Exergy optimization of buildings with different solar systems

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- Exergy, as a measure of useful work that can be obtained by the interaction of the system and the environment, is widely used in the design, simulation and performance evaluation of energy systems.
- Exergy analysis quantifies the losses of efficiency in a process due to the losses in energy quality.
- Today, solar energy is considered as an attractive source of renewable energy that can be used for electricity generation and domestic water heating in residential buildings.
- Using photovoltaics and solar collectors together, represent a great opportunity for reducing the consumption of primary energy in residential buildings.
- This paper reports investigations of the exergy optimization, with the major aim to determine the optimal size of PV panels and solar collectors on the roof, in order to achieve the maximum amount of exergy.

- The residential building with variable PV cell efficiency is analyzed.
- The investigated building was located in Kragujevac, Serbia.
- The building is designed with PV panels and solar collectors installed on the roof.
- Analyzed building has an electrical space heating system.

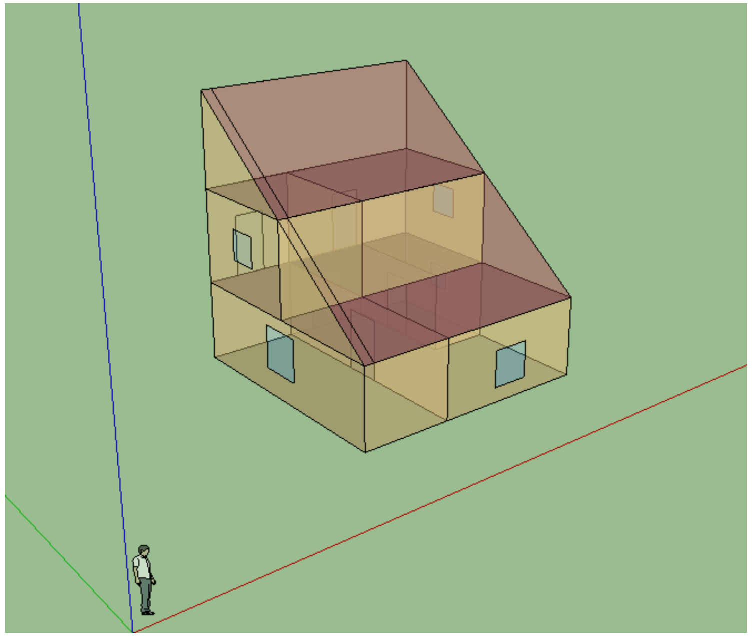
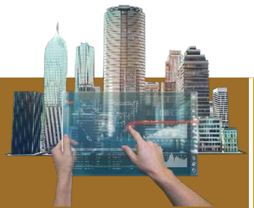


Figure 1 - Modeled residential building

SIMULATION SOFTWARES AND CLIMATE

- **EnergyPlus -** simulates the energy use in a building and energy behavior of the building for defined period.
- **Open Studio** is free plug-in that adds the building energy simulation capabilities of EnergyPlus to the 3D SketchUp environment.
- **GenOpt** is an optimization program for the minimization of a cost function evaluated by an external simulation program.
- **Hooke–Jeeves Algorithm** is used for the optimization, and it is direct search and derivative free optimization algorithm.
- The investigated residential building was located in the city of Kragujevac, which has the moderate continental climate. Summers are very warm and humid and winters are cool and snowy. The EnergyPlus uses weather data from its own database file.



BUILDING MODEL IN ENERGYPLUS SOFTWARE

- The building has the south-oriented roof with a slope of 37.5^0, and PV array and solar collectors installed on the roof.
- The building has two floors and 6 conditioned zones.

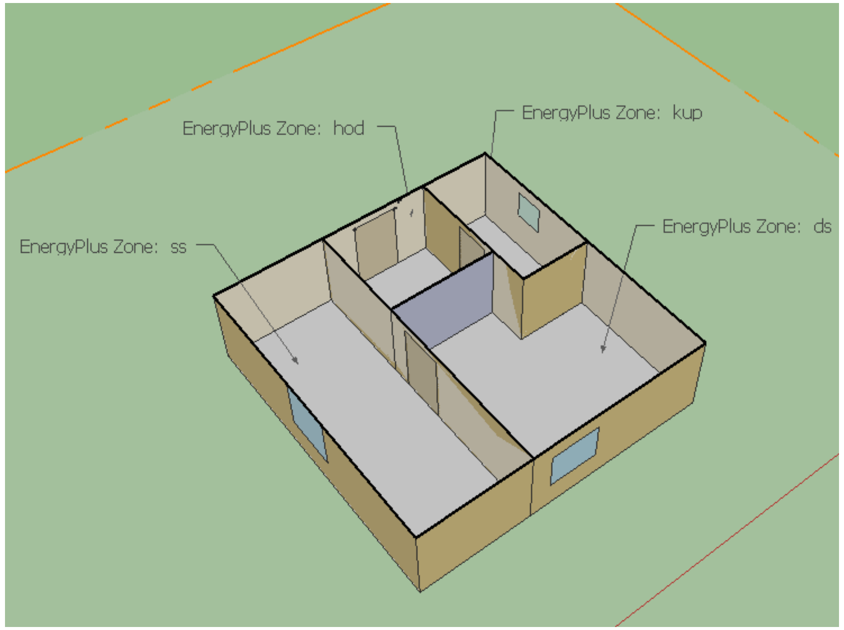


Figure 2- Modeled residential building

- The total floor area of the building is 160 m^2 and total roof area 80.6 m^2.
- The windows are double glazed. The concrete building envelope, roof, and the floor were thermally insulated by polystyrene.
- The PV system is an on-grid system. The main part of exergy (i.e. electricity) obtained from PV array, is consumed for electrical space heating in the building. Additionally, electricity was consumed for lighting, domestic hot water (DHW) and appliances.
- Exergy obtained from solar collectors is equal to the sum of exergy of the end consumers: shower, sink, cloth washing machine and dish washing machine.
- 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).

OPTIMIZATION PROCEDURE

- Through exergy optimization, the maximum value of the exergy efficiency of the system of photovoltaic panels and solar collectors is determined.
- Objective function in optimization procedure is exergy efficiency without embodied exergy:

$$\eta_X = \frac{E_{X,PV-KOL}}{E_{X,SUN}}$$

Where:

- $E_{x,\ SUN}$ – Sun exergy,
- $E_{x,\ PV\text{-}KOL}$ – exergy obtained by PV array and solar collectors, and it is equal to the sum of exergy obtained by the PV array and exergy obtained by the solar collectors

- It is also calculated the exergy efficiency with embodied exergy:

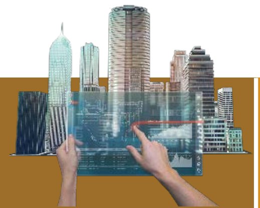
$$\eta_{X,EE} = \frac{E_{X,PV-KOL,EE}}{E_{X,SUN}}$$

Where $E_{x,\ PV\text{-}KOL,\ EE}$ is exergy obtained from PV array and solar collectors, with their embodied exergy.

- Through the exergy optimization, it is also calculated the ratios between required and obtained exergy e_x and $e_{x,\ EE}$ (without and with embodied exergy of solar systems):

$$e_X = \frac{E_{X,POT}}{E_{X,PV-KOL}} \qquad e_{X,EE} = \frac{E_{X,POT}}{E_{X,PV-KOL,EE}}$$

In the proces of exergy optimization, it is calculated total electricity consumption E_{EL} (GJ), primary energy consumption (GJ), generated finaly and primary energy (GJ), and avoided operative primary energy.

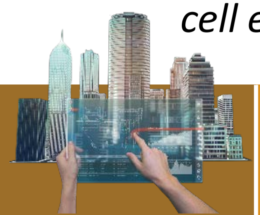


RESULTS AND DISSCUSION

› The residential building with variable cell efficiency of PV array was analyzed (12 %, 14 % and 16 % of cell efficiency).

	PV cell efficiency		
	12 %	14 %	16 %
η_x - exergy efficiency without embodied exergy (%)	12,64	14,71	16,78
$\eta_{x, EE}$ - exergy efficiency with embodied exergy (%)	7,63	9,71	11,78
e_x - ratio between required and obtained exergy (without embodied exergy)	1,075	0,9236	0,8095
$e_{x, EE}$ - ratio between required and obtained exergy (with embodied exergy)	1,78	1,4	1,153
$E_{x, POT}$ - total consumer exergy (GJ)	54,45	54,45	54,45
$E_{x, PV\text{-}KOL}$ – exeegy obtained by solar systems (without embidied exergy) (GJ)	50,65	58,96	67,26
$E_{x, PV\text{-}KOL, EE}$ - exeegy obtained by solar systems (with embidied exergy) (GJ)	30,6	38,91	47,21
E_{EL} - Total electricity consumption (GJ)	68,36	68,36	68,36
$E_{EL,PRIM}$ - Primary energy consumption (GJ)	207,81	207,81	207,81
Fraction of PV panels on the roof (%)	98,75	98,75	98,75
Generated energy (GJ)	55,68	64,42	73,17
Generated primary energy (GJ)	169,27	195,85	222,43
E_{PRIM}– avoided operative primary energy (GJ)	149,02	175,6	202,18
Building type (without embodied energy)	**NNEB**	**NNEB**	**PNEB**
Building type (with embodied energy)	**NNEB**	**NNEB**	**NNEB**

Table 1 *– The results obtained by exergetic optimization, for residential building with varieble cell efficiency of PV array*



- With the increasing of PV cell efficiency, there is a significant increase in both of the exergy efficiency (with and without embedded exergy).

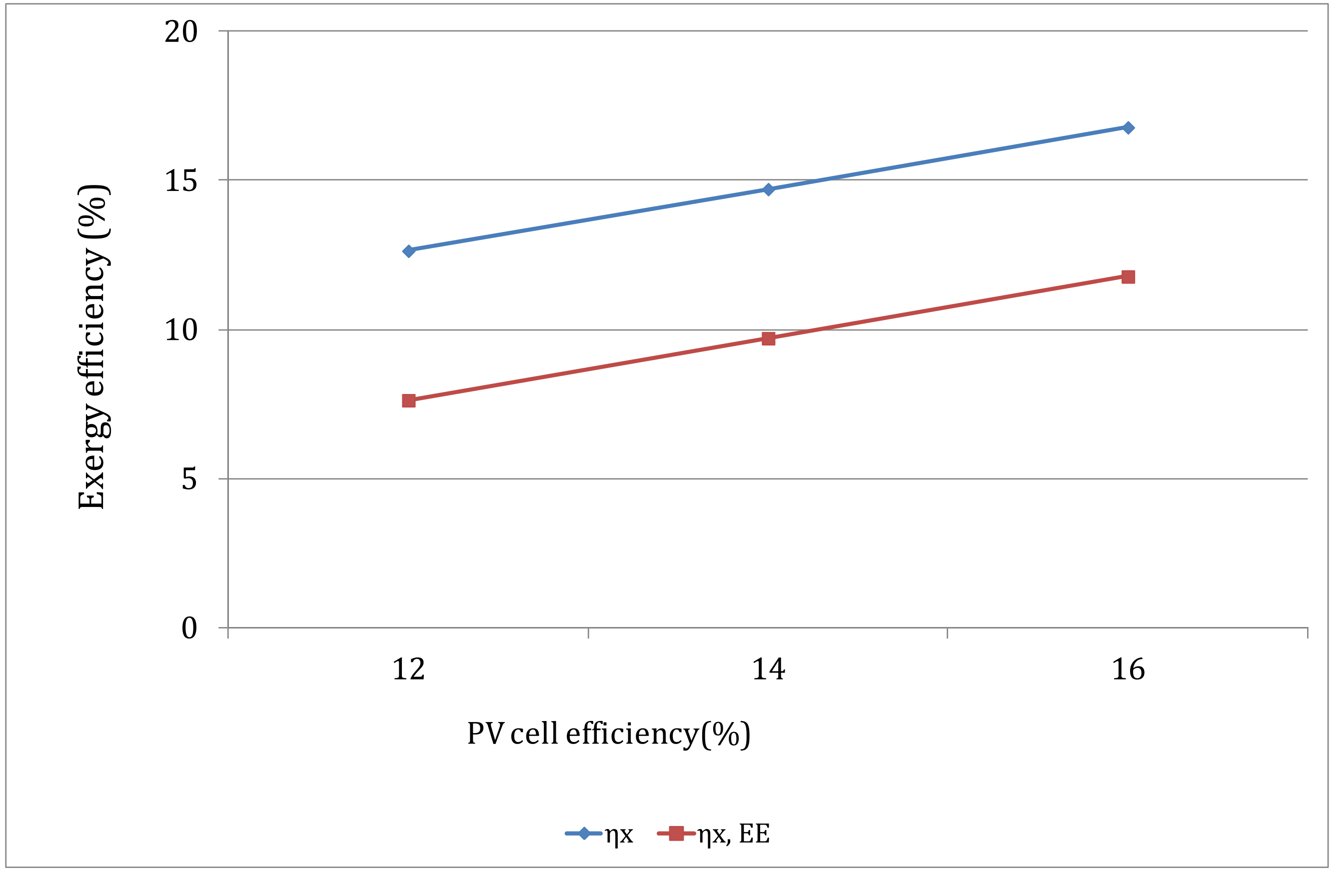


Figure 3 – Exergy efficiency for building with defferent cell efficiency

- Ratio between required and obtained exergy e_x and $e_{x,\ EE}$ (with and without embodied exergy), decreases with increasing PV cell efficiency.
- With the implementation of PV module with cell efficiency of 14% and 16%, it can be achieved the value of ratio between required and obtained exergy which is less then 1. This means that installed solar system generates more exergy than required exergy.

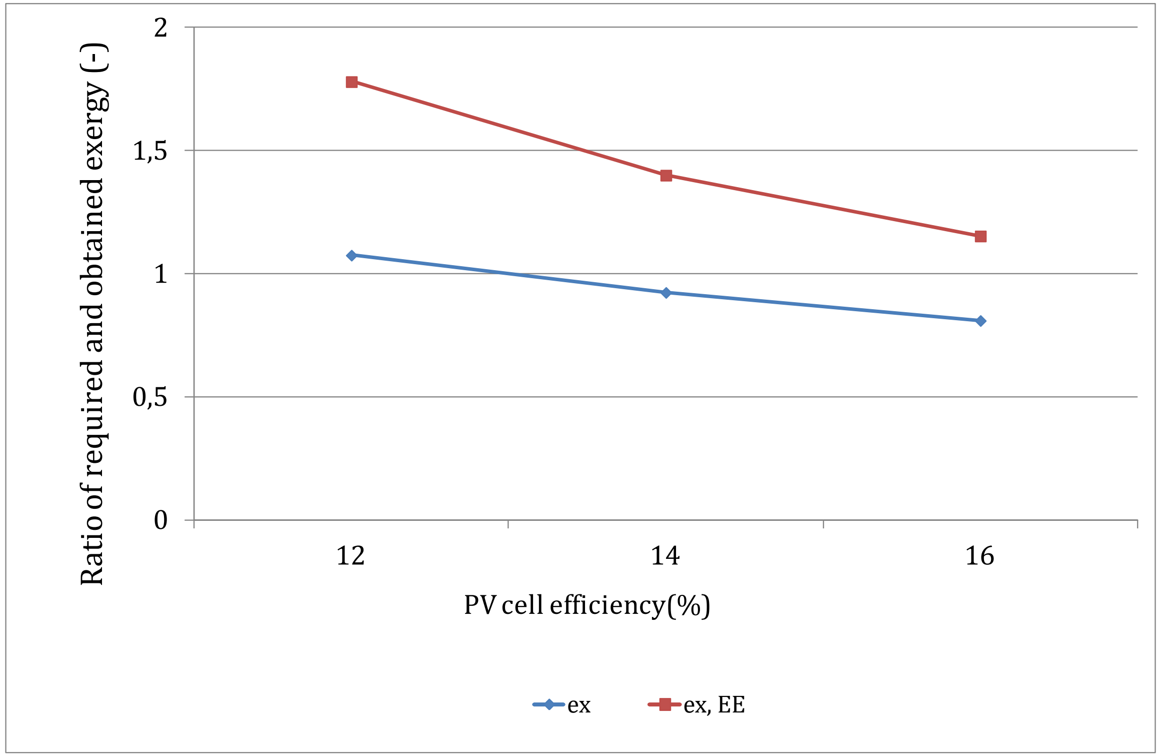


***Figure 4** – Ratio between required and obtained exergy for building with defferent cell efficiency*

- Required exergy of all building consumers and exergy obtaned from solar systems (with or without embodied exergy) for different PV cell efficiency and electric heating system.
- With PV cell efficiency increasing, exergy obtained from the solar system increases too.

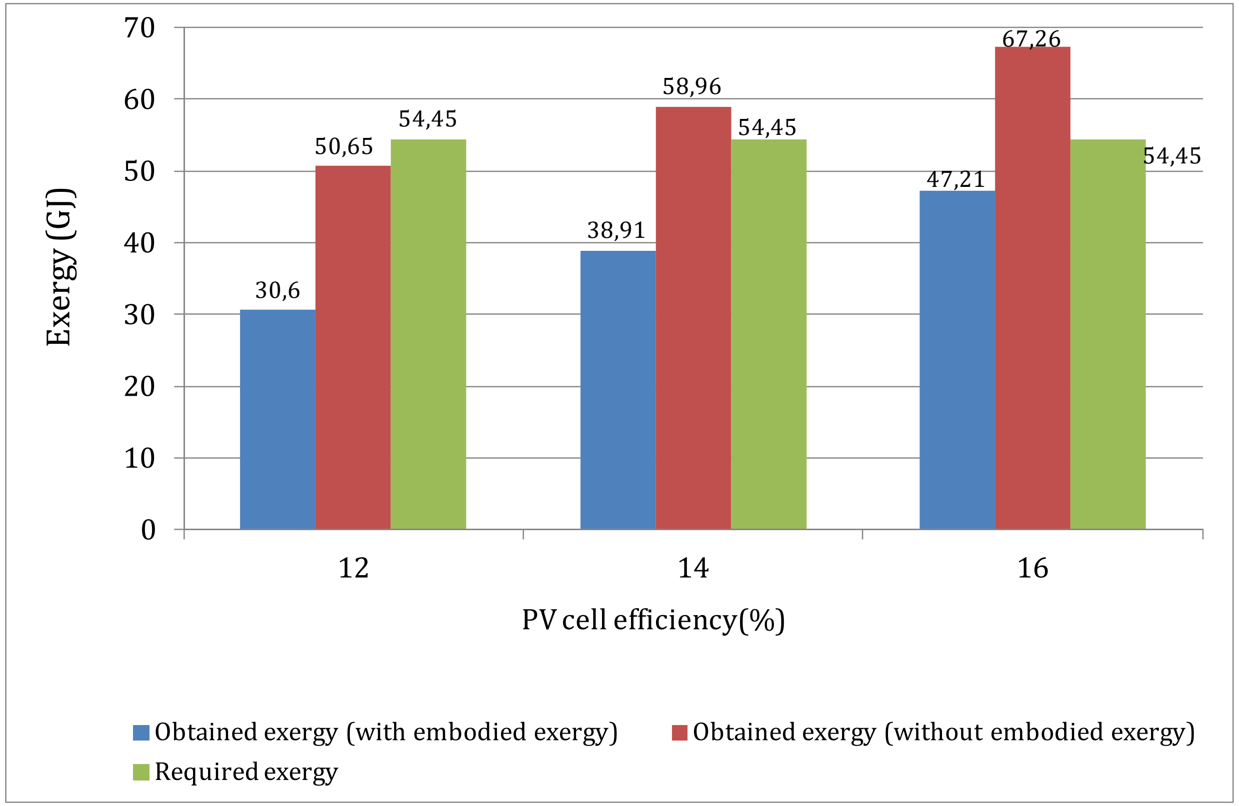


Figure 5 – Required and obtained exergy for building with defferent PV array cell efficiency

- Figure 6 - total electricity consumption, primary energy consumption, generated primary energy and avoided operative primary energy consumption in building with different cell efficiency of PV array.
- By using the PV array with 12 % and 14 % of cell efficiency, building will be NNEB. By using the PV array with 16 % of cell efficiency, it is possible to achieve the concept of positive-net energy building (PNEB) without embodied energy of installed solar systems and insulation.

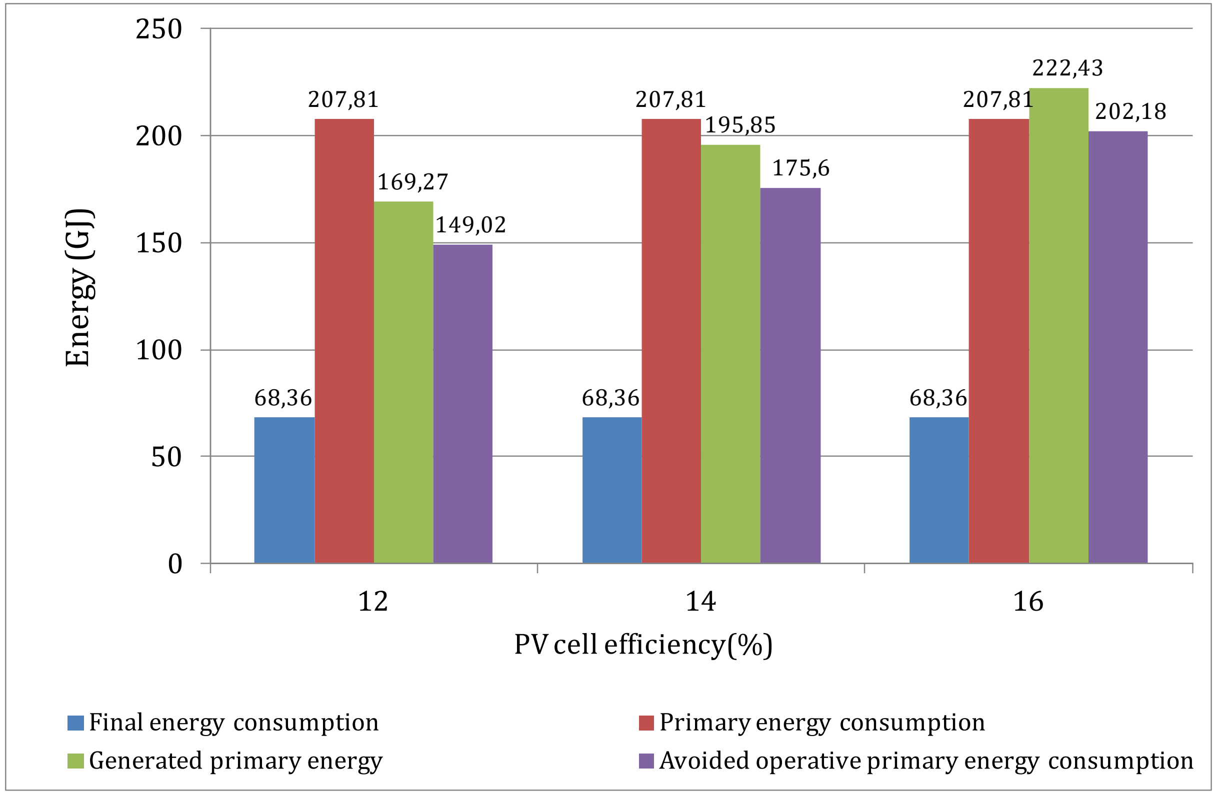


Figure 6

CONCLUSION

- In this paper exergy optimization was performed with the major aim to determine the maximum value of the exergy efficiency. On that way, the maximum value of the generated electricity can be achieved and primary energy consumption can be minimized.
- By using PV modules with greater cell efficiency (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 the exergy efficiency.
- Ratio between required and obtained exergy e_x and $e_{x,\ EE}$ decreases with increasing PV cell efficiency. If the values of ratio between required and obtained exergy is less then 1, then installed solar system generates more exergy than required exergy.
- By using the PV array with 14 % and 16 % of cell efficiency, building can produce more electricity, so the concept of PNEB can be achieved with PV cell efficiency of 16 %.