficiency.

3.3. Different hot water consumption in DHW system

In this investigation, variable hot water consumption in DHW system is analyzed. The first case was monthly hot water consumption of 8 m^3, and the other cases were 11.5 m^3 and 19 m^3 of monthly hot water consumption. Due to the increase in the building hot water consumption, a larger amount of electricity is needed for its heating, so the total electricity consumption is also increasing. Obtained results are in Table 3.

Fraction of PV panels on the roof was the same as in previous cases, i.e. 98.75%. The same amounts of electrical and heating energy are generated with installed PV systems in all investigated cases.

For all variable values of hot water consumption in DHW system, analyzed residential buildings with electric space heating system were negative-net energy buildings (NNEB - building type approach with and without embodied energy). Their final building energy consumption was larger than generated energy with solar systems.

In the building with district heating, concept of positive-net energy building (PNEB) without embodied energy, can be achieved in the building with the smallest hot water consumption in DHW system. The other analyzed buildings were NNEB.

Buildings with gas heating system, far all varied values of hot water consumption, and for both approaches of embodied energy, were positive-net energy buildings (PNEB). They have the lowest primary energy consumption (Table 3).

For all heating systems and hot water consumption of 8 m^3, 11.5 m^3 and 19 m^3, exergy efficiency η_x was 12.6%, 12.64%, and 12.73%, respectively, while exergy efficiency with embodied exergy, $\eta_{x,EE}$ was 7.63%, 9.71% and 11.78%, respectively. Ratios between required and obtained exergy e_x and $e_{x,\ EE}$, increase with increasing the hot water consumption. For building with electric heating and hot water consumption of 8 m^3, 11.5 m^3, and 19 m^3, e_x was 1.036, 1.075, and 1.186, respectively, while $e_{x,\ EE}$ was 1.718, 1.78, and 1.954, respectively.

For building with district/gas heating and hot water consumption of 8 m^3, 11.5 m^3 and 19 m^3, the ratio of required and obtained exergy (without embodied exergy) was 0.2924, 0.3341 and 0.4673, respectively, while the ratio between required and obtained exergy calculated with embodied exergy was 0.485, 0.5531 and 0.7373, respectively.

3.4. Environmental analysis of the most favourable solutions of exergy optimization

Fraction of PV panels on the roof was the same in all investigated cases of exergy optimization, regardless of the heating system and variable parameters, i.e. 98.75%, which means the area of 79.6 m^2 of PV panels and area of 1 m^2 of solar collector. From the aspect of exergy and exergetic efficiency, the most significant cases are different cell efficiency of PV panels, because with the increase of cell efficiency, the amount of generated energy also increases.

The CO_2 emission of solar systems in a case of 12% PV cell efficiency is 9.8 kg CO_2/m^2 of solar installation, and the total CO_2 emission is 20.8 kg CO_2/m^2 of solar installation. In the case of PV systems with PV cell efficiency of 14% and 16%, CO_2 emissions are 11.3 kg CO_2/m^2 and 12.85 kg CO_2/m^2, respectively, and total CO_2 emission is 23.5 kg CO_2/m^2 and 26.2 kg CO_2/m^2, respectively. That means that CO_2 emissions increase with increasing amount of generated energy (Fig. 9).

The emission payback time (EMPB) decreases with increasing PV cell efficiency, due to the larger amount of generated electricity. In the PV system with PV cell efficiency of 12%, 14% and 16%, the emission payback time is 1.11 years, 1.07 years and 1.04 years, respectively (Fig. 10).

3.5. Economic analysis of the most favourable solutions of exergy optimization

Economic optimization was realized for the most favourable cases of exergy optimization, as environmental analysis (fraction of

Table 3
Results obtained by exergetic optimization, for residential building with different hot water consumption and different heating systems.

Heating system	Energy/Exergy/Exergy efficiency/Ratio between required and obtained exergy	Hot water consumption, monthly (m^3)		
		8	11.5	19
	$Ex_{EE,\ COLL,\ PV}$, (GJ)	50.49	50.65	51.04
	$Ex_{COLL,\ PV}$, (GJ)	30.44	30.6	30.99
	E_{GEN}, (GJ)	55.68	55.68	55.68
	$E_{GEN,\ PRIM}$, (GJ)	169.3	169.27	169.27
	η_x, (%)	12.6	12.64	12.73
	$\eta_{x,EE}$, (%)	7.6	7.63	7.73
EH	Ex_{CONS}, (GJ)	52.29	54.45	60.55
	e_x, (−)	1.036	1.075	1.186
	$e_{x,EE}$, (−)	1.718	1.78	1.954
	E_{EL}, (GJ)	64.54	68.03	68.36
	$E_{EL,PRIM}$, (GJ)	196.2	207.8	207.8
	E_{PRIM}, (GJ)	149	149	149
	BT, (−)	NNEB	NNEB	NNEB
	BT_{EE}, (−)	NNEB	NNEB	NNEB
DH	Ex_{CONS}, (GJ)	14.76	16.92	22.85
	e_x, (−)	0.2924	0.3341	0.4673
	$e_{x,EE}$, (−)	0.485	0.5531	0.7373
	$E_{PRIM,\ DH}$, (GJ)	159.93	170.94	149.02
	BT, (−)	PNEB	NNEB	NNEB
	BT_{EE}, (−)	NNEB	NNEB	NNEB
GH	Ex_{CONS}, (GJ)	14.76	16.92	22.85
	e_x, (−)	0.2924	0.3341	0.4673
	$e_{x,EE}$, (−)	0.485	0.5531	0.7373
	$E_{PRIM,\ GH}$, (GJ)	125.35	134.96	164.39
	BT, (−)	PNEB	PNEB	PNEB
	BT_{EE}, (−)	PNEB	PNEB	PNEB

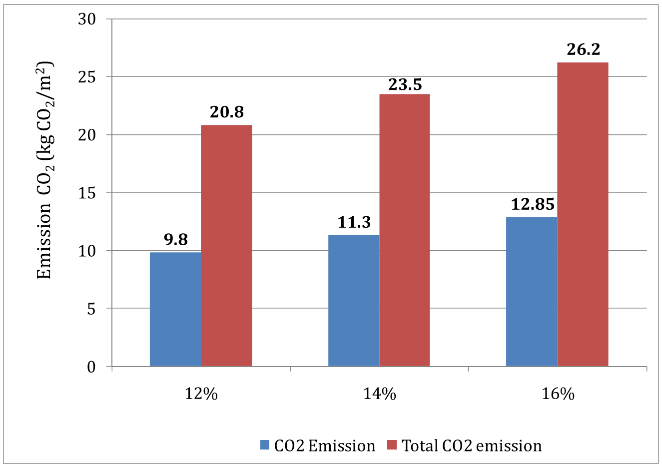

Fig. 9. Emission and total emission of CO_2 in buildings with different PV cell efficiency (exegy optimization).

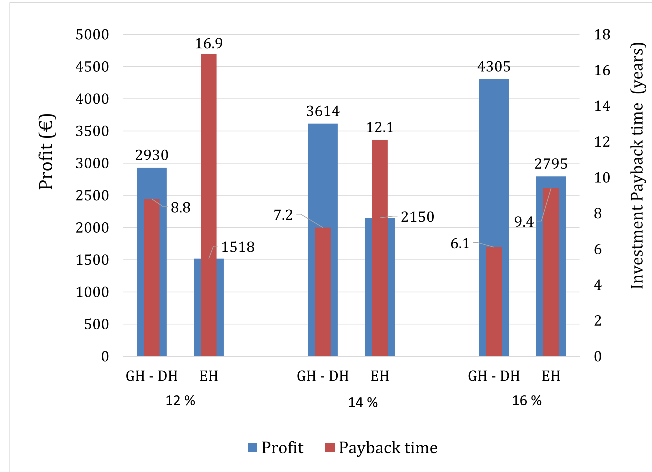

Fig. 11. Financial profit and investment payback time for different PV cell efficiency and different heating systems.

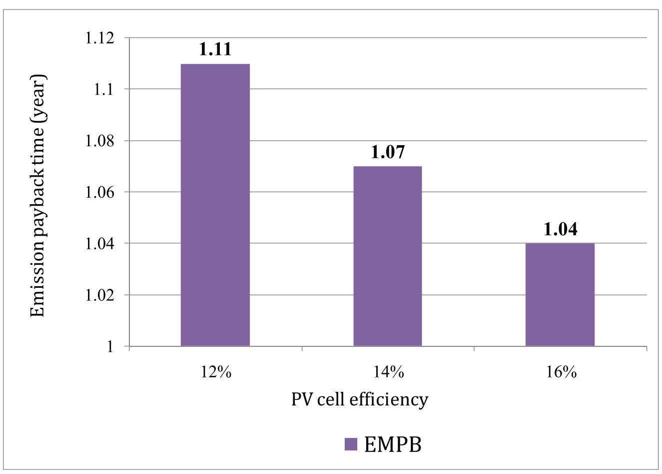

Fig. 10. Emission payback time for different PV cell efficiency (exergy optimization).

PV panels of 98.75% (area of PV panels - 79.6 m^2) and fraction of solar collectors of 1.25% (area of solar collector - 1 m^2). With this fraction of PV panels, the referent building with cell efficiency of 12% and electric heating system, has investment payback time of 16.9 years, and an annual profit of 1518 € (from solar systems), while building with district or gas heating, has investment payback time of 8.8 years and an annual profit of 2930 €. With the increase of PV cell efficiency, there is an increase in the annual financial profit, while at the same time, the investment payback period decreases. Fig. 11 shows the profit and investment payback period of solar systems, depending on the PV cell efficiency, for different heating systems. Building with PV cell efficiency of 14% and electric heating, has investment payback time of 12.1 years, and an annual profit of 2150 €, while building with district or gas heating, has investment payback time of 7.2 years and an annual profit of 3614 €. For PV system with PV cell efficiency of 16%, building with electric heating has investment payback time of 9.4 years, and an annual profit of 2795 €, while building with district or gas heating, has investment payback time of 6.1 years and an annual profit of even 4305 €.

According to the current feed-in tariff in Serbia, the highest payback time has PV system with the lowest cell efficiency (16.9 years). The higher cell efficiency means the shorter payback (for 14% - PB = 12.1 years, for 16% - PB = 9.4 years for building with electric heating). Numerical calculation showed that for a feed-in tariff of 0.35 €/kWh, the payback time is 6–10 years, depending on cell efficiency. For the feed-in tariff of 0.5 €/kWh, the payback time is 4–6 years, while for the feed-in tariff of 0.7 €/kWh, the investment payback time drops to 3–4.5 years, depending on heating system.

Next figure (Fig. 12) shows the results for surplus electricity ($E_{PV,S}$) sold to the electricity grid and net-purchased electricity from the grid ($E_{P,NET}$), obtained in the process of exergy efficiency optimization, for different values of PV cell efficiency and different heating systems (fraction of PV panels - 98.75%). Referent building with PV cell efficiency of 12% and electric heating has surplus sold electricity of 35.73 GJ and net-purchased electricity of 6.86 GJ. Buildings with gas heating and district heating have surplus sold electricity of 44.73 GJ and net-purchased electricity of −33.51 GJ. Negative value of purchased electricity means surplus sold electricity. With the increase of PV cell efficiency, there is an increase in surplus sold electricity, while at the same time, net-purchased electricity from the grid, decreases. Building with PV cell efficiency of 14% and electric heating, has surplus sold electricity of 44.04 GJ and net-

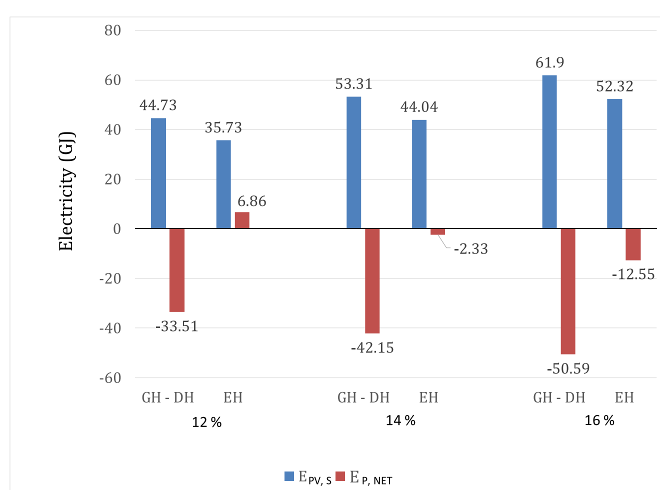

Fig. 12. Surplus sold electricity and net-purchased electricity for different PV cell efficiency and different heating systems.

purchased electricity of −2.33 GJ, while building with district or gas heating, has surplus sold electricity of 53.31 GJ and net-purchased electricity of −42.15 GJ. In a case of 16% of PV cell efficiency, building with electric heating has surplus sold electricity of 52.32 GJ and net-purchased electricity of −12.55 GJ, while building with district or gas heating, has surplus sold electricity of 61.9 GJ and net-purchased electricity of −50.59 GJ.

4. Conclusions

This paper represents exergy optimization of Serbian buildings, which was performed with the major aim to determine the maximum value of the exergy efficiency (without and with embodied exergy). On that way, the maximum value of the generated electricity can be achieved, and primary energy consumption can be minimized. Analyzed buildings had different heating systems: electric heating, district heating and gas heating.

With increasing the hot water temperature in DHW system, exergy efficiency and ratio of required and obtained exergy is increasing too, for all type of heating systems. It is possible to achieve PNEB in the building with gas heating system.

By using PV modules with cell efficiency of 14% and 16%, it is possible to generate significantly greater amount of electrical energy, compared with PV modules of 12% cell efficiency. With the increasing of PV cell efficiency, there is a significant increase in both the exergy efficiency. Ratios between required and obtained exergy e_x and $e_{x,\,EE}$, decreases with increasing PV cell efficiency. Concept of PNEB can be achieved with PV cell efficiency of 14% and 16% in the buildings with gas heating, and in the case of district heating - approach without embodied energy.

Hot water consumption also influence to exergy efficiency: with increasing the hot water consumption, exergy efficiency is increasing too, while the ratio of required and obtained exergy is decreasing. PNEB concept is possible in buildings with gas heating.

CO_2 emission and total CO_2 emission (with embedded emission) increases with increasing the amount of generated energy, and for PV system of cell efficiency of 12%, 14% and 16%, total CO_2 emission of installed solar systems is 20.8 kg CO_2/m^2, 23.5 kg CO_2/m^2 and 26.2 kg CO_2/m^2, respectively. The emission payback time decreases with increasing PV cell efficiency from 1.11 to 1.04 years, and it has the smallest value for PV cell efficiency of 16%.

Financial annual profit increases with the increase of PV cell efficiency, from 1518 (for the building with electric heating) to 4305 € (for the building with gas or district heating), while at the same time, the investment payback period decreases (from 16.9 to 6.1 years). Best results has the building with gas heating system.

Generally, with the proper choice of solar systems, it can be achieved a large value of exergy efficiency and, on that way building energy efficiency can be significantly improved due to minimizing the energy consumption. Also, in the case of gas heating systems, positive-net energy building concept may be achieved. PV system with the higher value of cell efficiency represent the good solution for improvement of building energy efficiency and environmental protection. Obtained results show that their emission payback time is very small and, also, these systems can be repaid in a short time period.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] C. Koroneos, M. Tsarouhis, Exergy analysis and life cycle assessment of solar heating and coling systems in the building environment, J. Clean. Prod. 32 (2012) 52–60.
[2] M. Bojić, N. Nikolić, D. Nikolić, J. Skerlić, I. Miletić, A simulation appraisal of performance of different HVAC systems in an office building, Energy Build. 43 (2011) 1207–1215, 6.
[3] D. Johari, A. Yadav, R. Verma, Study of solar water heaters based on exergy analysis, in: Proceedings of the National Conference on Trends and Advances in Mechanical Engineering, Faridabad, Haryana, 2012.
[4] R. Petela, Exergy of heat radiation, J. Heat Tran. 86 (1964) 187–192.
[5] R. Petela, Exergy of undiluted thermal radiation, Sol. Energy 74 (2003) 469–488, 6.
[6] Y. Candau, On the exergy of radiation, Sol. Energy 75 (2003) 241–247, 3.
[7] S.R. Park, A.K. Pandey, V.V. Tyagi, S.K. Tyagi, Energy and exergy analysis of typical renewable energy systems, Renew. Sustain. Energy Rev. 30 (2014) 105–123.
[8] A. Hepbasli, A key review on exergetic analysis and assessment of renewable energy resources for a sustainable future, Renew. Sustain. Energy Rev. 12 (2008) 593–661.
[9] N. Singh, S.C. Kayshik, R. Misra, Exergetic analysis of a solar thermal power system, Renew. Energy 19 (1–2) (2000) 135–143.
[10] C. Sunil, Exergy analysis of a flat plate solar collector, J. Energy South Afr. 24 (2013) 3.
[11] S. Farahat, F. Sarhaddi, H. Ajam, Exergetic optimization of flat plate solar collectors, Renew. Energy 34 (2009) 1169–1174, 4.
[12] H. Ajam, S. Farahat, F. Sarhaddi, Exergetic optimization of solar air heaters and comparison with energy analysis, Int. J. Therm. 8 (2005) 183–190, 4.
[13] S. Chamoli, Exergetic optimization of a flat plate solar collector, J. Energy South Afr. 24 (2013) 8–13, 3.
[14] R. Saidur, G. BoroumandJazi, S. Mekhlif, M. Jameel, Exergy analysis of solar energy applications, Renew. Sustain. Energy Rev. 16 (2012) 350–356.
[15] T. Fujisa, T. Tani, Annual exergy evaluation on photovoltaic-thermal hybrid collector, Sol. Energy Mater. Sol. Cell. 47 (1997) 1–4, 135–148.
[16] H. Saitoh, Y. Hamada, H. Kubota, M. Nakamura, K. Ochifuji, S. Yokoyama, K. Nagano, Field experiments and analyses on a hybrid solar collector, Appl. Therm. Eng. 23 (16) (2003) 2089–2105.
[17] F. Sarhaddi, S. Farahat, H. Ajam, A. Behzadmehr, Amin. Exergetic optimization of a solar photovoltaic array, J. Thermodynamics 4 (2009). Article ID 313561.
[18] A.S. Joshi, I. Dincer, B.V. Reddy, Thermodynamic assessment of photovoltaic systems, Sol. Energy 83 (2009) 1139–1149, 8.
[19] G. Evola, V. Costanzo, L. Marletta, Exergy analysis of energy systems in buildings, Buildings 8 (2018) 12.
[20] M. Kapsalaki, V. Leal, M. Santamouris, A methodology for economic efficient design of Net Zero Energy Buildings, Energy Build. 55 (2012) 765–778.
[21] J. Skerlic, M. Bojic, Optimizing performances of solar collectors by using EnergyPlus and Hooke Jeevs algorithm, in: Proceedings of 41h International HVAC&R Conference, 2010. Belgrade, Serbia.
[22] E.A. Alsema, E. Nieuwlaar, Energy viability of photovoltaic systems, Energy Pol. 28 (2000) 999–1010, 14.
[23] E.A. Alsema, Energy pay-back time and CO_2 emissions of PV systems, Prog. Photovoltaics Res. Appl. 8 (2000) 17–25, 1.
[24] E. Colombo, M.V. Rocco, C. Toro E. Sciubba, An exergy-based approach to the joint economic and environmental impact assessment of possible photovoltaic scenarios: a case study at a regional level in Italy, Ecol. Model. 318 (2015) 64–74.
[25] F. Ardente, G. Beccali, M. Cellura, V. Lo Brano, Life cycle assessment of a solar thermal collector, Renew. Energy 30 (2005) 1031–1054.
[26] F. Ardente, G. Beccali, M. Cellura, V. Lo Brano, Life cycle assessment of a solar thermal collector: sensitivity analysis, energy and environmental balances, Renew. Energy 30 (2005) 109–130.
[27] S. Kalogirou, Environmental benefits of domestic solar energy systems, Energy Convers. Manag. 45 (2004) 3075–3092.
[28] R. Battisti, A. Corrado, Environmental assessment of solar thermal collectors with integrated water storage, J. Clean. Prod. 13 (2005) 1295–1300.
[29] D. Nikolic, Energy and Exergy Optimization of Photovoltaic and Solar Collectors Area at Zero-Net Energy Building. PhD Thesis 2015, Faculty of engineering, University of Kragujevac, Serbia, 2015.
[30] N. Lukić, M. Babić, Solar Energy, Faculty of mechanical engineering, Kragujevac, Serbia, 2008.
[31] L.F. Cabeza, L. Rincón, V. Vilariño, G. Pérez, A. Castell, Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: a review, Renew. Sustain. Energy Rev. 29 (2014) 394–416.

[32] NREL Laboratory, Life Cycle Greenhouse Gas Emissions from Solar Photovoltaics, http://www.nrel.gov/docs/fy13osti/56487.pdf, (accessed March 2021.).
[33] Emission Gap Report, 2020. https://www.unep.org/emissions-gap-report-2020. (Accessed February 2021).
[34] The British Centre for Alternative Technology CAT, https://www.cat.org.uk, (accessed February 2021.).
[35] M. Bojić, N. Nikolić, D. Nikolić, J. Skerlić, I. Miletić, Toward a positive-net-energy residential building in Serbian conditions, Appl. Energy 88 (2011) 2407–2419, 7.
[36] Energetski portal, https://www.energetskiportal.rs/ministarstvo/fid-in-tarife/. February 2021.
[37] Elektroprivreda Srbije, http://www.eps.rs/lat/snabdevanje/Stranice/cene.aspx, (accessed February 2021.).
[38] M. Bojić, J. Skerlić, D. Nikolić, D. Cvetković, M Miletić. Toward future: positive net-energy buildings. Proc. of 4th IEEE International Symposium on Exploitation of Renewable Energy Sources - EXPRES 2012, Subotica, Serbia.