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Performance evaluation of a building integrated photovoltaic (BIPV) system combined with a wastewater source heat pump (WWSHP) system

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Abstract

This paper deals with both energetic and exergetic performance assessments of two combined systems as a whole. The first one is a Building Integrated Photovoltaic (BIPV) system while the second one is a wastewater (WW) Source Heat Pump (WWSHP) system. Both systems were installed at Yasar University, Izmir, Turkey within the framework of EU/FP7 and the Scientific and Technological Research Council of Turkey (TUBITAK) funded projects, respectively. The BIPV system was commissioned on 8 February 2016 and has been successfully operated since then while the WWSHP system was put into operation in October 2014. The BIPV system has a total peak power of 7.44 kW and consists of a total of 48 Crystalline Silicon (c-Si) modules with a gap of 150 mm between the modules and the wall, and a peak power per PV unit of 155 W_p. The WWSHP system consists of three main sub-systems, namely (i) a WW system, (ii) a WWSHP, and (iii) an end user system.
Two systems considered have been separately operated while the measured values obtained from both systems have been recorded for performance assessment purposes. In this study, a combined system was conceptually formed and the performance of the whole system was evaluated using actual operational data and some assumptions made. Exergy efficiency values for the WWSHP system and the whole system were determined to be 72.23% and 64.98% on product/fuel basis, while their functional exergy efficiencies are obtained to be 20.93% and 11.82%, respectively.

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It may be concluded that the methodology presented here will be very beneficial to those dealing with the design and performance analysis and evaluation of BIPV and WWHP systems.

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Keywords: buildings; BIPV; building integrated photovoltaic; wastewater source heat pump; WWSHP; exergy; exergy efficiency.

1. Introduction

The energy consumption of the buildings accounts for 40% of the total energy consumption in the EU while buildings are also responsible for 36% of the CO_2 emissions [1]. These numbers clearly indicate how important energy efficiency issue in buildings is and therefore the building sector can be regarded as one of the most important factors for the achievement of the EU's 20/20/20 targets. Currently, there are two main legislations in the EU regarding the energy consumption in buildings, namely Energy Performance of Buildings Directive (2010) and Energy Efficiency Directive (2012). Within the context of these two directives; EU countries should make energy efficient renovations to at least 3% of buildings owned and occupied by central government, only purchase buildings with high energy efficiency and all new buildings must be nearly zero energy buildings by 31 December 2020 (public buildings by 31 December 2018) [1].

Wastewater (WW) discharged from buildings to sewerage systems reserves huge amounts of thermal energy, which can be used as heat source in HPs. It can also be considered as a sustainable and renewable source in big cities [2,3].

According to a study performed, the heat loss via WW for a traditional building in Switzerland accounts to 15% of its demand and 6000 GWh of thermal energy is lost via WW every year in Switzerland [4]. This study indicates that the sew-age systems are one of the largest sources of heat loses in buildings. Therefore, any attempt to recover this heat loss has the potential to increase the energy efficiency of the buildings. One of the ways to benefit from this heat is using WW as a heat source of heat pumps (HPs), which are known as clean and energy efficient heating and cooling solutions in buildings. At present, there are more than 500 WWSHPs installed around the world, with a capacity range of 10 kW – 20 MW [4]. This makes sense because WW represents a very suitable and efficient heat source for HPs with its main characteristics: (i) huge amounts especially in big cities, (ii) having higher temperatures than the outdoor air temperature in winter, (iii) having lower temperatures than the outdoor air temperature in summer, (iv) having low temperatures fluctuations during the seasons. According to the measurement data of Beijing Gaobedian WW treatment plant (WWTP), the WW temperature ranges from 13.5 to 16.5 ℃ in winter, which is about 20℃ higher than outdoor temperature while in summer the WW temperature varies be-tween 22 and 25℃, which is 10℃ lower than outdoor temperature [5]. Due to the huge potential of WW, numerous studies have been conducted and found in the open literature, as comprehensively reviewed by Hepbasli et al [2]. For further information about WWSHPs, this study can be addressed.

According to the International Energy Agency, the share of renewables in electricity generation is expected to rise up to 25% of the total power generation in 2018 [6]. PV generated electricity is also estimated to double its share by 2018 compared to 2011 [7]. In this regard, Building Integrated PV (BIPV) systems play an important role in generating electricity. BIPVs are defined as PV modules, which can be integrated in the building envelope (into the roof or façade) by replacing convention-al building materials (e.g., tiles) [8]. Therefore, BIPVs have an impact of building's functionality and can be considered as an integral part of the energy sys-tem of the building.

As stated earlier, according to the energy performance of buildings directive, all new buildings have to be nearly zero-energy by the end of 2020. To achieve this target, renewable energy sources (RESs) should be used as much as possible to cover the energy consumption of the buildings. In this context, solar energy (especially, PV technology) seems to be the most suitable RES technology to be used in buildings. PV systems in buildings can be divided in two sections as building attached PVs (BAPVs) and BIPVs. BAPVs are mostly roof-top mounted PV systems, which are added after the construction and have no direct effect on the functionality of the structure [9]. On the other hand, BIPVs are integrated on the façade or the roof of the building by replacing building materials, such as tiles and glasses, on the building envelope and therefore they combine standard functions of building materials with the function electricity generation [10]. Considering the limited available area in buildings BIPVs seems to be a better solution compared to BAPVs and as an application of the PV technology, BIPV systems have attracted an increasing interest in the past decade, and have been shown as a feasible renewable power generation technology to help buildings partially meet their load.

In this study, an experimental WWSHP system located at Yasar University and the 7.44 kW_p BIPV system installed at the façade of a building at the same university are conceptually combined and the performance of the combined system is experimentally evaluated using energy and exergy analysis methods.

Nomenclature

A	Area, m^2
$C_{p,a}$	Specific heat of air, kJ/kg·K
$C_{p,v}$	Specific heat of vapor, kJ/kg·K
COP	Coefficient of performance, ND
$\dot{E}$	Energy rate, kW
$\dot{Ex}$	Energy rate, kW
f	Power generation-consumption ratio, ND
$\dot{F}$	Exergetic fuel rate, kW
h	Entahlpy, kJ/kg
I_m	BIPV current, A
I_{sol}	Solar irradiation, W/m^2
$\dot{m}$	Mass flow rate, kg/s
$\dot{IP}$	Improvement potential rate, kW
$\dot{P}$	Exergetic product rate, kW
$\dot{Q}$	Heat transfer rate, kW
R_a	Gas constant of air, kJ/kg·K
RI	Relative irreversibility, ND
s	Specific entropy, kJ/kg
$\dot{S}$	Entropy rate, kW
T	Temperature, °C or K
V_m	BIPV voltage, V
$\dot{W}$	Work rate or power, kW
η	Energy efficiency, ND
φ	Exergy efficiency, ND
ω	Specific humidity, kg vapor/kg dry air

2. System Description

A schematic of the conceptually combined system is given in Fig. 1. As can be seen in the figure, the systems are connected to each other on the building grid (main electrical board of the building). The WW draws electricity from the grid while the BIPV system feeds it.

The WWSHP system consists of three main sub-parts, namely (i) a WW system, (ii) a WWSHP, and (iii) an end user system. The WW sub-system is comprised of two main parts, namely WWHEs and WW tanks. A local WW drainage system, through which WW flows, was not used because it was not possible to connect the WWSHP system to it. Therefore, two 500 L tanks, where water was stored and circulated by pumps, were used to simulate it. An eight kW resistance and cooling coil is located in one of the tanks in order to set the WW temperature to the desired temperature and to keep it constant, so that the system can reach steady state conditions. For transferring heat from/to the WW, two different WWHEs, a plate heat exchanger and an immersed heat exchanger, connected in parallel were used in the system. In the HP sub-system, there are two compressors (1 AC and 1 DC), three water source heat exchangers, one air source heat ex-changer, an electronic expansion valve, a four-way valve and some other auxiliary equipment, such as the drier, oil separator and etc. In the end user system, there exists a fan-coil unit, which is connected parallel to the air source heat exchanger and a domes-tic hot water (DHW) tank.

In the present study, the WWSHP system, whose picture is illustrated in Fig. 2, is operated in the cooling mode and valves 2, 4, 8, 9, 10, 11, 12, and 13 are open. The plate heat exchanger is used as the evaporator while the AC compressor and plate type WWHE are selected as the main units.

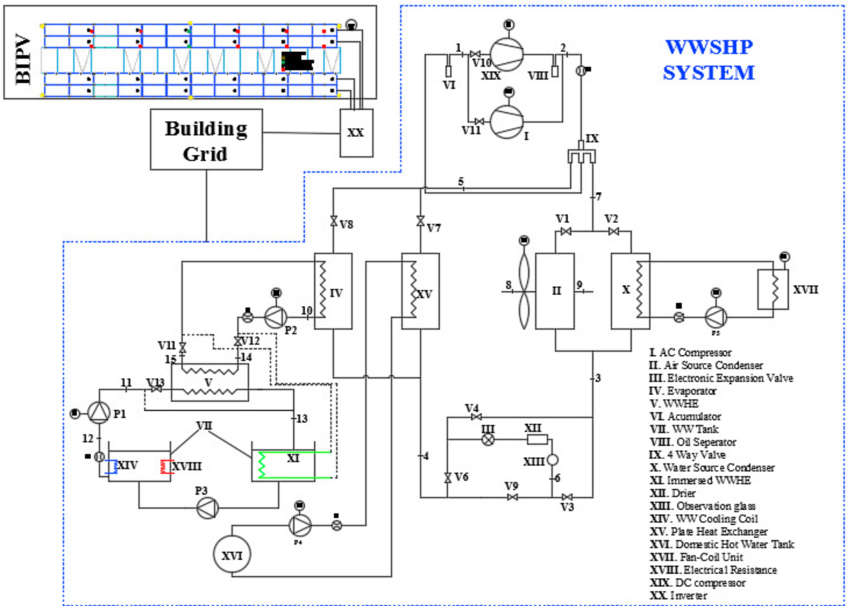

Fig. 1. A schematic of the combined system.

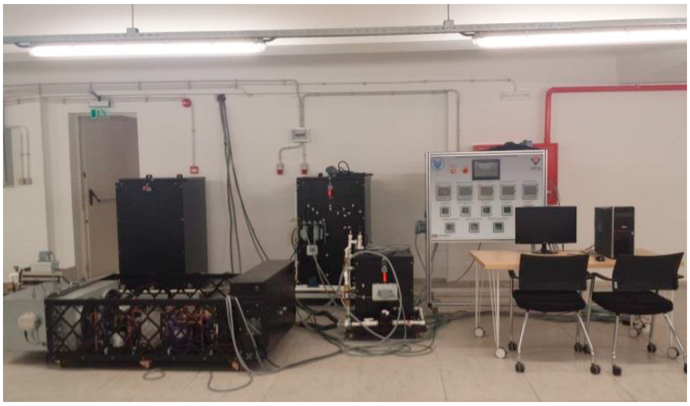

Fig. 2. A photo of the WWSHP system.

The refrigerant is compressed to the condenser by an AC compressor, where it transfers heat to the water in the intermedium cycle. So, the temperature of the water in the intermedium cycle increases and this water is sent to the WWHE. In the WWHE, WW is used to cool down the intermedium water and is pumped back to the WW tank. After the process on the wastewater side, the refrigerant enters the electronic expansion valve and is expanded to the evaporator pressure. The refrigerant enters the evaporator in two-phase state and absorbs heat from the room and generates the cooling effect. All the necessary data for the analyses, temperatures, pressures, flow rates and power consumptions were continuously measured at the shown locations in the schematic while data loggers were used to record those values.

A closer look to the BIPV system is given in Figs. 3 and 4.

Fig. 3. A photo of the BIPV system.

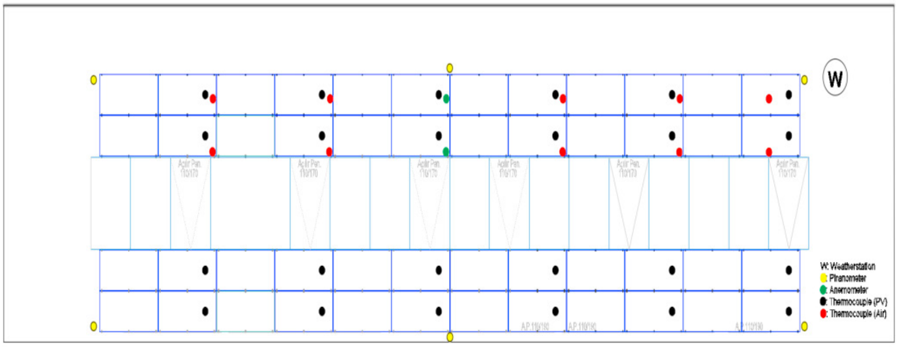

Fig. 4. Locations of the measurement devices.

This system is mounted on the south-east facing façade of a building located at the campus of Yasar University, Izmir, Turkey. The system has a total peak power of 7.44 kW_p and consists of 48 mono-crystalline PV modules with each 155 W_p. The panels have a transparency of 30% and therefore, the cell area is 42.08 m^2 while the total area is 57.6 m^2.As can be seen from the figures, these panels were installed in 4 rows (2 rows on below, 2 rows above the windows and 12 panels in each row) and 2 strings (each 2 row is forming 1 string). There is a 15 cm air gap between the PV modules and the wall. The air enters the PV modules from the bottom and exits from the top by cooling down them. This system is called as a ventilated façade and increases the efficiency of the system due to cooling effect. A 7 kW 3-phase inverter with 2 independent MPPT inputs has been selected for the system. The inverter converts the DC input to AC and feeds the building grid. It also serves as a measuring instrument and all electrical data are recorded to the integrated FTP server inside the inverter with 5-minute intervals. As can be seen in Fig. 4, the surface temperatures of the PV modules are measured on 24 points, while the air temperatures between the wall and the modules are measured at 12 different locations. The air velocity behind the modules is also measured on two points. For the irradiation measurements, 6 pyranometers are mounted on the system (4 in the corners and 2 at midpoints) while a weather-station is located just next to the upper string. Wind velocity and direction, air temperature and humidity are measured at this point. All these measurements are continuously recorded on a 60-channel internet-connected data logger.

This system was commissioned on 8 February 2016 and has been monitored since then. A total electrical energy of 5461 kWh has been produced as of 19 January 2017. On the other hand, the WWSHP system is only used during the experiments. Therefore, hourly data on 18^{th} of September 2016, when both systems were in operation, have been chosen for the analysis.

3. Modeling

The following assumptions are made during the analyses:

- All processes are steady state and steady flow with negligible potential and kinetic energy effects and no chemical or nuclear reactions.
- Water properties are used instead of WW.
- The pressure and heat losses in the pipelines are ignored.
- The inverter and BIPV modules are taken as a whole in the analysis.
- The values for the dead (reference) state and pressure are taken to be 37.47 °C and 101.325 kPa, respectively.

General energy, entropy and exergy balance equations given below are used and then further reduced to specific equations for each component (for each control volume) [11-13].

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

$$\dot{E}_{in} = \dot{E}_{out} \tag{2}$$

$$\dot{S}_{out} - \dot{S}_{in} = \dot{S}_{gen} \tag{3}$$

$$\dot{Ex}_{in} - \dot{Ex}_{out} = \dot{Ex}_{dest} \tag{4}$$

The exergy transfer by mass is determined by Eqs. (5) and (6) while Eq. (7) is used for calculating the exergy transfer rate by work and Eq. (8) is used to determine the exergy transfer rate by heat.

$$ex = \left(h - h_0\right) - T_0\left(s - s_0\right) \tag{5}$$

$$\dot{Ex} = \dot{m}\left(ex\right) \tag{6}$$

$$\dot{Ex}_W = \dot{W} \tag{7}$$

$$\dot{Ex}_Q = \sum\left(1 - \frac{T_0}{T}\right)\dot{Q} \tag{8}$$

The specific exergy of air can be calculated by Eq. (9) where ω is the specific humidity of the air;

$$\begin{aligned} ex_{air} &= \left(C_{p,a} + \omega C_{p,v}\right)T_0\left[\left(\frac{T}{T_0}\right) - 1 - \ln\left(\frac{T}{T_0}\right)\right] + \left(1 + 1.6078\omega\right)R_a T_0 \ln\left(\frac{P}{P_0}\right) \\ &+ R_a T_0\left\{\left(1 + 1.6078\omega\right)\ln\left[\frac{\left(1 + 1.6078\omega\right)}{\left(1 + 1.6078\omega_0\right)}\right] + 1.6078\omega\ln\frac{\omega}{\omega_0}\right\} \end{aligned} \tag{9}$$

The COP of the WWSHP and the whole system can be calculated using Eqs. (10) and (11):

$$COP_{WWSHP} = \frac{\dot{Q}_{cond}}{\dot{W}_{comp,elec}} \tag{10}$$

$$COP_{sys} = \frac{\dot{Q}_{cond}}{\left(\dot{W}_{comp,elec} + \sum\dot{W}_{pumps,elec} + \dot{W}_{fan,elec}\right)} \tag{11}$$

Although the COP parameter indicates the performance of the system, it is clear that it does not reflect the effect of the generated electricity in the BIPV. The efficiency definition given in Eq. (12) can be used for this purpose [14]:

$$\eta_{sys} = \frac{\left(\dot{Q} + \dot{W}_{BIPV}\right)}{\left(\dot{W}_{tot} + I_{sol} A_{BIPV}\right)} \tag{12}$$

The ratio of the generated electricity and consumed power can also be used as an indicator:

$$f = \frac{\dot{W}_{BIPV}}{\dot{W}_{tot}} \tag{13}$$

The exergy efficiency of each component can be obtained from Eq. (14):

$$\varepsilon = \frac{\dot{E}x_{output}}{\dot{E}x_{input}} \tag{14}$$

The overall exergy efficiency based on product/fuel basis can be calculated by

$$\varepsilon_{overall} = \frac{\sum Exergetic\,\mathrm{Pr}oduct}{\sum Exergetic\,Fuel} = \frac{\sum \dot{P}_i}{\sum \dot{F}_i} \tag{15}$$

The functional exergy efficiency of the WWSHP system and overall system can be calculated using the following equations:

$$\varepsilon_{WWSHP} = \frac{\dot{E}x_{evap}}{\dot{W}_{comp,elec}} \tag{16}$$

$$\varepsilon_{sys} = \frac{\dot{E}x_{fancoil}}{\left(\dot{W}_{comp,elec} + \sum \dot{W}_{pumps,elec} + \dot{W}_{fan,elec}\right)} \tag{17}$$

where Ex_{evap} and $Ex_{fancoil}$ represent the exergetic product rates of the evaporator and fan-coil unit, respectively. Van Gool's improvement potential and relative irreversibilities can be calculated as follows:

$$\dot{IP} = (1-\varepsilon)\left(\dot{Ex}_{in} - \dot{Ex}_{out}\right) \tag{18}$$

$$RI = \frac{\dot{Ex}_i}{\dot{Ex}_{tot}} \tag{19}$$

For the BIPV part, the power conversion efficiency η_{pc} can be defined as a function of the area, actual power generation and solar irradiance as [15]:

$$\eta = \frac{\dot{W}_{BIPV}}{I_{sol} A_{BIPV}} \tag{20}$$

The area in this equation is important since the BIPV panels used are 30% transparent. In this study, the power conversion and exergy efficiencies will be calculated based on both the total and cell areas. The exergy efficiency of the BIPV part can be found using Eq. (19) where Ex_{sol} represents the exergy rate of the solar irradiance.

$$\varphi = \frac{\dot{Ex}_{BIPV}}{\dot{Ex}_{sol}} \tag{21}$$

There are different relations for the calculation of Ex_{sol} in the open literature. In the present study, the following relation proposed by Petela was used [16]:

$$\dot{Ex}_{sol} = IA\left[1 - \frac{4}{3}\left(\frac{T_0}{T_{sun}}\right) + \frac{1}{3}\left(\frac{T_0}{T_{sun}}\right)^4\right] \tag{22}$$

The temperature of the sun can be taken as 6000 K. Ex_{BIPV} is the exergy rate of the PV system, which is mainly electrical power output of the system.

$$\dot{Ex}_{BIPV} = V_m I_m \tag{23}$$

4. Results and Discussion

As stated earlier, the BIPV part has been successfully operated since 8 February 2016 while the WWSHP part is just an experimental system and is only used during the experiments. Therefore, hourly data on 18th of September 2016, when both systems were operating, have been chosen for the analysis. WW temperature is set to 27 °C, which is a typical WW temperature in summer for the city of Izmir, Turkey, during the experiments and kept nearly constant. All necessary data are recorded and the analyses have been conducted using the equations given in the previous section. The results are listed in Table 1 where P and F represent the exergetic product and exergetic fuel rates, respectively.

Table 1. Results.

Component no.	Component	P (kW)	F (kW)	Ex_{dest} (kW)	IP (kW)	RI_{WWSHP} (%)	$RI_{overall}$ (%)	ε (%)	ε (%) Eq. (15)	COP
I	Compressor	0.690	1.452	0.762	0.400	70.28	9.38	47.52	-	-
II	Evaporator	0.304	0.383	0.079	0.016	7.29	0.97	79.37	-	-
III	Expansion Valve	0.963	1.008	0.045	0.002	4.13	0.55	95.55	-	-
IV	Condenser	1.046	1.216	0.199	0.032	18.30	2.44	83.68	-	-
V	Fan-coil Unit	0.234	0.499	0.265	0.141		3.26	46.87	-	-
VI	WWHE	0.064	0.14	0.077	0.042		0.94	45.36	-	-
VII	WW Pump	0.018	0.133	0.115	0.010		1.42	13.50	-	-
VIII	Intermedium Water Pump	0.020	0.152	0.133	0.116		1.64	12.83	-	-
IX	Fan-coil Pump	0.015	0.104	0.089	0.077		1.1	13.93	-	-
X	BIPV	0.949	7.312	6.363	5.537		78.3	12.98		
I-IV	Heat Pump Unit					100.0		20.93	70.39	2.66
I-X	Overall System						100.0	12.73	65.34	1.96

The COP of the WWSHP is obtained to be 2.66 while that of the overall system is calculated as 1.96. The efficiency of the system is determined as 40% using Eq. (12), while the power generation/demand ratio is obtained to be 48%. As can be seen in the table, the greatest exergy destruction (irreversibility) occurred in the BIPV part, which is followed by the compressor. It may be concluded that the high exergy destruction rate and low exergy efficiency values occurred in the compressor are mainly related to the mechanical-electrical losses. Although the expansion valve has the highest exergy efficiency among all the components, it should be noted that expansion valves are dissipative devices and the exergy rate always decreases during the throttling process. The intermedium water pump has the lowest exergy efficiency with 12.83%, while the BIPV has the highest improvement potential. Exergy efficiencies for WWSHP and the whole system are determined to be 70.39% and 65.34%, on product/fuel basis while their functional exergy efficiencies are found to be 20.93% and 12.73%, respectively.

On the second part of the study, energy and exergy efficiencies of the BIPV sub-system are dynamically analyzed for the day of the experiment (18 September 2016). Daily power generation and irradiation data are illustrated in Fig. 5.

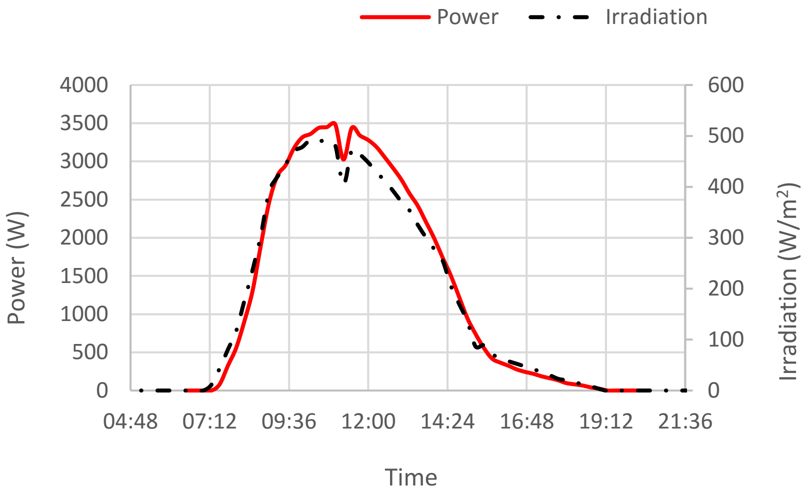

Fig. 5. Daily power generation and irradiation distribution on 18th of September.

Energy and exergy efficiencies of the BIPV sub-system are highly affected by the area since the PV modules have a transparency of 30%. Therefore, the efficiency terms are calculated for both the total and cell areas and are compared with each other. The results can be seen in Fig. 6. As expected, the efficiencies based on the cell area are higher and the difference is approximately 4% throughout the day.

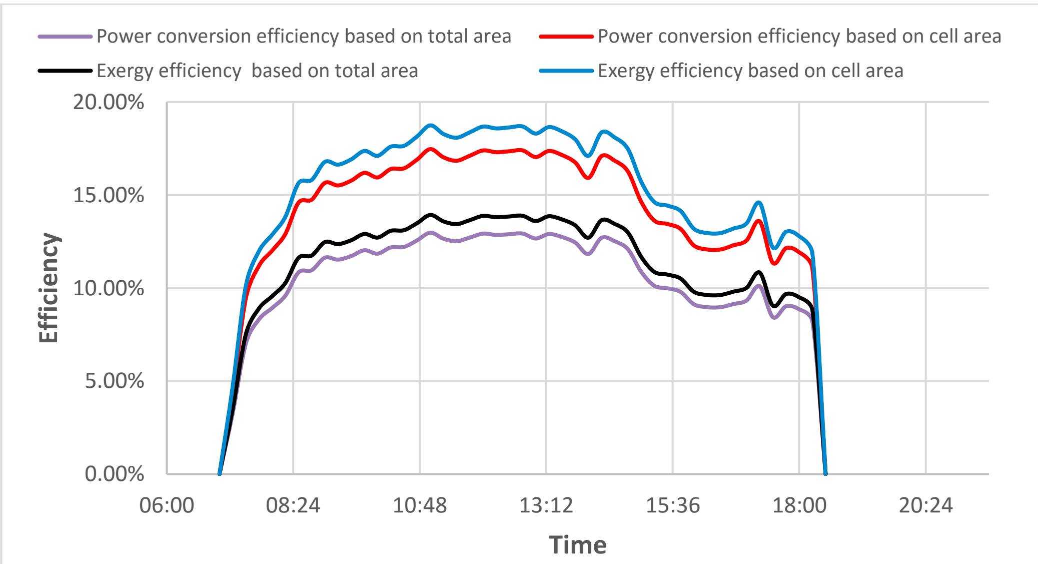

Fig. 6. Energy and exergy efficiencies of the BIPV system.

5. Conclusions

In this study, two different concepts, WWSHPs and BIPVs, are introduced within the context of nZEBs. Then, an experimental WWSHP system located at Yasar University and a 7.44 kWp BIPV system installed at the façade of a building at the same university were conceptually combined and the performance of the combined system was experimentally evaluated using energy and exergy analysis methods.

The main concluding remarks drawn from the results of the present study may be listed as follows:

- WW with its main characteristics represents an efficient source for HPs due to its main characteristics. Huge amounts of waste heat are discharged from buildings to the sewage with WW, being important to recover this energy.
- BIPVs replace conventional building materials and need no additional space. Therefore, they may have an important role to achieve the targets set in the EU directives, recovering the energy demand of buildings.
- The efficiency of the system, which also considers the power generation of the BIPV part, is determined as 40%.
- The power generation/demand ratio is determined to be 48% for the chosen point. But the BIPV system can reach a power generation of 3.5 kW during the day and it can cover the whole demand of the WWSHP during the peak loads.
- Exergy efficiencies for the WWSHP system and the whole system are estimated to be 70.39% and 65.34%, on product/fuel basis while their functional exergy efficiencies are obtained to be 20.93% and 12.73%, respectively.
- The biggest relative irreversibility and improvement potential occurred in the BIPV system, followed by the compressor. The reason for this is mainly the low power conversion efficiencies of the PV technology.
- For a further work, combined exergy analyses, such as technoeconomic and exergoenvironmental, can be conducted to have useful insights into the economics and environmental effects of the system.

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