Exergo-economics of Hybrid Renewable Energy System

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Abstract – In this study, the exergo-economic analysis of a hybrid renewable energy system is performed in terms of exergetic and exergo-economic performance. A dynamic simulation tool is built into Matlab/Simulink, and yearly analysis is conducted under climate conditions of Strasbourg, France. As result, the daily dynamic behavior of the system and, on monthly basis, exergy destruction, production and efficiency are presented. Additionally, exergo-economic costs of produced electricity and heat products are presented on a monthly and yearly basis.

Nomenclature

A	area, m^2
$\dot{C}$	exergy cost rate, €
c	specific cost, €/kWh$_{ex}$ (exergy) or €/kg (mass flow)
CRF	Capital Recovery Factor
E	electrical energy, kWh
EL	energy level
Ex	exergy, kWh
$\dot{Ex}$	exergy rate, kW, W
G	solar irradiation, W/m^2
H	enthalpy, kJ
h	specific enthalpy, J/kg
I	component specific initial investment, €
i	interest rate
m	mass, kg
OM	operating and maintenance
Q	thermal energy, W, kW
S	entropy, kJ/K
s	specific entropy, J/kgK
T	temperature, K, °C
t	time, h
U	heat transfer coefficient, W/m^{2}K
Z	non-exergetic costs
Greek symbols	
β	temperature coefficient, %/K
η	efficiency
ζ	exergy efficiency
Index and exponent	
b	boiler
CD	conduction
CV	convection
cw	cold water
d	destruction
e	environment
eng	engine
f	fluid, fuel
g	glass cover
HX	heat exchanger
in	inlet
out	outlet
p	product
pv	photovoltaic

1. Introduction

A micro combined heat and power (micro-CHP) unit generates simultaneously heat and power from a single fuel source at high efficiency for buildings. The micro-CHP unit can be fueled by renewable energy sources, such as solar or biomass and has typically an electrical power below 15 kW [1]. The photovoltaic-thermal (PVT) collector converts solar energy to electricity and heat, simultaneously. On the other hand, the Stirling engine powered micro-CHP unit produces, in a controlled manner, energy from biomass.

To support fluctuating solar-based cogeneration, an HRES [2] can be formed by combining the PVT collectors and a controllable Stirling engine micro-CHP unit with multi-port thermal energy storage. In addition to support the fluctuating solar energy production, the

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hybridization enables highly efficient and 100% renewable energy production, higher system flexibility and reliability, and a reduction in CO_2 emissions, primary energy use and costs. However, the HRES based on cogeneration requires further analysis, especially, in terms of dynamic simulation due to highly dynamic behavior of the PVT collectors and thermal load.

In this paper, a dynamic model of the described HRES is presented and built to Matlab/Simulink in order to perform the exergo-economic analysis. The system produces domestic hot water (DHW), space heating (SH) and electricity for residential building use under climate conditions of Strasbourg, France. The hourly demand and weather data are used to simulate the operation of the HRES. Exergo-economics take into account the quality of energy (exergy), instead of quantity, and combines the quality with the monetary value. The quality of energy defines the usefulness of the considered energy quantity and has real correlation with the monetary value. Due to this, the exergo-economic analysis is a more rational costing method than conventional energy-economic analysis which is based on the energy quantity.

2. Methodology

The analyzed HRES in Fig. 1 consists of the thermal energy storage (TES), a biomass-fueled micro-CHP unit and water-cooled photovoltaic-thermal (PVT) collectors. The system produces electricity, space heating (SH) and domestic hot water (DHW) at 55 °C for a residential building. The stratified TES have a volume of 2 m^3 and multiple connection ports to store thermal energy from the PVT field and micro-CHP, simultaneously. The Ökofen Stirling engine micro-CHP has an electrical and thermal power of 1 kW and 12 kW, respectively. It utilizes wood pellets (flow 2) and air (flow 1) to produce electricity (flow 3) and hot water flow (flow 4). The PVT field consists of 9 collectors in a matrix of 3x3 of which reference electrical efficiency is 18.7%. The PVT collectors are used to convert solar energy into electricity (flow 12) and heat (flow 11).

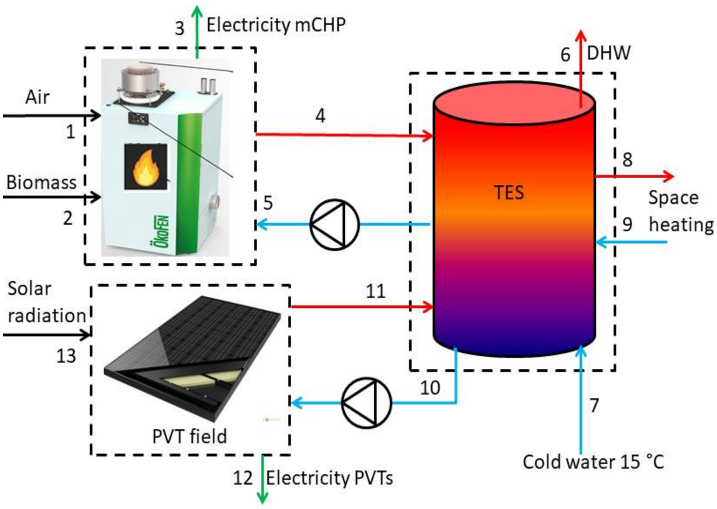

Figure 1: The hybrid renewable energy system

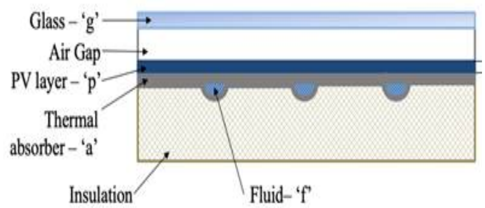

Figure 2: The layout of the PVT layers

2.1. HRES simulation model

Energy demand in the building environment and renewable energy production has both highly dynamic behaviors. Due to this, a dynamic analysis is required, and the simulation model of the considered HRES was built into Matlab/Simulink environment.

The stratified multi-port thermal energy storage was modelled using the open-source CARNOT-Toolbox [3]. A model of the single PVT collector, presented in the authors' previous work [4,5], was extended to present a field of PVT collectors. In the model, the main heat transfer mechanisms between each PVT layer in Fig. 2 to the coolant fluid were considered, and the following key governing equations were used:

$$m_g \times c_{p,g} \times dT_g/dt = Q_{g,sol} + Q_{g-e,CV} + Q_{g-sky,RD} + Q_{g-pv,CV} + Q_{g-pv,RD} \quad (1)$$

$$m_{pv} \times c_{p,pv} \times dT_{pv}/dt = Q_{pv,s} + Q_{pv-g,CV} + Q_{pv-g,RD} + Q_{pv-f,CV} - E \quad (2)$$

$$m_f \times c_{p,f} \times dT_f/dt = Q_{f-pv,CV} + Q_f \quad (3)$$

The electrical efficiency of the PVT collectors depends linearly on the PV module temperature T_{pv}, the efficiency η_{STC} at standard conditions T_{ref} and the temperature coefficient β_{PV}.

$$\eta_{el(T)} = \eta_{STC} \times \left[1 - \beta_{PV} \times \left(T_{pv} - T_{ref}\right)\right] \quad (4)$$

A biomass-fueled Stirling engine micro-CHP unit called Pellematic Condens_e manufactured by ÖkoFEN [6] has been tested in the laboratory of INSA Strasbourg ICUBE and integrated into the HRES model. Annex 42 [7] modelling approach based on energy balance was used to model the micro-CHP unit. The heat transfer from the engine to the coolant fluid was modelled as follows [8]:

$$MC_{eng}\, dT_{eng}/dt = UA_{HX} \times \left(T_{w,out} - T_{eng}\right) + UA_{loss} \times \left(T_e - T_{eng}\right) + q_{gen} \quad (5)$$

$$MC_w \times dT_{w,out}/dt = \dot{m}_w \times c_{p,w} \times \left(T_{w,in} - T_{w,out}\right) + UA_{HX} \times \left(T_{eng} - T_{w,out}\right) \quad (6)$$

The engine specific heat transfer coefficient UA_{HX} and UA_{loss}, and the thermal capacity of the engine MC_{eng} and cooling water MC_w in J/K were identified by Simulink Parameter Estimator Tool. The previously obtained experimental data of the micro-CHP operation was used in the identification. Finally, the recovered heat from the micro-CHP (flow 4) is calculated as follows [9]:

$$Q_{CHP} = \dot{m}_w \times c_w \times \left(T_{w,in} - T_{w,out}\right) \quad (7)$$

As regards the exergy analysis, the HRES receives its fuel exergy from biomass and solar radiation. These can be calculated as follows, respectively [10,11]:

$$\mathrm{Ex}_{in,CHP} = f_{q,bm} \dot{m}_f \mathrm{LHV}_{bm} \quad (8)$$

$$\mathrm{Ex}_{in,PVT} = A \times G \times (1 - 4/3 \times T_0/T_{sol} + 1/3 \times (T_0/T_{sol})^4) \quad (9)$$

where $f_{q,bm}$ is a biomass quality factor of 1.13 [12] and LHV_{bm} is the biomass lower heating value of 4900 Wh/kg. T_0 is the monthly reference temperature and T_{sol} is the solar temperature of 5777 K. In terms of energy products, electricity is seen as pure exergy and the exergy content of thermal products depends on the specific enthalpy (h) and entropy (s) of the flow. This leads to the presentation of thermal exergy of a certain flow in the system [10]:

$$\mathrm{Ex}_{th} = \dot{m}[h_{out} - h_{in} - T_0(s_{out} - s_{in})] = \dot{m} c_{p,f}[(T_{out} - T_{in}) - T_0 \ln T_{out}/T_{in}] \quad (10)$$

where $\dot{m}$ is the mass flow rate and $c_{p,f}$ is the fluid specific heat.

In this study, the cumulative exergy flows over a certain time period are used to calculate the monthly results.

$$Ex_j = \int_{t_1}^{t_2} \dot{Ex}_j\, dt \quad (11)$$

The overall exergy efficiency of the system is calculated as follows:

$$\zeta = \frac{(\mathrm{Ex}_8 - \mathrm{Ex}_9) + (\mathrm{Ex}_6 - \mathrm{Ex}_7) + \mathrm{Ex}_3 + \mathrm{Ex}_{12}}{\mathrm{Ex}_{in,CHP} + \mathrm{Ex}_{in,PVT}} \quad (12)$$

2.2. Building energy demand

A reference building was simulated by the IDA ICE software to obtain annual hourly space heating demand in Fig. 3. To have a reference building that represents the general building stock characteristics of France, the U-values of the building envelope were selected based on the European Union building factsheets [13] in Table 1.

The DHW demand was simulated using the DHW-calc tool developed for IEA-SHC Task 26 [14]. A daily sample of the DHW and electricity profiles are presented in Fig. 4 and 5, respectively.

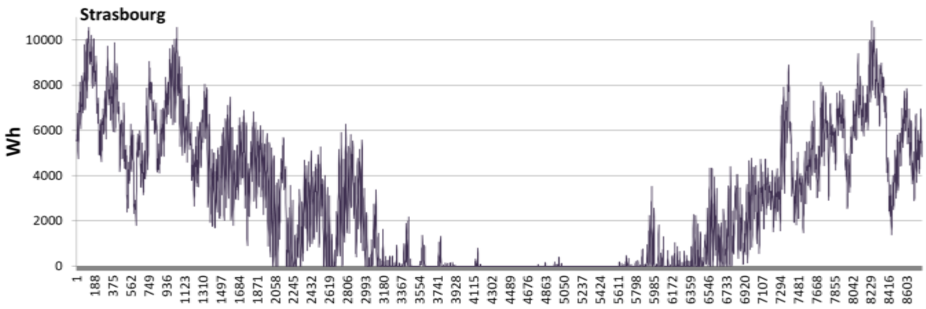

Figure 3: *Hourly space heating demand profile in Strasbourg*

	Geometry [m^2]	*U-value* [W/m^{2}K]
Windows	19	2.83
Walls	111	0.97
Floor	150	0.89
Roof	143	0.83

Table 1: *Geometry and U-values of the reference building.*

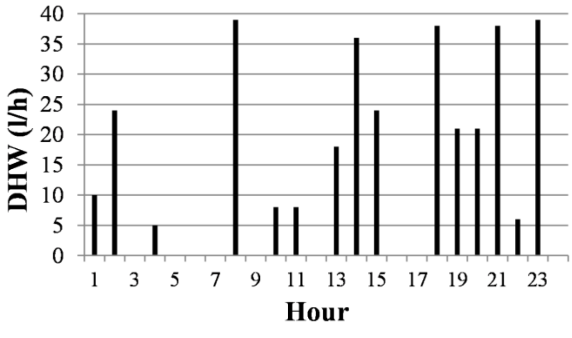

Figure 4: *DHW demand profile*

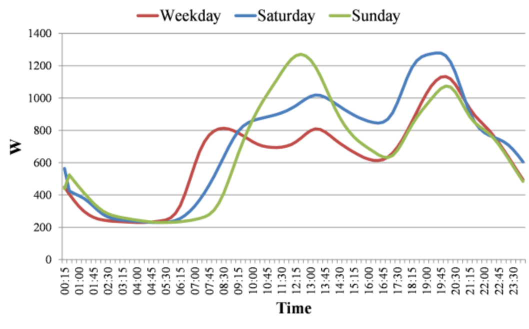

Figure 5: *Electricity demand profile* [15].

2.3. Exergo-economic analysis

The Specific Exergy Costing (SPECO) approach proposed by Lazzaretto and Tsatsaronis [16] is used in this paper. The exergo-economic analysis combines exergy approach with an economic analysis. It is used to allocate investment and operation costs of the system for its three energy products: electricity, space heating and DHW. As a result of the analysis, the exergo-economic costs for the energy products are defined.

According to SPECO, the exergo-economic balance equation of each kth component is presented as follows:

$$\dot{C} = c\dot{Ex} \tag{13}$$

$$\sum_{fuel} \left(c_f \dot{Ex}_f\right)_k + \dot{Z}_k = \sum_{product} \left(c_p \dot{Ex}_p\right)_k \tag{14}$$

Where $\dot{Z}_k$ is non-exergetic costs including investment and operation costs.

To have a dynamic exergo-economic analysis, the cumulative exergy and costs flows over defined period t_{period} are taken into account. The cumulative non-exergetic costs of each k^{th} component are calculated as follows:

$$\tilde{Z}_k = I_k \times CRF \times t_{period}/8760 + OM_k = I_k \times \frac{i(1+i)^n}{(1+i)^n - 1} \times t_{period}/8760 + OM_k \tag{15}$$

In this paper, the energy levels of different energy products are taken into account in the costing method according to [17] in order to give higher price for the higher quality flow. The energy level of electricity is 1 and of heat is calculated as follows [17]:

$$EL = 1 - T_0 \frac{\Delta S}{\Delta H} \tag{16}$$

	Exergo-economic balance equation	*Auxiliary Equations*	*Initial investment I_k*
Micro -CHP	$\dot{C}_1 + \dot{C}_2 + \tilde{Z}_{CHP} = \dot{C}_3 + (\dot{C}_4 - \dot{C}_5)$	$\dot{C}_1 = 0$, $\dot{C}_2 = \dot{m}_{bm} c_{bm}$, $\frac{(c_4 - c_5)}{c_3} = \frac{EL_{4-5}}{EL_3}$	17600 € excl. VAT
PVT field	$\dot{C}_{13} + \tilde{Z}_{PVT} = \dot{C}_{12} + (\dot{C}_{11} - \dot{C}_{10})$	$\dot{C}_{13} = 0$, $\frac{(c_{11} - c_{10})}{c_{12}} = \frac{EL_{11-10}}{EL_{12}}$	295 €/m² excl. VAT
TES	$(\dot{C}_4 - \dot{C}_5) + (\dot{C}_{11} - \dot{C}_{10}) + \dot{Z}_{TES} = (\dot{C}_8 - \dot{C}_9) + (\dot{C}_6 - \dot{C}_7)$	$\frac{(c_8 - c_9)}{(c_6 - c_7)} = \frac{EL_{8-9}}{EL_{6-7}}$, $\dot{C}_7 = \dot{m}_7 c_{CW}$,	2300 €/m³ excl. VAT
	Exergo-economic costs of electricity		*Exergo-economic costs of heat*
Micro -CHP	$c_{el,CHP} = \frac{\dot{C}_2 + \tilde{Z}_{CHP}}{\left(1 + \frac{(\dot{Ex}_4 - \dot{Ex}_5) \times EL_{4-5}}{\dot{Ex}_3 \times EL_3}\right)\dot{Ex}_3}$		
PVT	$c_{el,PVT} = \frac{\tilde{Z}_{PVT}}{\left(1 + \frac{(\dot{Ex}_{11} - \dot{Ex}_{10}) EL_{11-10}}{\dot{Ex}_{12} EL_{12}}\right)\dot{Ex}_{12}}$		
HRES	$c_{el,sys} = \frac{c_{el,CHP} \times \dot{Ex}_3 + c_{el,PVT} \times \dot{Ex}_{12}}{\dot{Ex}_3 + \dot{Ex}_{12}}$		$c_{DHW} = \frac{\dot{C}_6}{\dot{Ex}_6}$, $c_{SH} = \frac{(\dot{C}_8 - \dot{C}_9)}{(\dot{Ex}_8 - \dot{Ex}_9)}$

Table 1: *The main equations of the exergo-economic analysis and the initial investment cost.*

3. Results and discussion

The exergetic and exergo-economic performance of the HRES was evaluated by the dynamic simulation. The simulation tool was used to calculate the daily dynamic behavior of the system and on a monthly basis, exergy destruction, production and efficiency of the system. The exergy-economic costs of electricity, SH and DHW were calculated on a monthly and annual basis.

Figures 6-7 present the exergy flows in the system during a summer and winter day. During the summer day, the main exergy input came from the sun during the sunny hours of the day. During the night hours, the exergy input came from the biomass to fully satisfy the energy demand. The highest exergy destruction occurred in the PVT collectors but was also relatively high in the micro-CHP when it was running. Due to a good availability of solar radiation, the main exergy product was electrical energy produced by the PVT field followed by the micro-CHP electrical energy. During the summer day, the heat products had a significantly smaller magnitude than the other exergy flows. Due to low solar availability during the winter day, the fuel exergy flow was caused mainly by biomass. The micro-CHP was running more during the winter day due to the higher space heating demand, and the magnitude of the costly exergy destruction was higher than on the summer day.

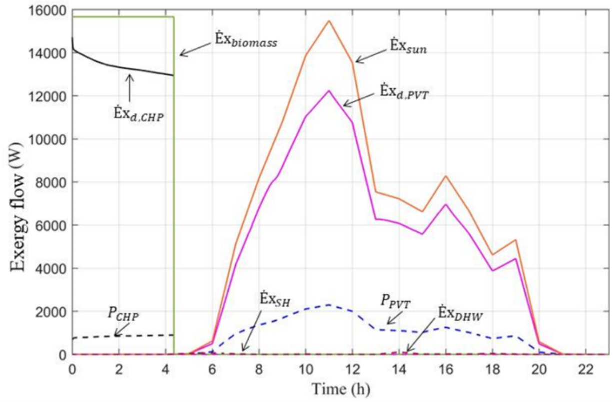

Figure 6: *Exergy flows during a summer day*

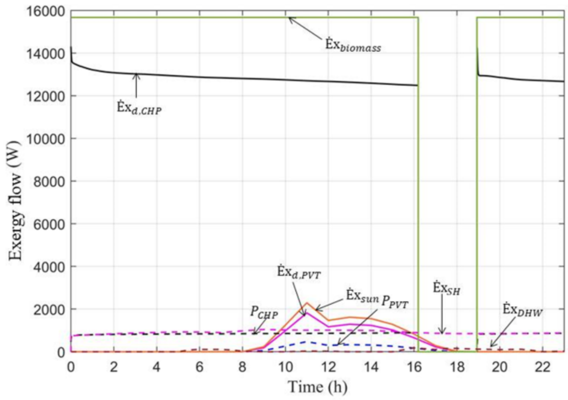

Figure 7: *Exergy flows during a winter day*

In Fig. 8 is presented the monthly fuel exergy flows from biomass and solar energy. The results show that the hybrid renewable energy system is required to fulfil the energy demand each month. The biomass is used more during the cooler months and reduced almost to zero during the summer months when free solar energy is available. The monthly exergy products and overall exergy efficiency of the system are presented in Fig. 9. The electrical exergy produced by the PVT collectors had the highest magnitude amongst the exergy products. The overall exergy efficiency of the system varied from 14% to 16% depending on the month.

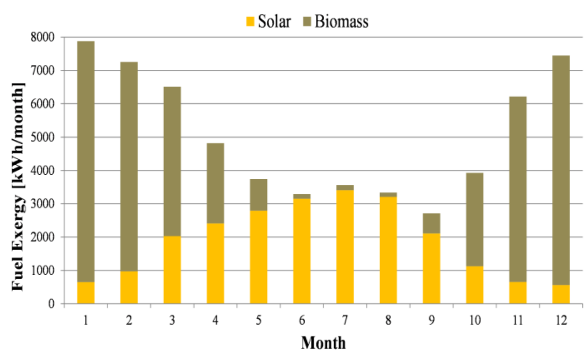

Figure 8: *Monthly fuel exergy*

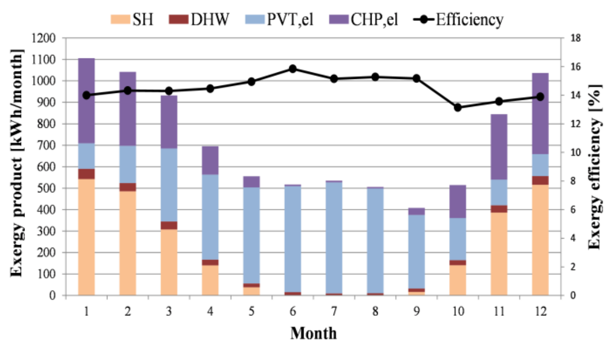

Figure 9: *Monthly exergy products*

The monthly and annual cumulated exergo-economic costs of the electricity and heat products produced by the HRES are presented in Fig. 10-11. The results show high monthly variation in the exergo-economic costs which should be taken into account when pricing the energy products of the system. The lowest costs of electricity were resulted during the summer months due to the high availability of cost free-solar energy. The annual specific cost of electricity was 0.41 €/kWh presented in Fig. 10. This should be saved by the system owner by avoiding the power grid use. At the moment, the grid electricity has a lower price in France but in the future, the electricity price is assumed to increase. Such high electricity prices have been seen in some European countries, such as Spain.

The heat products resulted also in the highly varying exergo-economic costs in Fig. 11. The highest costs were during the summer months when the heating demand was low. Additionally, the thermal exergy was smaller during the warmest months due to the higher monthly reference temperature used in the exergy analysis. Figure 11 shows that DHW had a higher exergo-economic cost than the SH over the year due to the higher temperature and energy level.

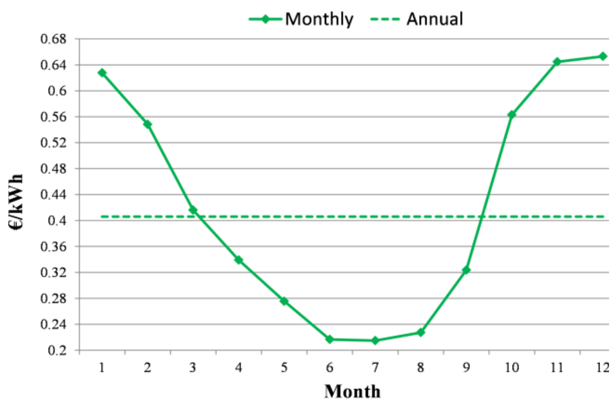

Figure 10: *Monthly and annual exergo-economic costs of electricity*

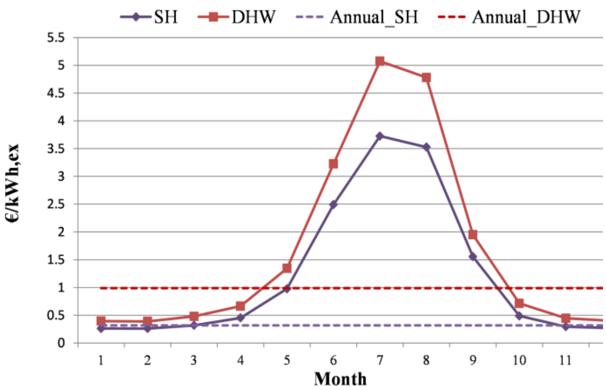

Figure 11: *Monthly and annual exergo-economic costs of the heat products*

4. Conclusion

In this study, a HRES based on solar and biomass cogeneration was dynamically analyzed in terms of exergo-economics.

During the summer day, the main exergy fuel was solar energy and the use of biomass fuel was reduced compared to the winter day. Both cogeneration units produced high exergy destruction rate due to produced low grade heat. The PVT electricity was the main monthly exergy product of the system from April to October. The exergy efficiency of the system varied from 14% to 16%. The specific costs of energy products varied strongly over the year by having the lowest costs during the summer months for electricity and the highest costs for heat products.

The hybridization of biomass and solar is required to fulfill the energy demand and reduce biomass use. The high initial investment costs of the units resulted in relatively high specific costs of electricity. However, it is expected to have a decrease in the initial investment costs and an increase in the grid electricity price that can make the HRES favorable. For future work, a sensitivity analysis of the heat storage size will be conducted.

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