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INFLUENCE OF HOT WATER TEMPERATURE IN DHW SYSTEM ON BUILDING EXERGY OPTIMIZATION

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Abstract: Exergy can be used for the optimization of energy losses in different energy system. Exergy is also used for design and performance evaluation of energy systems. In this paper it is investigated the Serbian residential building with photovoltaics and solar collectors on the roof. The building has electrical space heating. Exergy optimization (including embodied exergy) was performed with the aim to determine the maximum value of the generated electricity. The residential buildings with variable temperature in DHW system are investigated. It is also analyzed building energy consumption with or without embodied energy of solar systems. The buildings were simulated in EnergyPlus, Open Studio plug-in in Google SketchUp was used for buildings design and Hooke-Jeeves algorithm for optimization. GENOPT was used for software execution control during optimization.
Keywords: Exergy; Photovoltaic; Solar collector; Simulation; Optimization

1. INTRODUCTION

Performances of energy-related engineering systems are evaluated primarily by using the energy balance. In recent years, the exergy concept has gained considerable interest in the thermodynamic analysis of thermal processes [1]. The exergy analysis is a method based on the Second law of thermodynamics and it quantifies the loss of efficiency in a process that is due to the losses in energy quality.

At the other side, due to increasing demand for energy and rising cost of fossil fuels, solar energy is considered an attractive source of renewable energy that can be used for electricity generation and domestic water heating in residential buildings. Photovoltaic (PV) technology is an attractive option for clean and renewable electricity generation because it represents the direct conversion of solar radiation into electricity. Electrical energy can be treated as totally convertible to work, so the electricity is pure exergy. Also, heating water consumes nearly 20% of total energy consumption for an average family [2]. So, solar water heating systems are the cheapest and most easily affordable clean energy available to homeowners that may provide most of hot water required by a family. Using PVs 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. On that way, it can be obtain the maximum value of exergy efficiency for installed solar systems, and primary energy consumption will be minimized. The residential building with variable temperature in DHW system is analyzed. The investigated building was located in Kragujevac, Serbia. The building is designed with PV panels and solar collectors installed on the roof. Generated heat energy is used for domestic hot water (DHW) heating. Electricity generated by the PV may be used for space heating, cooling, lighting, and electric equipment. Analyzed building has an electrical space heating system. Heating devices operated from 15 October to 14 April next year.

In this paper, the EnergyPlus, Open Studio plug-in in Google SketchUp, Hooke-Jeeves algorithm and Genopt were used for simulation and optimization.

2. SIMULATION SOFTWARES AND CLIMATE

- **EnergyPlus** software simulates the energy behavior of the building for defined period. In this study, the version 8.1.0 was used. EnergyPlus is made available by the Lawrence Berkley Laboratory in USA [3] and it has been tested using the IEA HVAC BESTEST E100-E200 series of tests [4]. For PV electricity generation, EnergyPlus uses the different component, like PV array and inverter [5].
- **Open Studio** plug-in is a free 3D software tool that combines a tool-set with an intelligent drawing system [6]. The software enables to place models using real world coordinates. The OpenStudio 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 cost function evaluated by an external simulation program. GenOpt serves for optimization problems where the cost function is computationally expensive and its derivatives are not available or may not even exist. It can be coupled to any simulation program that reads its input from text files and writes its output to text files. GenOpt is written in Java so that it is platform independent. It has a library with adaptive Hooke-Jeeves algorithm [7].
- Hooke–Jeeves optimization algorithm is used for the optimization, and it is direct search and derivative free optimization algorithm [8]. 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.
- Climate. The investigated residential building was located in the city of Kragujevac, Republic of Serbia. Its average height above sea level is 209 m. Its latitude is $44^0 10$ N and longitude $20^0 55$ E. The time zone for Kragujevac is GMT+1 h. In the city of Kragujevac summers are very warm and humid, with temperatures as high as 37^0C. The winters are cool, and snowy, with temperatures as low as -12^0C. The EnergyPlus uses weather data from its own database file.

3. MATHEMATICAL MODEL

Modeled building in energyplus software

The modeled residential building in EnergyPlus software is shown in Figure 1. The building has the south-oriented roof with a slope of 37.5^0, with PV array and solar collectors installed on the roof. The building has two floors with total floor area of 160 m^2 and total roof area of 80.6 m^2. The windows are double glazed. The concrete building envelope, roof, and the floor were thermally insulated by polystyrene (thermal insulation thickness - 0.15 m). Air temperatures in the heated rooms are set to 20^0C from 07:00-09:00 and from 16:00-21:00, and to 15^0C from 09:00-16:00. The simulation time step is 15 min.

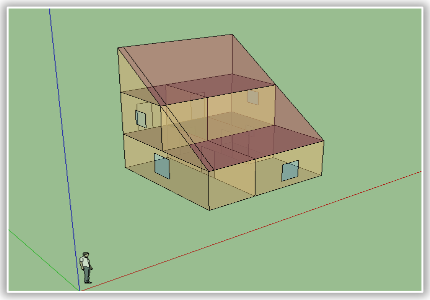

Figure 1. Modeled residential building

The PV system consists is an on-grid system. 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 [9, 10], and the embodied exergy of PV panels is set to 5 GJ/m^2 [11]. The PV panel is represented by the mathematical model of Photovoltaic:Simple from EnergyPlus [4]. The life cycle of solar collectors is also set to 20 years, the embodied energy of solar collectors is set to 2.75 GJ/m^2 [11], and the embodied exergy of solar collectors is set to 3.8 GJ/m^2 [11].

The main part of exergy (i.e. electricity) obtained from PV array ($E_{X,PV}$), is consumed for electrical space heating in the building. Additionally, electricity was consumed for lighting, domestic hot water (DHW) 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) [11].

Optimization procedure

Exergy optimization gives the maximum value of the exergy efficiency of the system of PV panels and solar collectors [12]. The maximum exergy efficiency is achieved at the optimal size of PV array and solar collectors, which is given by the roof area covered with PV array in the optimization code (value y). The value y exists in the calculated total exergy of PV system and solar collectors. 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 (J), $E_{X,PV-KOL}$ (J) – exergy obtained by PV array and solar collectors, and it is equal to the sum of exergy obtained by the PV array ($E_{X,PV}$) and exergy obtained by the solar collectors ($E_{X,KOL}$), i. e.

$$E_{X,PV-KOL} = E_{X,PV} + E_{X,KOL}$$

It is also calculated the exergy efficiency with embodied exergy:

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

where: $E_{X,PV-KOL,EE}$ (J) – exergy obtained from PV array and solar collectors, with their embodied exergy. This value is equal to the subtraction of exergy obtained by the PV array and solar collectors ($E_{X,PV-KOL}$) and embodied exergy of PV array (EE_{PV}) and solar collector (EE_{KOL}), i. e.

$$E_{X,PV-KOL,EE} = E_{X,PV-KOL} - EE_{PV} - EE_{KOL}$$

Through the exergy optimization, it is also calculated some other parameters, which can be very useful as a valid indicators of the exergy flows in the analyzed solar systems. They are ratios between required and obtained exergy ex and ex, $_{EE}$ (without and with embodied exergy of solar systems):

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

where: $E_{X,POT}$ – total consumer exergy (J) (sum of needed exergy of all consumers, yearly). Ratios of required and obtained exegy should be as small as possible.

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 E_{PRIM}. Avoided operative primary energy consumption due to operation of the solar systems (J) is [13]:

$$E_{PRIM}=R_{EL}(E_{PV}+E_{COLL})-Cm((E_{em,PV}+E_{em,COLL})C_{inst})-C_{m1}E_{em,ISO}$$

where: R_{EL}=3.04 - primary conversion multiplier; E_{PV} – yearly electrical energy generated by PV array (J); E_{COLL} – yearly heat 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, in years, Cm1=1/LC_{ISO}; where LC_{ISO} is life cycle of thermal isolations, in years, $E_{em,ISO}$ – insulation embodied energy (J) [13] and C_{inst} – coefficient of instalation and maitenance of solar systems during their life cycle [14].

4. RESULT AND DISCUSSION

Exergy optimization (including embodied exergy) was performed with the aim to determine the maximum value of the exergy efficiency. The residential building with electrical space heating and with variable water temperature in the hot water tank (central part of DHW system) was analyzed. The first case was the hot water temperature 50 °C (referent case), the second case was the hot water temperature 60°C and the third case was the hot water temperature of 70 °C, respectively. Due to different required hot water temperature, there was a small change in electricity consumption, which referred to the electricity for the operation of electrical appliances and for water heating. Results obtained by exergetic optimization are given at Table 1. Acording to the table, 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 embedded exergy). Exergy efficiency ηx for hot water temperature of 50 °C, 60 °C and 70 °C are 12.64%, 12.83% and 12.84%, respectively, while the exergy efficiency ηx,EE for the same values of hot water temperature are 7.63%, 7.82% and 7.83%, respectively. Preview the two of these exergy efficiencies is given in Figure 2.

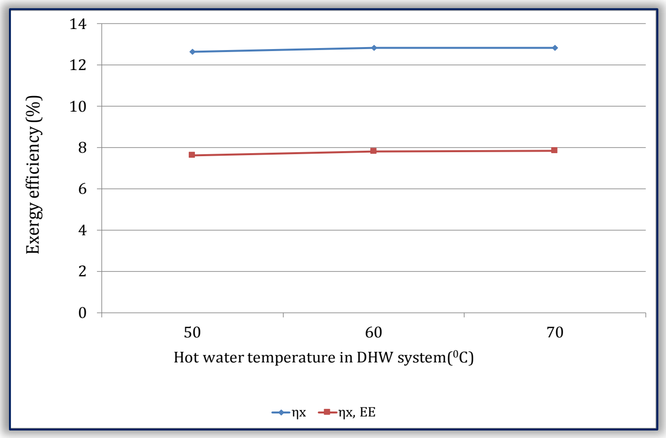

Figure 2. Exergy efficiency for building with defferent hot water temperature

Table 2. The results obtained by exergetic optimization, for residential building with variable hot water temperature in DHW system

	Hot water temperature		
	50°C	60°C	70°C
η_x - exergy efficiency without embodied exergy (%)	12.64	12.83	12.84
$\eta_{x,EE}$ - exergy efficiency with embodied exergy (%)	7.63	7.82	7.78
e_x - ratio between required and obtained exergy (without embodied exergy)	1.075	1.101	1.143
$e_{x,EE}$ - ratio between required and obtained exergy (with embodied exergy)	1.78	1.804	1.874
$E_{x,POT}$ - total consumer exergy (GJ)	54.45	56.58	58.82
$E_{x,PV-KOL}$ – exeegy obtained by solar systems (without embidied exergy) (GJ)	50.65	51.41	51.44
$E_{x,PV-KOL,EE}$ - exeegy obtained by solar systems (with embidied exergy) (GJ)	30.6	31.36	31.39
E_{EL} - Total electricity consumption (GJ)	68.36	69	69.67
$E_{EL,PRIM}$ - Primary energy consumption (GJ)	207.8	209.8	211.8
Fraction of PV panels on the roof (%)	98.75	98.75	98.75
Generated energy (GJ)	55.68	55.68	55.68
Generated primary energy (GJ)	169.3	169.3	169.3
E_{PRIM}– avoided operative primary energy (GJ)	149	149	149
Building type (without embodied energy)	NNEB	NNEB	NNEB
Building type (with embodied energy)	NNEB	NNEB	NNEB

Required exergy of all building consumers and exergy obtaned from solar systems (with or without embodied exergy) for different hot water temperature and electric heating system, are graphically shown in Figure 3.

When hot water temperature increases, exergy obtained from the solar system increases too. Compared to the referent case (hot water temperature of 50 ^{0}C and total required of 54.45 GJ), in the case of hot water temperature of 60^{0}C required exergy is greater for 2.13 GJ (3.9%); in the case of hot water temperature of 70 ^{0}C required exergy is greater for 4.37 GJ (8%).

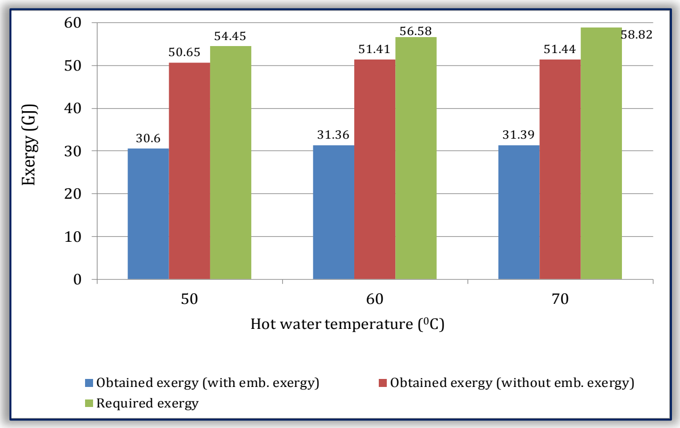

Figure 3. Required and obtained exergy for building with defferent hot water temperature

Figure 4 represents total electricity consumption, primary energy consumption, generated primary energy and avoided operative primary energy consumption 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 % (79,6 m^2 of PV panels and 1 m^2 of solar collector), and building generates 169.3 GJ of primary energy, while maximum avioded operative primary energy is 149 GJ.

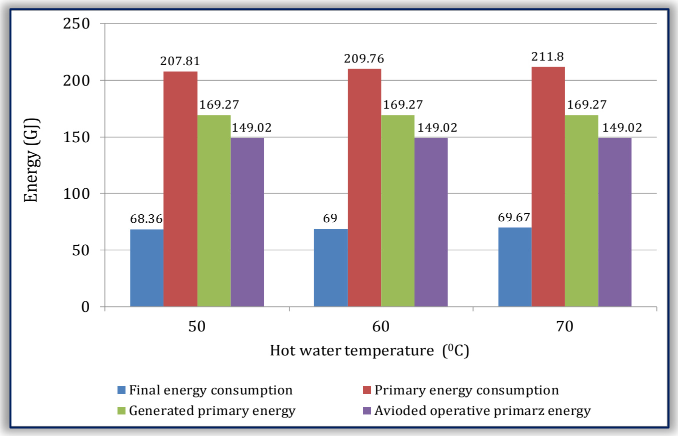

Figure 4. Total electricity consumption, primary energy consumption, generated primary energy and avoided operative primary energy for buildings with different hot water temperature (Yearly values)

5. CONCLUSION

The major aim of this investigation was optimization to determine the optimal area of PV array due to achieving the maximum avoided primary energy consumption of the buildings. The investigation shows that in all cases it is the maximum roof coverage with PV arrays. All the buildings were neto-negative energy building (NNEB) - with or without consideration of embodied energy. In the case of some other, low-temperature, heating system, positive-net energy building (PNEB) concept may be acchieved.

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