ENERGY OPTIMIZATION OF SERBIAN BUILDINGS WITH SOLAR COLLECTORS AND DIFFERENT PV SYSTEMS

ENERGETSKA OPTIMIZACIJA SRPSKIH KUĆA SA SOLARNIM KOLEKTORIMA I RAZLIČITIM FOTONAPONSKIM SISTEMIMA

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In the modern world today, the significant part of the total energy consumption is related to the building, so research and development of methods for improving energy efficiency in buildings are very important. In this paper it is investigated the Serbian residential building with photovoltaic panels and solar collectors on the roof. The building with electrical space heating is analyzed. Energy optimization (including embodied energy) was performed with the major aim to determine the optimal area of the PV array and solar collector area on the roof. With the optimal PV and solar collector areas, primary energy consumption may be minimized. The residential buildings with variable PV cell efficiency are investigated in order to achieve zero-net energy building (ZNEB) or positive-net energy building (PNEB).

The buildings are simulated in EnergyPlus environment. Open Studio plug-in in Google SketchUp was used for buildings design, Hooke-Jeeves algorithm for optimization and GENOPT software for software execution control. The obtained results gave the optimal size of PV array and solar collectors system. With these optimal sizes, the concept ZNEB and PNEB can be achieved.

Key words: *ZNEB; Photovoltaic; Solar collector; Simulation; Optimization;*

U modernom svetu danas, značajan udeo u ukupnoj potrošnji energije se odnosi na zgrade, pa su istraživanja i razvoj metoda za poboljšanje energetske efikasnosti zgrada veoma važne. U ovom radu je analizirana srpska kuća koja na krovu ima sistem solarnih kolektora i sistem fotonaponskih panela. Analizirana je zgrada sa električnim sistemom grejanja. Energetska optimizacija (uključujući ugrađenu energiju) je rađena sa glavnim ciljem da se odredi optimalna površina fotonaponskih panela i solarnih kolektora na krovu. Sa optimalnim vrednostima njihovih površina, potrošnja primarne energije se minimizira. Istraživana je stambena zgrada sa fotonaponskim panelima različite ćelijske efikasnosti u cilju dostizanja koncepta neto-nulte energetske zgrade (ZNEB) ili neto-pozitivne energetske zgrade (PNEB).

Zgrade su simulirane u okruženju softvera EnergyPlus. Open Studio plug-in u Google SketchUp-u je korišćen za dizajniranje zgrade, Hooke-Jeeves algoriam za optimizaciju i GENOPT softver za izvršnu kontrolu softvera pri optimizaciji. Dobijeni rezultati su dali optimalne vrednosti površine PV panela i solarnih kolektora. Sa ovim vrednostima je moguće dostići koncept ZNEB ili PNEB.

Ključne reči: *Neto-nulta energetska zgrada (ZNEB); fotonaponski (PV) paneli; solarni kolektori; optimizacija; simulacija;*

I. INTRODUCTION

The concept of Zero Net-Energy Building (ZNEB) has wide international attention during last few years and is now seen as the future target for the design of buildings. However, before being fully implemented in the national building codes and international standards, the ZNEB concept requires clear and consistent definition. Kapsalaki [1] defined the concept of the ZNEB like a building which produces all energy it consumes during year, and 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, and yearly electrical energy supplied to the electricity grid is higher than the amount received from the electricity grid, and Negative-Net Energy Building (NNEB) produces less energy than it consumes during the [2, 3].

Solar energy is the leading chain of sustainable development. When one observes the development programs of energy systems in the countries or nations that move towards sustainable development, it is found that the solar energy (and through it the production of energy through photovoltaic's) represents the main axis of development. At the other side, a great amount of heat energy can be obtained by solar collectors. So, using of photovoltaic and solar collectors represent a significant opportunity to energy generation and reducing the consumption of primary energy. On that way, the green house emission can be minimized.

In this paper, energy consumption is analyzed for a residential building located in Kragujevac, Serbia. The building is designed with PV array and solar collectors installed on the roof – Figure 1.

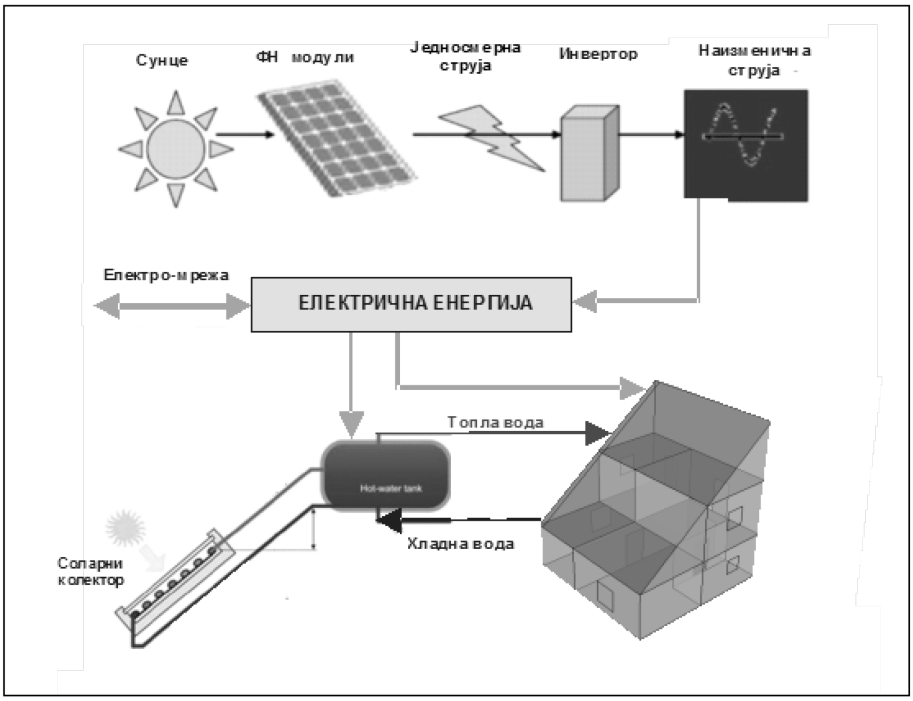

Figure 1 – Positive-Net Energy Building with PV array and solar collectors

From solar energy, the building produces heat energy by the solar collectors on its roof. Generated heat energy is used for domestic hot water (DHW) heating. Also, from solar energy, the building produces electrical energy by the PV array on its roof. Electricity generated by the PV array is limited by the size of PV array. When 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 electricity needs, then the rest of PV generated electricity will be fed-in the electricity grid. In buildings, energy is used for space heating and cooling, lighting, and electric equipment. The analyzed building has an electrical space heating system.

The major objective of this investigation is to determine the optimal sizes of PV panels and solar collectors on the roof, in order to minimize the consumption of primary energy. In order to achieve zero-net energy building or positive net-energy building, the buildings are investigated for variable cell efficiency of PV panels.

In this paper, the EnergyPlus, Open Studio plug-in in Google SketchUp, Hooke-Jeeves algorithm, and Genopt were used to achieve this objective.

II. SIMULATION SOFTWARES AND CLIMATE

A. Software

EnergyPlus software simulates the energy use in a building and energy behavior of the building for defined period. EnergyPlus is made available by the Lawrence Berkley Laboratory in USA [4] and it has been tested using the IEA HVAC BESTEST E100-E200 series of tests [5]. For PV electricity generation, EnergyPlus uses the three different PV models and model of inverter [6].

Open Studio plug-in in Google SketchUp software is a free 3D software tool that combines a tool-set with an intelligent drawing system [7]. 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 a cost function evaluated by an external simulation program [8]. GenOpt is written in Java so that it is platform independent. It has a library with adaptive Hooke-Jeeves algorithm.

Hooke–Jeeves optimization algorithm is used for the optimization, and it is direct search and derivative free optimization algorithm [9]. 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.

B. 2.2 Climate

The analyzed building is located at Kragujevac, Serbia. Kragujevac lays in Balkan Peninsula. Its average height is 209 m above sea-level. The latitude of Kragujevac is 44.1^{0}N, and the longitude is 20.55^{0}E. The time zone is GMT+1.0 h. The summers are worm and humid with temperatures as high as 37^{0}C. The winters are cold with snow and temperatures as low as - 19^{0}C. The EnergyPlus uses weather data from its own database file.

III. MATHEMATICAL MODEL

A. EnergyPlus Model for the residential building

The investigated building is shown in Figure 2. The building has the south-oriented roof with the slope of 37.5^0. On the roof, the PV array and solar collectors are installed. The building has two floors and 6 conditioned zones. There are two attic zones. The working period of the heating systems is from October 15th to April 14th (07:00–21:00 h). Air temperatures in the heated rooms are set to 20^{0}C from 07:00-09:00 and from 16:00-21:00, and to 15^{0}C from 09:00-16:00. The simulation time step is 15 min. The amount of infiltration is 1.5 ach^{-1}.

The building has the total floor area of 160 m^2. Total area of external walls is 200 m^2 and total roof area is 80.6 m^2. The windows are double glazed. The concrete building envelope, roof and the floor are thermally insulated by polystyrene (thickness 0.15 m).

The main part of electricity, in the case of the electrical heating, was consumed for electrical space heating in the building (E_{EH}). Additionally, electricity was consumed for lighting, domestic hot water (DHW), and appliances (E_{EL*}).

The PV system consists is an on-grid system. The operations of the PV array and the electrical heating system are together simulated by using EnergyPlus. The life cycle of PV array is set to 20 years, and the embodied energy of PV panels is set to 3.75 GJ/m^2 [10, 11]. The main assumption is that when the PV system operates, all generated electricity would be immediately consumed. The PV panel is represented by the mathematical model of Photovoltaic:Simple from EnergyPlus [4], which describes a simple model of PV that may be useful for early phase design analysis.

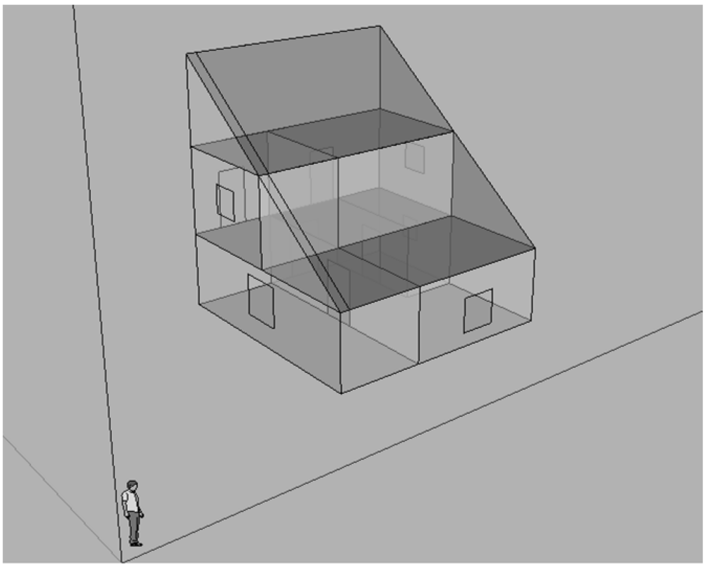

Figure 2 – Modeled residential building

B. 3.2 Optimization procedure

The optimization procedure was performed with the aim to determine the optimal size of PV array and solar collector, due to minimizing the primary energy consumption in analyzed building. The primary energy saving (E_{PRIM}) consists of the primary energy covered by energy generated by PVs (E_{PV}) and energy generated by solar collectors (E_{COLL}), embodied energy in the PV array ($E_{em,PV}$), embodied energy in the solar collectors ($E_{em,COLL}$) and embodied energy of the thermal insulation ($E_{em,ISO}$) [12]. For the optimization, the following objective function was used

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

Where: E_{PRIM} – the yearly avoided operative primary energy consumption due to operation of the PV array and solar collectors (J); R_{EL} = 3.04 - primary conversion multiplier [12]; 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); C_m=1/LC; where LC is life cycle of PV and solar collectors, in years, $C_{m1}=1/LC_{ISO}$; where LC_{ISO} is life cycle of thermal isolations, in years, $E_{em,\ ISO}$ – insulation embodied energy (J) and C_{inst} – coefficient of instalation and maitenance of solar systems during their life cycle (-) [13].

The part of the roof covered by the PV array is marked by y. The value y – ratio between PV panel area and roof area exists in the calculated total embodied energy and electrical energy generated by PV array.

Alsema [11, 12], reports that the energy requirement of crystalline silicon modules varies between 2400 and 7600 MJ/m^2 for mc-Si, and between 5300 and 16500 MJ/m^2 for sc-Si technology (module efficiencies 13% and 14%, respectively). Sanchez [14] reports that the total energy requirement of a frameless a-Si module is in the range of 710 - 1980 MJ/m^2 (module efficiency 7 %). Alsema [11] reports that the average PV life time is 30 years.

The thermal insulation has the embodied energy of 86.4 MJ/kg, density of 16 kg/m^3, and thermal conductivity of 0.037 W/mK [15].

IV. RESULTS AND DISCUSION

The residential building with electrical space heating and with variable cell efficiency of PV array was analyzed in order to achieve ZNEB or PNEB and to minimize the consumption of primary energy. The first case is the PV array with 12 % of cell efficiency, the second case is the PV array with 14 % and the third case is PV array with 16 % of cell efficiency, respectively. Results are in Table 1.

Table 1 - Energy consumption, generated energy, fraction of PV panels and avoided operative primary energy consumption of the buildings with different PV cell efficiency (Yearly values)

	PV cell efficiency		
	12 %	14 %	16 %
E_{EL} - Total electricity consumption (GJ)[1]	68,36	68,36	68,36
$E_{EL,PRIM}$ - Primary energy of total electricity consumption (GJ)	207,81	207,81	207,81
Fraction of PV panels on the roof (%)	91,25	92,5	93,13
Total generated electricity by PV (GJ)	48,48	57,33	65,96
Total generated heat energy (GJ)	14,19	12,4	11,98
Primary energy of generated energy (GJ)	190,51	211,98	236,96
E_{PRIM} – maximum of avoided operative primary energy (GJ)	170,59	192,01	216,96
Embodied energy in solar systems (GJ)	17,75	17,81	17,83
Embodied energy in thermal insulation (GJ)	2,17	2,17	2,17
$E_{PV,S}$ - Electricity surplus sold (GJ)	33,02	40,7	48,35
$E_{P,NET}$ - Electricity net-facility (GJ)	6,27	-1,89	-10,18
E_P – Electricity total facility (GJ)	39,29	38,82	38,17
Building type (without embodied energy)	**NNEB**	**PNEB**	**PNEB**
Building type (with embodied energy)	**NNEB**	**NNEB**	**PNEB**

Acording the Table 1, it can be concluded that PNEB can be achieved by using the PV panels with higher cell efficiency. Using the PV array with 14 % of cell efficiency, building is PNEB (building type

[1] Total electricity consumption by building includes the electricity consumption by space heating, electric equipment, lighting and hot water heating

approach without embodied energy) and NNEB (building type approach with embodied energy). Using the PV array with 16 % of cell efficiency, buildings are PNEB in both of cases.

Figure 3 represent total electricity consumption, primary energy consumption, primary energy of generated energy and maximum of avoided operative primary energy in buildings with different cell efficiency of PV array.

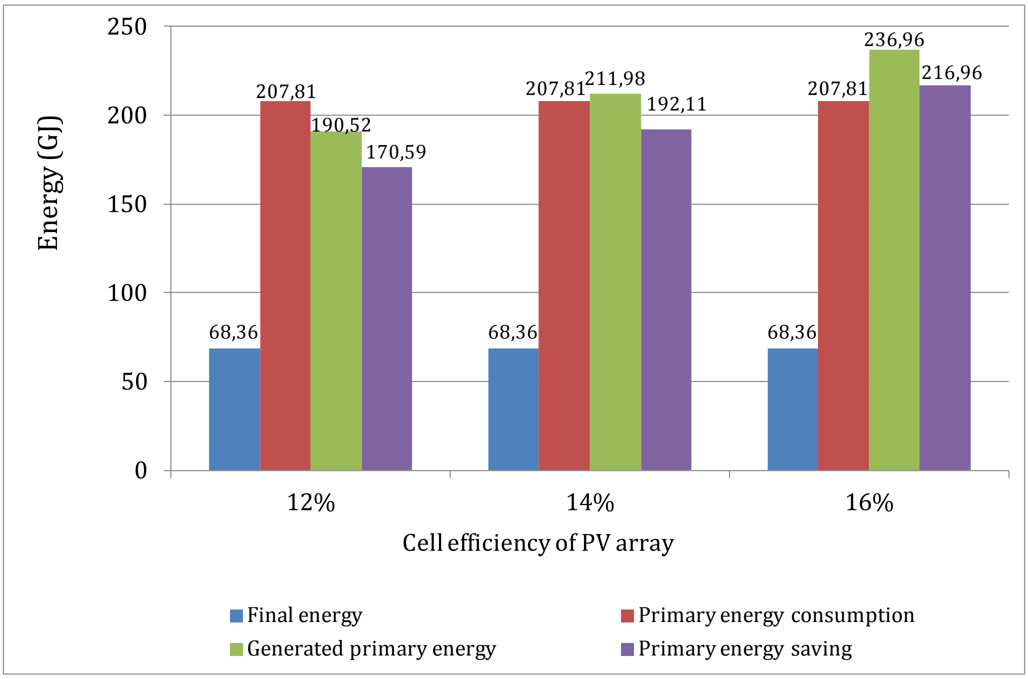

Figure 3 *– Total electricity consumption, primary energy consumption, primary energy of generated energy and maximum of avoided operative primary energy for buildings with different cell efficiency of PV panels (Yearly values)*

With 14 % cell efficiency of PV array, it can be possible to generate 57.33 GJ of electricity. Compared to the 12 % cell efficiency of PV array, this is the increase of 18.25 %. With 16 % cell efficiency of PV array, it can be possible to generate 65,96 GJ of electricity, which is the increase of 36 %.

Primary energy of generated energy is increasing with higher values of cell efficiency of PV array. So, with cell efficiency of PV array of 14 %, it can be possible to generate 211.98 GJ, which is increasing of 11.26 % compared to PV array with 12 % of cell efficiency. With 16 % cell efficiency of PV array, it can be possible to generate 236,96 GJ of primary energy, which is the increase of 24,38 %.

Figure 4 represent the area ratios of PV panels and solar collectors on the roof, for different cell efficiency of PV panels. Fraction of PV panels on the roof increases with increase of cell efficiency of PV panels, while the fraction of solar collectors on the roof decreases. Fraction of PV panels with cell efficiency of 12 % on the roof is 91.25 % (area of PV array is 73.6 m^2 while the other 7 m^2 roof covered with solar collectors). Fraction of PV panels with cell efficiency of 14 % on the roof is 92.5 % (area of PV array is 74.6 m^2 while the other 6 m^2 roof covered with solar collectors) and fraction of PV panels with cell efficiency of 16 % on the roof is 93.13 % (area of PV array is 75.1 m^2 while the other 5.5 m^2 roof covered with solar collectors).

Primary energy saving or maximum of avoided operative primary energy for PV array with cell efficiency of 12 %, 14 % and 16 % is 170.59 GJ, 192.01 GJ and 216.96 GJ, respectively. In percents, for PV array with cell efficiency of 14 % and 16 %, primary energy saving is greater a 12.6 % and 27.2 %, respectively, according to the PV array with cell efficiency of 12 %. It can be concluded that with increasing of cell efficiency of PV array, primary energy savings also increase (Figure 5).

Figure 6 represent the electricity surplus sold (surplus of energy sold to distribution network) and electricity total facility (the total amount of purchased electricity) for different cell efficiency of PV array.

From Figure 6 it can be concluded that concept of ZNEB can be achieved using the PV arrays with a cell efficiency of 13.5%. In that case, the total amount of purchased electricity is equal to the surplus of electricity sold to the electric distribution network, and the net amount of purchased electrici is equal to 0.

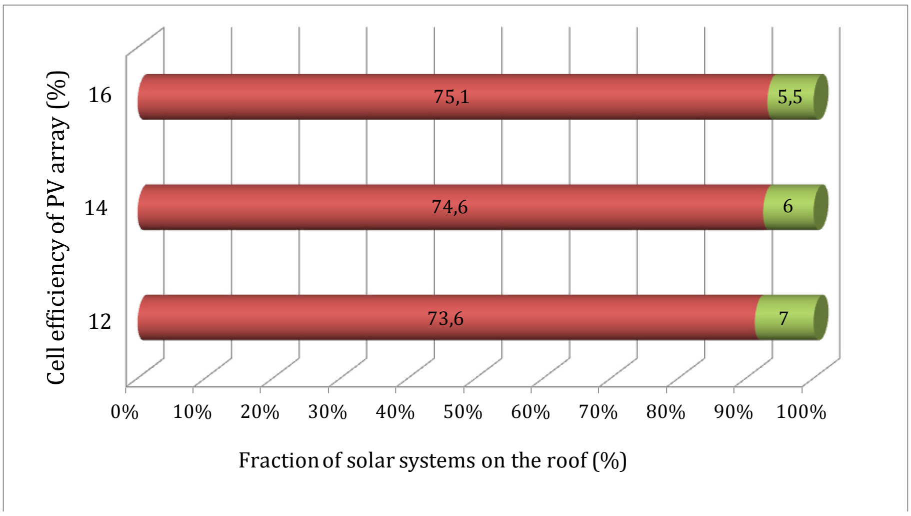

Figure 4 *- Area ratios of PV panels and solar collectors for different cell efficiency of PV array*

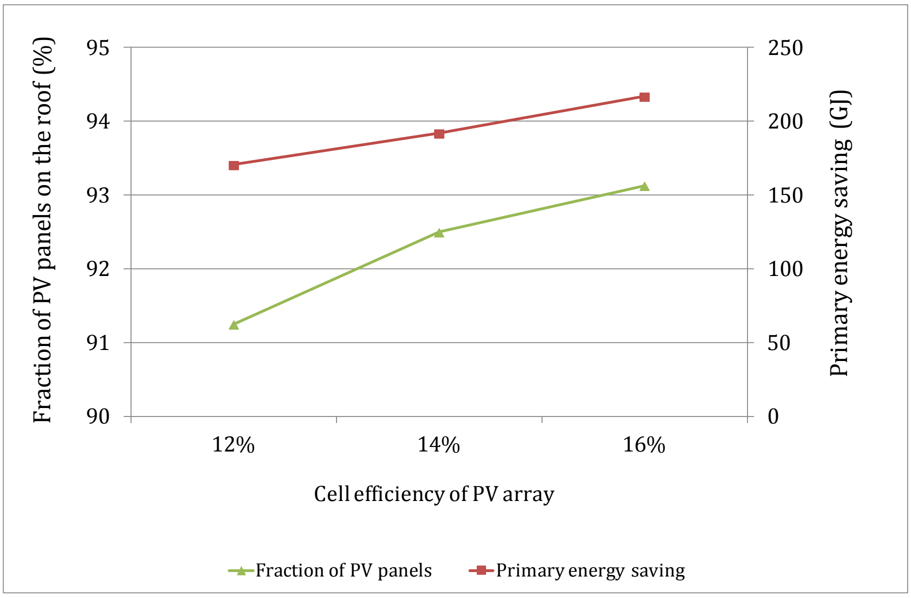

Figure 5 *– Fraction of PV panels on the roof and primary energy savings for different values of PV cell efficiency*

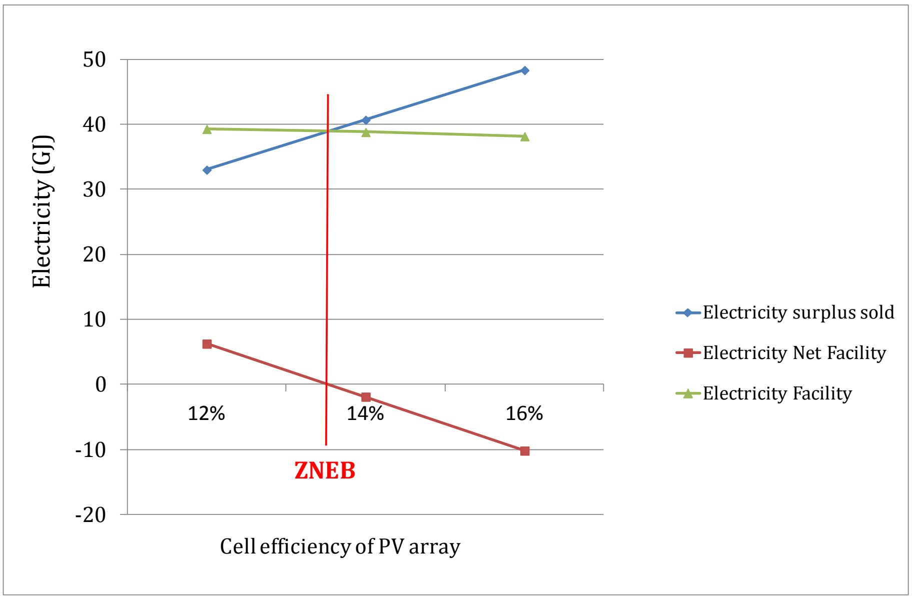

Figure 6 *– Electricity surplus sold and electricity total facility for buildings with different cell efficiency of PV array*

For value of PV cell efficiency above the 13.5%, it will be a case of building with positive net-energy consumption (PNEB). This means that the building annually, through its installed solar systems generate more energy than it needs to settle its energy needs. This can be inferred from Figure 6, where right of the ZNEB line of surplus sold electricity is over the lines of the total purchased electricity. The difference between the surplus sold and the total purchased energy is precisely the negative net purchased energy.

V. CONCLUSION

The major aim of this investigation was optimization to determine the optimal area of PV array and solar collectors on the roof, due to achieving the maximum avoided primary energy consumption of the buildings.

In recent years photovoltaic technology achieved great advances in development. That is why increasingly used PV modules of greater cell efficiency. Using these modules (cell efficiency of PV array 14% and 16%) is generated significantly greater amount of electrical energy compared with modules of cell efficiency 12%, so it is obtained the different optimal areas ratio of PV array and solar collectors.

By using photovoltaic array with cell efficiency of 14%, a building with electric heating was positive net-energy building (PNEB) to generated primary energy, and negative net-energy building (NNEB) according to the maximum primary energy savings. The application of photovoltaic modules with cell efficiency of 16%, all considered buildings were positive net-energy building (PNEB) according to both approaches.

With the increase of the cell efficiency of PV modules, the amount of generated electricity increases too.

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