Exergetic and energy-economic analysis of a Building Integrated PhotoVoltaic and Thermal system

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Abstract: This paper presents a detailed exergetic and techno-economic analysis of a Building Integrated PhotoVoltaic Thermal (BIPVT) system. BIPVT systems, consisting of flat-plate PVT solar collectors, are integrated in the south facing façade of a non-residential high-rise building. BIPVT collectors produce: i) thermal energy for space heating purposes, by a radiant floor system; ii) Domestic Hot Water (DHW); iii) electricity. Electric air-to-water heat pumps/chillers and a condensing gas fired boiler are used as auxiliary systems for space heating / cooling and DHW, respectively. In addition, the system also includes an electricity storage system coupled to the BIPVTs, in order to mitigate the effects of solar energy intermittency and to obtain a virtually grid-independent system. In order to compare the proposed BIPVT system to a conventional building, a reference building model is considered. Here, the space heating and cooling energy is supplied by air-to-water heat pumps, DHW is produced by a condensing boiler and electricity is supplied by the national grid. The comparison is performed for 3 thermal zones, well representative of the thermal behaviour of the whole building. In this paper, a detailed dynamic simulation model is developed to predict the transient behaviour of BIPVT system. Energy and exergy balances are taken into account to determine the exergy destructions and exergetic efficiencies of each of the investigated components. The economic viability of the proposed system is also discussed and the resulted Simple Pay Back period is about 4 years. From the carried out exergy analysis the average exergetic efficiency of BIPVTs electricity is resulted about 8.4%.

Keywords: Dynamic exergetic analysis, Building Integrated PhotoVoltaic Thermal (BIPVT), electricity storage.

1. Introduction

During the last years, European energy policy implemented several actions (European Parliament 2012) to reduce the buildings overall primary energy consumption, mainly in the framework of renewables. Here, solar devices - PhotoVoltaic (PV), PV Thermal (PVT), Solar Thermal Collectors (STC) - are considered as one of the most promising technologies. In fact, differently from the other renewables, solar technology may be easily architectonically integrated within façades, roofs, windows, etc., by obtaining the Building Integrated Solar Technologies (BISTs) (COST Action TU1205 2015). In case of BIPV systems, PV operating temperature may significantly increase with respect to a stand-alone case (Memari, Iulo et al. 2014). This effect may be mitigated using PVT collectors, producing electricity and low-temperature heat, available for Domestic Hot Water (DHW) and space heating (Buonomano, Calise et al. 2016) and cooling (Buker, Mempouo et al. 2015) purposes. In case of building integration, the basic technology consists of building integrated PVT (BIPVT) collectors. Several papers are available in literature regarding energy and exergy analyses of water PVT collectors (Hazami, Riahi et al. 2016), (Jahromi, Vadiee et al. 2015), BIPV systems (Shukla, Sudhakar et al. 2016), (Gupta, Tiwari et al. 2016) and air BIPVT systems (Vats, Tomar et al. 2012), whilst only a few studies deal with water BIPVT systems up to now. Therefore, further experimental and analytical studies should be carried out to improve the knowledge dealing with water BIPVT systems. A number of recent works (Ibrahim, Fudholi et al. 2014) (Buker, Mempouo et al. 2014) presented energy and exergy analyses of air and water BIPVT systems.

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Anyway, at the best of authors' knowledge, no work is available in literature concerning the energy and exergy analysis of water BIPVTs coupled to a Lead Acid Battery LAB electricity storage system by dynamic simulations. In particular, the majority of the exergy studies focused on the BIPVT collector itself, omitting to analyse the whole building-plant (Lamnatou, Mondol et al. 2015) and the exergetic effects of BIPVT collectors on the building thermal and electricity loads. In order to cover the lacks of knowledge regarding this topic, the present work analyses the potential application of BIPVTs coupled to electricity storage system, from both exergetic and energy-economic points of view.

2. System layout

The Reference System RS and the Proposed System PS are shown in Fig. 1. Here, only three Zones, well-representative of all the other Zones, of a conventional office high-rise building, are taken into account. In fact, all floors are designed for office building usage except for a floor, where a fitness center is located. This assumption allows one to reduce the simulations computation time of the developed building-plant model and the obtained results can be easily extended to whole building.

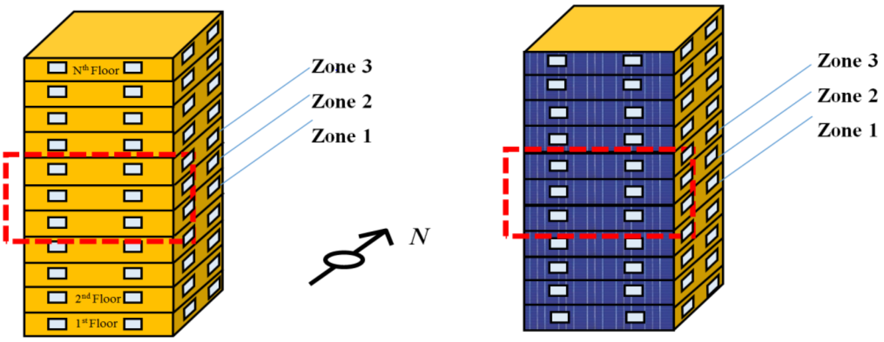
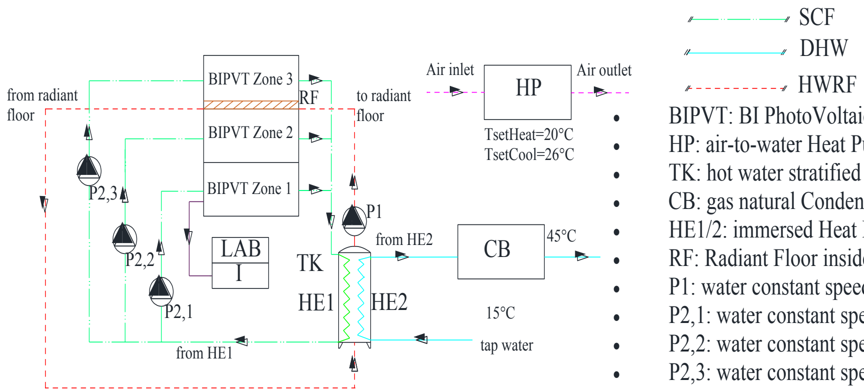


Fig. 1. Reference System (left). Proposed System: BIPVT façade collectors (right)

The RS corresponds to a conventional building without BIPVTs, including heat pumps/chillers for space heating and cooling, a natural gas condensing boiler CB for the DHW production, whilst the electricity is provided by the national grid. The PS configuration consists of south facing façade unglazed BIPVTs, designed for the same building of RS. BIPVTs produce thermal energy exploited through a suitable radiant floor RF system for the space heating of Zone 3 (Fig. 2) and electricity is used for the building energy demand. The excess of BIPVT thermal energy is used to produce DHW for an open space office at Zone 2, a single office at Zone 3 and of fitness center at Zone 1. In layout of PS (Fig. 2), 3 main loops are modelled: the Solar Collector Fluid (SCF) loops; the Hot Water of the Radiant Floor (HWRF) loop; the DHW loop. BIPVTs are arranged in 3 separate hydraulic loops, controlling separately BIPVT outlet water temperature for the 3 zones by suitable controllers. Each controller receives the temperature readings from the outlet of HE1 heat exchanger (i.e., solar collector inlet temperature) and the outlet pipe of its solar collector loop. Hot water produced by the solar loop can be supplied to TK tank through HE1. The controllers stops their controlled pumps (P2,1, P2,2 or P2,3, depending on the Zone loop) when the respective collectors outlet temperature is lower than the inlet one, in order to avoid heat dissipation. CB is activated only if HE2 outlet temperature is lower than user DHW set point one. The tap water enters HE2 only if: i) the thermal energy for RF is not required (i.e. when P1 pump is off); ii) a simultaneous demand of DHW occurs (Table 2). Consequently, a suitable controller manages the activation of P1 pump. In particular, the control strategy managing the operation of P1 pump is detailed in (Buonomano, Calise et al. 2016). Auxiliary heat pump/chillers are also used for heating/cooling each building zone at the selected set-point temperatures.



- BIPVT: BI PhotoVoltaic and Thermal collectors;
- HP: air-to-water Heat Pump;
- TK: hot water stratified vertical storage tank;
- CB: gas natural Condensing Boiler;
- HE1/2: immersed Heat Exchanger 1/2 into TK;
- RF: Radiant Floor inside the building;
- P1: water constant speed pump for RF;
- P2,1: water constant speed pump for solar loop, Zone 1;
- P2,2: water constant speed pump for solar loop, Zone 2;
- P2,3: water constant speed pump for solar loop, Zone 3;
- LAB: Lead-Acid Battery;
- I: Inverter.

Fig. 2. System layout

Table 1. Main system design parameters

	Parameter	Description	Value	Unit
LAB	C_{cell}	Cell Energy Capacity	16.7	Ah
	$N_{S}*N_{P}$	Number Cells in Series * Number Cells in Parallel	24*11	-
	η_{LAB}	Battery efficiency	0.9	
TANK	H_{TK}	Height	2	m
	q_{HE1}/A_{PVT}	Heat Exchanger 1 flow rate per unit of BIPVT area	10	kg/m^{2}h
	q_{HE2}	Heat Exchanger 2 maximum flow rate	2106	kg/h
	$V_{HE1/2}/V_{TK}$	HE1 and HE2 volume per unit of TK volume	1/20	-
	$T_{TK,topSET}$	Tank top temperature for radiant floor activation	22	°C
	$T_{in,RF}$	Zone 3 indoor air temperature for radiant floor activation	19	
CB	$P_{CB,rated}$	Rated CB heat power	88.24	kW
	$\eta_{RS,DHW}$	Efficiency of the condensation boiler (also for RS)	95	%
	q_{DHW}	DHW flow rate per day	17210	kg/ day
HEAT PUMP/ CHILLER	COP	Nominal coefficient of performance heating / cooling	3.5/3.0	-
	$Q_{heat/cool,rated1}$	Rated heating / cooling capacity Zone 1	16 / 13	kW
	$Q_{heat/cool,rated2}$	Rated heating / cooling capacity Zone 2	12 / 9	
	$Q_{heat/cool,rated3}$	Rated heating / cooling capacity Zone 3	11 / 9	

Table 2. Simulation assumptions

Zone 1	Number of occupants per occupancy schedule [occ·hour]	20 × 9:00 am - 1:00 pm; 30 × 1:00 pm - 6:00 pm; 60 × 6:00 pm - 10:00 pm
	Occupants heat gain [W/occ]	Sensible: 185. Latent: 340
	Air ventilation rate [l/s occ]	16.5
	DHW demand [l/day occ]	50
	DHW demand schedule	09:00 am - 10:00 pm
Zone 2&3	Number of occupants per occupancy schedule [occ·hour]	Zone 2: 18 × 9:00 am - 7:00 pm Zone 3: 9 × 9:00 am - 7:00 pm
	Occupant heat gain [W/occ]	Sensible: 75. Latent: 75
	Air ventilation rate [l/s occ]	11.5
	DHW demand [l/day]	30 (0.2 l/day m^2)
	DHW demand and machineries schedule	9:00 am - 07:00 pm

3. Case study

Simulations of both case studies refer to a high-rise building, well-representative of conventional Italian constructions, designed for single and open space offices and one floor for a fitness center, located in the weather zone of Naples (South-Italy). According to the Italian regulation (Italian Republic 1993), the heating period goes from November 15th to March 31st; the cooling period is set from June 1st to September 30th. As above mentioned, the exergy and the energy-economic analyses are performed on three thermal Zones of the whole building. The building has a rectangular shape with an East-West oriented longitudinal axis; the height, the floor area and the glazed area of each thermal Zone are equal to 3.5 m, 150 m^2 and 19.5 m^2, respectively. The envelope features are reported in Table 3, whereas the simulation assumptions of three thermal Zones are reported in Table 2.

Table 3. Opaque and transparent elements features

Building element	**U-value** [W/m^{2}K]	**Thickness** [m]	**ρ_s** [-]	**ε** [-]
Façades (without BIPVT collectors)	0.981	0.30	0.40	0.90
Internal floor/ceiling (tile flooring)	0.682	0.33		
Windows glass	2.83	0.004/0.016 (air)/0.004	0.13	0.18

In both systems, a specific windows opening strategy is also considered (free cooling strategy). In PS, the BIPVTs are mounted on the south facing façades, occupying an area of 135 m^2. All design parameters of BIPVTs, as well as the RF ones, are provided in reference (Buonomano, Calise et al. 2016) whereas the inverter ones are reported in ref. (Buonomano, Calise et al. 2016). The design parameters regarding the LAB, TK, CB, and heat pump / chillers are shown in Table 1. Note that, both in RS and PS, the same rated power of CB and HPs are considered and the DHW and indoor set point temperatures of building thermal Zones (45°C, 26° for cooling and 20°C for heating, respectively) as well as the air infiltration and free cooling rate (0.4 and 2.0 vol/h).

4. Results

The results, referred to the climate zone of Naples, of dynamic exergy and energy - economic model (reported in (Buonomano, Calise et al. 2016)) are provided by the well-known tool TRNSYS 17 (Klein, Beckman et al. 2006). Details about the significant components included in the model are reported in (Buonomano, Calise et al. 2016). The exergy analysis is based on the method reported in (Calise, Libertini et al. 2016), following the well-known approach reported in (Kotas 1995), (Rosen and Dincer 2004). Part of exergy building model is based on the model developed in (Schmidt 2004). By the yearly results it is clearly shown that the Primary Energy PE for DHW (Fig. 3) is significantly higher than the space heating one (PE_{heat}). This is due to the huge DHW demand of Zone 1. By exploiting the BIPVT thermal energy, PE_{DHW} reduces from 230.9 to about 209.7 MWh/year.

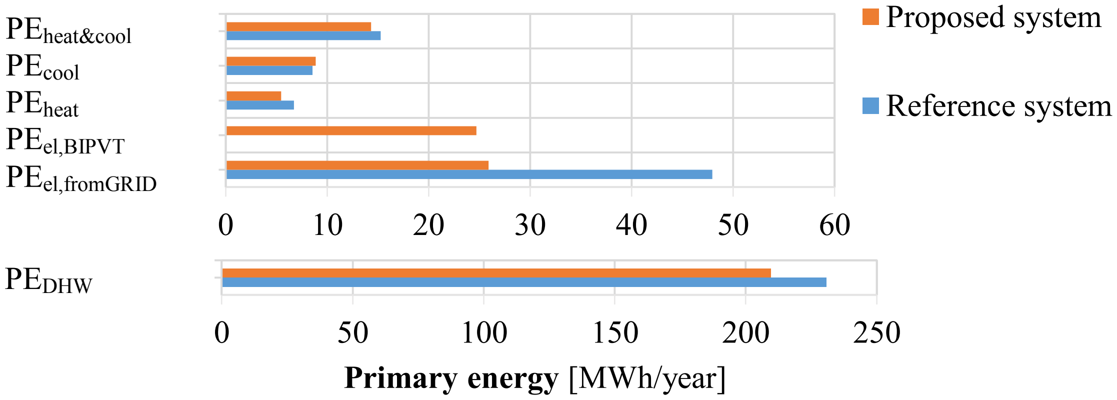


Fig. 3. Primary energies of RS and PS

In winter, PE_{heat} decreases from 7.6 to 5.5 MWh/year, for the adoption of RF in Zone 3 and for the BIPVT positive winter passive effect, justified by the hot water flowing through the BIPVTs, which heats the external surfaces of the south-façades, in contact with the collectors back surface, at a temperature higher than the ambient one. In summer, the overheating effect due to collectors integration leads to a slight negative increase of PE_{cool}. Anyway, such increase is not significant, because the summer overheating is balanced by the reduction of solar incident radiation, about 40% (lower solar gain) on the south external facades. The electricity required from national grid reduces from 48.0 (RS) to 25.9 MWh/year (PS). This is due to: i) the decrease of $PE_{heat\&cool}$; ii) BIPVTs system self-consumed electricity; iii) the use of an electricity storage system. The highest destroyed exergy is achieved by the CB $Ex_{d,CB}$, (Table 4) due to its irreversible chemical reactions. Note that, in PS $Ex_{d,CB,PS}$ decreases with respect the one obtained in RS $Ex_{d,CB,RS}$, by reducing the system irreversibilities. This is mainly due to the reduction of exergetic input (higher inlet temperature at CB for the solar preheating of the DHW) and of the chemical exergy of reaction (lower PE consumption of CB). A remarkable destroyed exergy, equal to about 126 MWh/year, is shown for the BIPVTs, due to the very large temperature difference between the collector surface and the sun, although the high exergetic product due to the electricity produced. This high destroyed exergy is common for whatever solar technology. Conversely, very low values of TK and LAB destroyed exergy are obtained, by suggesting that such components efficiently manage large exergetic products (solar heat and electricity, respectively). A remarkable reduction of the building destroyed exergy, about 31%, is achieved by comparing the $Ex_{d,BUI,PS}$ vs $Ex_{d,BUI,RS}$.

Table 4. Yearly results of proposed system

Parameter	**Description**	**Value**	**Unit**
$Ex_{d,CB,PS}$	Destroyed exergy of condensing boiler in PS	239.0	MWh/year
$Ex_{d,BIPVT}$	Destroyed exergy of BIPVT collectors	126.1	
$Ex_{d,TK}$	Destroyed exergy of tank	0.7	
$Ex_{d,LAB}$	Destroyed exergy of lead acid battery	0.3	
$Ex_{d,BUI,PS}$	Destroyed exergy of building in PS	308.7	
$Ex_{d,tot,PS}$	Total destroyed exergy in PS	674.9	
$Ex_{d,CB,RS}$	Destroyed exergy of condensing boiler in RS	263.8	
$Ex_{d,BUI,RS}$	Destroyed exergy of building in RS	450.0	
$Ex_{d,tot,RS}$	Total destroyed exergy in RS	713.8	
$\eta_{ex,LAB}$	Lead acid battery exergetic efficiency	85.5	%
$\eta_{ex,TK}$	Tank exergetic efficiency	74.2	
$\eta_{ex,BIPVT}$	BIPVT collectors exergetic efficiency	8.4	
$\eta_{ex,CB}$	Condensing boiler exergetic efficiency	2.0	
PES_{el}	Primary Energy Saving for electricity	32.8	
PES_{DHW}	Primary Energy Saving for DHW	9.2	
$PES_{heat\&cool}$	Primary Energy Saving for space heating and cooling	6.2	
SPB	Simple Pay Back	3.9	year

This is specifically due to the following reasons: i) in RS the inlet solar exergy to the building, is higher than the PS one, since in PS, it is converted by south façades BIPVTs and not directly absorbed by the walls; ii) the exergy due to heat transmission through the external walls in PS is lower, mainly for the useful winter passive effect of BIPVTs; iii) the inlet exergy due to electricity supplying the HPs for producing space heating is lower in PS (for the previous point and for the effect of RF system). A significant result can be clarified by observing the values of total destroyed exergies, $Ex_{d,tot,RS}$ and $Ex_{d,tot,PS}$. In fact, when the whole building - plant system is considered, by considering the system boundary including all components, although in PS further components (namely, BIPVTs, TK, LAB and auxiliaries), with respect the RS ones (consisted of building and CB) are included, $Ex_{d,tot,PS}$ is lower than $Ex_{d,tot,RS}$. This depends mainly by the reduction of $Ex_{d,BUI,PS}$. The obtained values exergetic efficiency are equal to 2.0, 8.4, 74.2 and 85.5 %, respectively for $\eta_{ex,CB}$, $\eta_{ex,BIPVT}$, $\eta_{ex,TK}$ and $\eta_{ex,LAB}$. In Table 4, the results of the developed energy and economic analysis are also reported. By assuming a capital cost contribution equal to 50% of total capital cost, the SPB is equal about to 3.9 years. Such positive result is mainly due to high saving of natural gas cost of the PS for DHW preparation. This occurs although the PES_{DHW} is not that high, 9.2 %, because the DHW demand of RS is noteworthy. $PES_{heat\&cool}$ is equal only to 6.2 %, mainly because the useful passive effect of winter overheating of BIPVTs is slightly higher than the unwanted summer cooling one. Such saving is due also to the adoption of the RF system providing space heating for the Zone 3. The PES for electricity is also shown, 32.8 %. Fig. 4 shows the cumulated weekly exergy destructions of the main components of the investigated building - plant system. It is clearly shown that the weekly trends of building destroyed exergy $Ex_{d,BUI}$ of RS and PS are growing during the summer weeks, basically due to the higher demand electricity of HPs for space cooling. $Ex_{d,BUI,RS}$ is noticeably greater than $Ex_{d,BUI,PS}$, according to the yearly exergy results. In both RS and PS, $Ex_{d,CB}$ and $Ex_{d,BUI,}$ show that CB and BUI are the main sources of system irreversibilities. This occurs for the highly irreversible chemical reaction occurring in CB, and because in BUI several conversion processes occur. Such irreversibility cannot be reduced. $Ex_{d,CB}$ is slightly higher in winter. The weekly values of $Ex_{d,CB,PS}$ decrease with respect to $Ex_{d,CB,RS}$, according to the yearly results obtained in the previous section. BIPVTs also represent a remarkable source of irreversibilities for the system, showing a destroyed exergy rate $Ex_{d,BIPVT}$ variable all year long, as a consequence of the variations of exergy fuel related to solar energy. In fact, higher exergy destructions are achieved during winter weeks, as a consequence of the higher winter exergetic fuel and the lower summer exergetic products. This is mainly due to the collectors slope, equal to 90°, corresponding to a lower summer incident radiation with respect to the winter one, for the latitude of Naples. The significant value of $Ex_{d,BIPVT}$ is consistent with the theories available in literature regarding exergy analysis of solar systems. In fact, heat transfer within the collector suffers for the huge temperature differences between the sun and the collector itself. Therefore, the exergy analysis suggests that solar collectors are affected by large unavoidable irreversibilities.

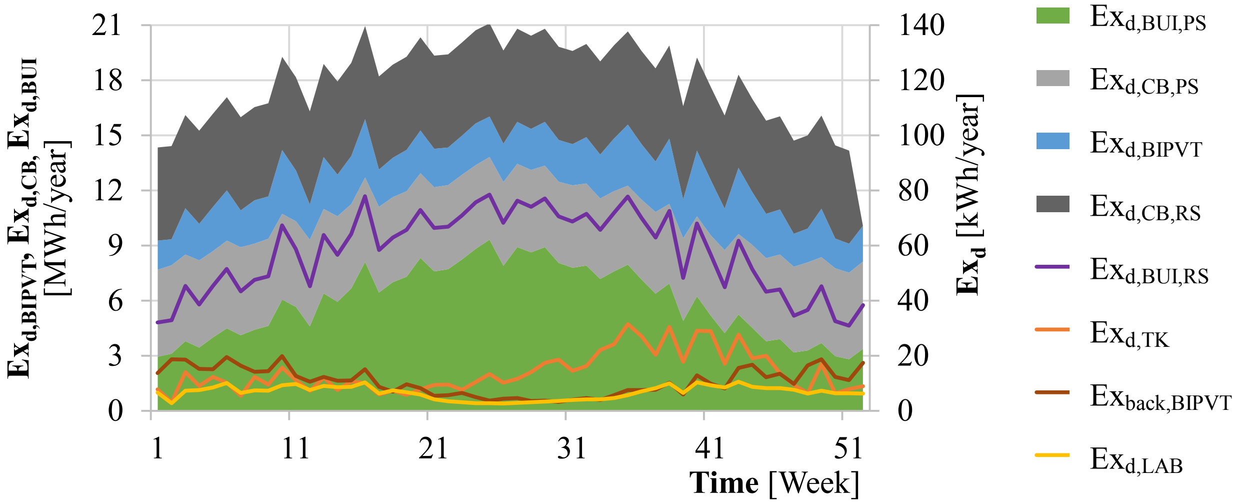


Fig. 4. Weekly destroyed exergy

On the other hand, it must be considered that such technology uses a renewable and free source energy and, therefore, such irreversibilities can be also considered acceptable. Anyway, $Ex_{d,BIPVT}$ is usefully reduced by $Ex_{,back,BIPVT}$ (reported on the right axis), which represents the transferred exergy through the back surface of the collectors to the building façades, which is higher in winter. This term reduces the space heating demand, as explained-above, and simultaneously $Ex_{d,BIPVT}$, with respect the stand-alone ones. In fact, at the same conditions, the exergy of collector back surface will be lower in case of the stand-alone collectors, mainly during the winter when the back surface temperature of the collectors is higher than the ambient one. In any case, such effect is negligible with respect the global $Ex_{d,BIPVT}$. The destroyed exergy of the TK and LAB are negligible with respect $Ex_{d,BUI}$, $Ex_{d,CB}$, and $Ex_{d,BIPVT}$. The hourly exergetic efficiencies and destroyed exergies of BIPVTs, CB, TK and LAB, are reported in Fig. 5, for a representative summer day. An interesting result concerns $\eta_{ex,LAB}$, which assumes lower values during charging phase, about 77.0%, and higher ones during discharging one, about 94.0%. By averaging both values, an average exergetic efficiency equal to 85.5% (corresponding to yearly efficiency).

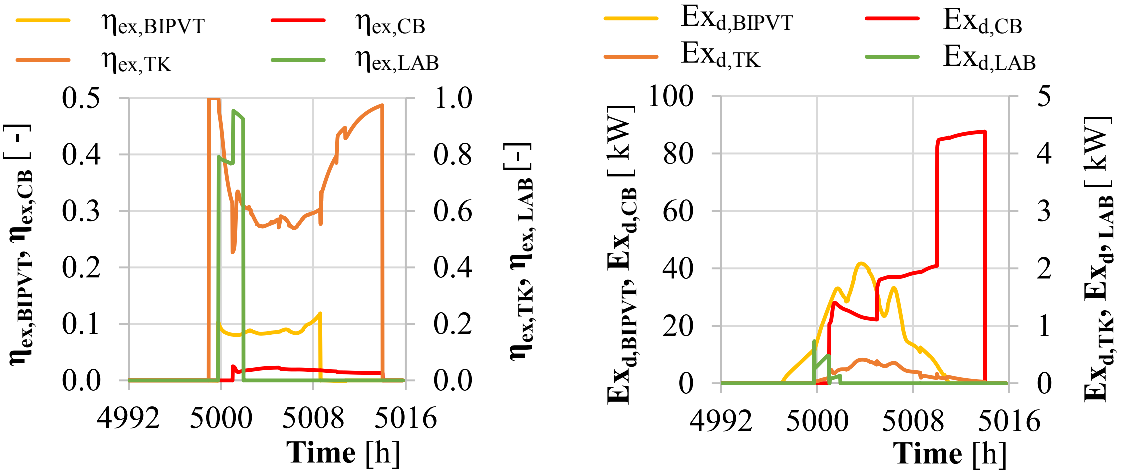


Fig. 5. Sample summer day in Naples: hourly exergetic efficiency and destroyed exergy

$\eta_{ex,TK}$ shows a maximum close to 100% during early morning hours, when the TK exergetic input due to thermal power production by BIPVTs is zero and, for the same reason, in the late evening, when a significant TK exergetic output due to DHW demand also occurs. $Ex_{d,\,CB}$ shows a maximum of about 90 kW, simultaneous with the high DHW demand. The huge $Ex_{d,\,BIPVT}$ is due to conversion of solar radiation into heat and power by the BIPVTs occurs mainly at midday when the incident radiation is maximum. This corresponds to the significant temperature difference between BIPVTs and the sun, in accordance with theory by Petela. The LAB and TK destroyed exergies are negligible with respect $Ex_{d,\,BIPVT}$ and $Ex_{d,\,CB}$.

5. Conclusion

This work presents a detailed exergetic and energy-economic model of BIPVT collectors coupled to an electricity storage system and to a condensing gas-fired boiler. Such model is developed using TRNSYS software in order to compare, by dynamic simulations, the Proposed System (PS) with a Reference one (RS). A case study is presented and is assumed to be located in Naples (South Italy), where flat-plate PVT collectors are integrated in the south facing façades of a non-residential high-rise building. BIPVT produced thermal energy is exploited to supply a radiant floor for the winter heating and the excess is used for DHW production. Heat pumps/chillers are adopted as auxiliary devices. The main findings of investigated system can be resumed as follows: i) the yearly demand for DHW / space heating and the electricity from grid reduces from 230.9 to 209.7 MWh/year, from 7.6 to 5.5 MWh/year, and from 48.0 to 25.9 MWh/year, respectively; ii) BIPVTs destroyed exergy is very high, in according to the low collectors exergetic efficiency; iii) weekly BIPVTs exergetic efficiency ranges from 7.0 to 10.0%; iv) a remarkable decrease of the building destroyed exergy, equal to about 31.0%, is obtained; v) yearly heat storage tank shows an exergetic efficiency very high by reaching 74.2%; vi) battery exergetic efficiency is about 77.0%, during charging phase, and 94.0% during discharging one; vii) condensing boiler exergetic efficiency is stably close to 2.0% during all year; viii) the economic profitability of PS is positive: a SPB of about 4 years is achieved; ix) PS allows one to achieve a significant enhancement from the exergetic point of view.

6. Acknowledgments

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