THERMO-ECONOMIC INVESTIGATION OF A HYBRID SOLAR/BIOMASS MULTIGENERATION SYSTEM FOR OFF-GRID COMMUNITIES

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ABSTRACT

This work aims to evaluate the thermo-economic performances of a renewable energy-based multigeneration system supplying electricity, freshwater, domestic hot water, space heating and cooling requirements for an off-grid community, based on the combination of compound parabolic collectors, biomass boilers, an ORC and a vapor compression cycle (VCC). Solar collectors are used to preheat the heat transfer fluid (HTF). During highly solar irradiated off-peak periods, a fraction of the preheated HTF is transferred to charge a thermocline thermal energy storage, with the aim to reuse the stored energy during peak-demand periods; whereas the remaining part of the HTF is sequentially transmitted to biomass boilers, providing the complementary energy to drive the ORC. Rejected heat from the ORC is recovered through a counter-current heat exchanger to meet domestic hot water and space heating requirement of the community. Depending on the community electricity load demand, part of the turbine energy will be used to drive the VCC and/or a reverse osmosis unit allowing a continuous operation of the system. The studied system was co-simulated using Ebsilon® Professional and the WAVE Software, to assess the plant's thermodynamic and exergoeconomic performances under both winter and summer modes operation. Results showed that the considered system is able to meet the community requirements in winter mode with a solar field contribution of 35 %, a solar field exergy efficiency of 13.67 %, an overall exergy efficiency of 6.32 % and a total exergetic cost of 28.8 €/month/inhabitant, whereas in summer mode solar field's contribution reaches 27.86 %, solar field exergy efficiency is 14.15 %, overall exergetic efficiency is 5.15 % and the total exergetic cost is 39.51 €/month/inhabitant. Sensitivity analysis results showed that the choice of the ORC working fluid can have a significant impact on the thermodynamic and economic performances of the plant. Results showed also that the increase of the solar field aperture can lead to a decrease of the useful outputs cost if its specific cost is less than 150 and 200 €/m² respectively in winter and in summer modes. Finally, results indicated that biomass cost is a critical parameter highly impacting the economic viability of the studied plant.

1. INTRODUCTION

In the energy transition context, it is essential to develop sustainable and cost-effective solutions providing affordable, clean energy and water as targeted by the sixth and the seventh sustainable development goals. This can be achieved through renewable energy-based multigeneration systems. In fact, multigeneration is a convenient way to address the energy supply challenges, as the integration of a single or different input(s) to produce different useful outputs allow an improvement of the global energy conversion efficiency, a reduction of greenhouse gas emissions and an optimization of the available resources use (Jana *et al.*, 2017).
On the other hand, different fuels can be used to drive multigeneration systems, including fossil fuels, biomass and solar energy if hybridized with other resources (biomass, coal…) (Jana *et al.*, 2017). Indeed, hybridization of renewables is an appropriate solution to combine their mutual advantages and minimize the impact of their drawbacks, this is particularly true for the combination of biomass (flexible energy generation, costly) and solar energy (clean and sustainable generation, intermittent). In this sense, several solar/biomass multigeneration have been assessed in the literature. Calise *et al*. (2015) examined the exergetic and the exergoeconomic performances of a hybrid photovoltaic-thermal/biomass system driving a polygeneration system under different operating modes. Results showed that the studied system is viable in the case of small islands. Khalid *et al.* (2017) investigated the thermoeconomic performances of a multigeneration system driven by solar and biomass energies to provide electricity, cold, hot air and water for a community. Thermodynamic analysis of the system was conducted to evaluate the energy and exergy efficiencies of the overall system and its subsystems and to assess the impact of system operating conditions on the system's performances. Moreover, an economic study was carried out to optimize the levelized cost of electricity and net present value of the system. Karellas and Braimakis (2016) investigated the thermodynamic and economic performances of a solar/biomass trigeneration system. Energetic and exergetic performances of the system were assessed under different operating conditions, whereas an economic study was conducted for the case of a residential building in a Greek Island. In (Bellos *et al.*, 2018) a solar/biomass system producing 2 heat level, cold and electricity was assessed. Optimal operating conditions were determined under steady state conditions, whereas dynamic simulations were conducted to investigate the system's performances throughout the year. Finally, the financial analysis of the system showed promising results with a payback-time less than 6 years.
From the above literatures, it can be remarked that the potential of solar/biomass multigeneration systems is already recognized, however few works addressed the exergoeconomic evaluation of such systems, particularly in the Middle East and North Africa region context. For this purpose, this work aims to investigate the performances of a novel hybrid solar thermal/biomass system producing multiple useful outputs (electricity, freshwater, hot and cold water) based on exergetic and exergoeconomic analysis. The impact of the ORC working fluid, the solar field aperture and the corresponding thermal storage capacity will be addressed as well through a sensitivity analysis.

2. PLANT'S DESCRIPTION

The studied system is assumed to be installed in Benguerir's region (32.2208N, 7.9286 W), Morocco, to meet the requirement of an off-grid community consisting of 150 inhabitants. Heating, cooling, domestic hot water (DHW), freshwater and electricity demands for two typical days of winter and summer are represented in Figure 1(a), whereas Figure 1(b) depicts the assumed typical electricity demand profile of the community.

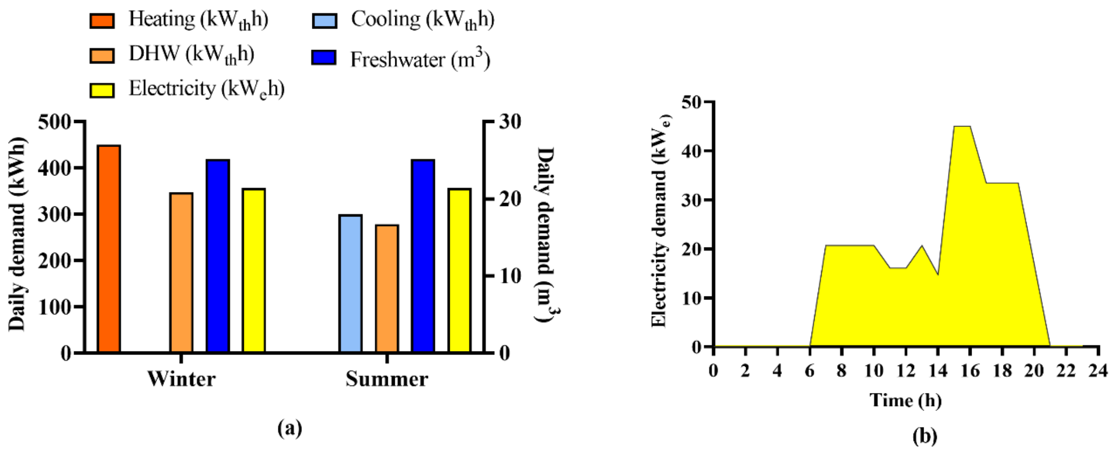


Figure 1: Considered community load demands: a) total load demands, b) electricity load demand

System's configuration is depicted in Figure 2. Compound parabolic collectors (CPC) are used to preheat the heat transfer fluid (HTF). During highly solar irradiated off-peak periods, a fraction of the preheated HTF (Therminol VP-1) is transferred to charge a thermocline thermal energy storage, with the aim to reuse the stored energy during peak-demand periods; whereas the remaining part of the HTF is sequentially transmitted to two biomass boilers using olive waste residues as a biomass fuel. The two parallel boilers configuration was chosen to provide more flexibility for the system's operation allowing a continuous operation of at least one boiler, regardless the load demand and the heat provided by the solar field. The produced heat by the solar field and the biomass boilers is then transmitted to the ORC block through a heat exchanger to evaporate the working fluid of the cycle (R245-fa). Depending on the load demand, part of the produced electricity is used to drive a reverse osmosis (RO) unit and/or a vapor compression cycle (VCC). Finally, part of the rejected heat from the ORC is recovered through a hybrid (water/air) condenser : during the wet mode, part of the desalinated water is heated to meet domestic hot water and space heating requirement of the community, whereas during the dry mode excess energy will be cooled using air. Considering the community requirement for the two considered typical days (Figure 1), plant's configuration was adapted to allow its operation under two modes, depending on the ambient temperature:

- winter mode: additional heat is recovered through the ORC condenser to meet the space heating requirement of the community,
- summer mode: the excess electricity after deducing community and RO unit requirements, is used to drive the VCC unit.

The studied system was co-simulated using Ebsilon® Professional 13.0 and the water application value engine (WAVE) software. The main parameters considered for the simulation are summarized in Table 1.

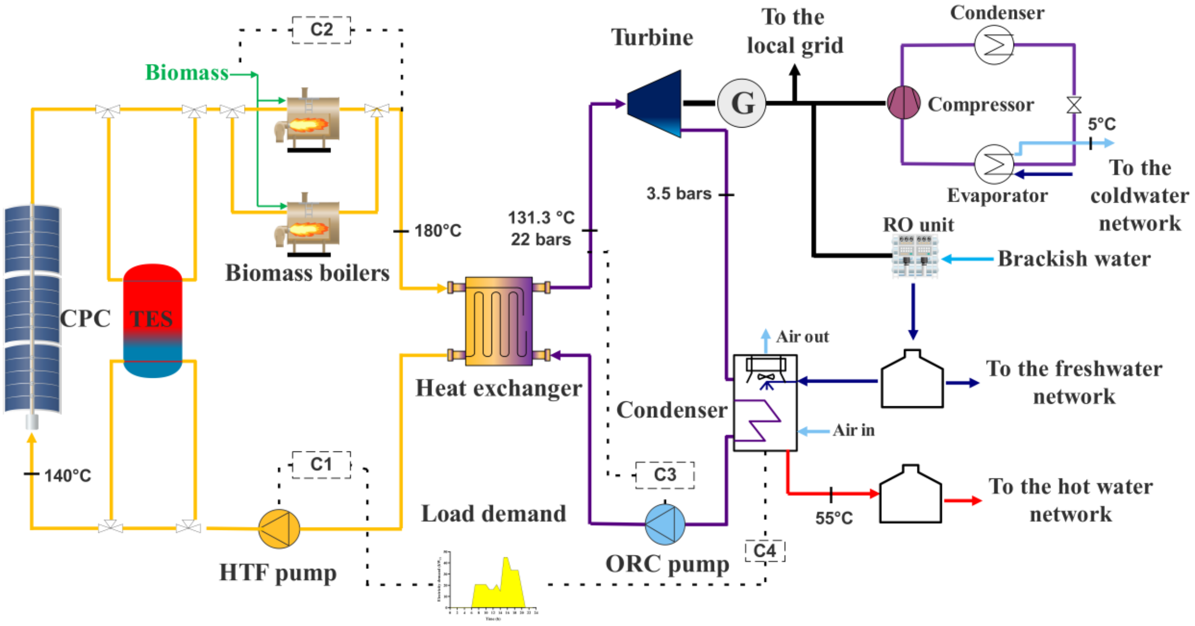


Figure 2: Plant's layout

Table 1: Main considered parameters for the simulations

Parameter	Value
CPC concentration ratio	2.5
Solar field aperture, m²	388.5
Collectors thermal efficiency curve parameters	η_0 = 0.623, a_1 = 0.59 W/m².K, a_2 = 0.004 W/m².K² (Palmero and Oliveira, 2016)
Thermal storage volume, m³	25
Biomass lower heating value (LHV), kJ/kg	18750
Biomass composition, kg/kg	C: 47.36; H: 6.04; O: 45.52
Biomass boiler capacities, kW	150 + 270
ORC capacity, kW	50
Turbine isentropic efficiency, %	82.3
Pumps isentropic efficiency, %	80
Brackish water total dissolved solids, mg/L	3500
Brackish water flow, m³/h	5.6
Element type	DOW BW30-365
Total active area, m²	206
Feed pressure, bar	16.1
Freshwater flow, m³/h	4.2
VCC working fluid	R134A

3. EXERGETIC AND EXERGOECONOMIC EVALUATIONS

To assess the performances of the studied system, the exergetic and exergoeconomic analysis of the plant were conducted. The following assumptions are considered for both analysis:

- The reference environment has a temperature T_0 = 21°C and a pressure P_0 = 1 atm,
- Heat losses from the heat exchangers are negligible,
- Exergy efficiency of the reverse osmosis process is 25 % (Blanco-Marigorta *et al.* , 2017) ,
- Kinetic energy and potential energy variations are negligible.

3.1 Exergetic analysis

Exergy analysis is an effective tool for the thermodynamic investigation of a system, by focusing on both quality and quantity of the involved energy conversion processes. Exergy efficiency is used as an indicator for the exergetic analysis of the plant's components and it is defined as the ratio of the exergy output to the exergy input of a given component. $\dot{Ex}_i$, the exergy of a material stream *i* is expressed as function of m_i, the material flowrate, h_i and s_i, respectively the material stream enthalpy and entropy and h_0, s_0 which are respectively the dead state enthalpy and entropy:

$$\dot{Ex}_i = m_i \cdot [(h_i - h_0) - T_0 \cdot (s_i - s_0)] \tag{1}$$

The solar field absorbed exergy $\dot{Ex}_A$ is evaluated as function of the solar field aperture area *(A)*, the solar radiation temperature (T_{sun} = 6000 K) and the effective solar radiation on the aperture plan of the CPC (G_{eff}):

$$\dot{Ex}_A = A \cdot G_{eff} \cdot (1 + \frac{1}{3} \cdot \left(\frac{T_0}{T_{sun}}\right)^4 - \frac{4}{3} \cdot \frac{T_0}{T_{sun}}) \tag{2}$$

The biomass exergy input $\dot{Ex}_B$ is calculated using the following equation:

$$\dot{Ex}_B = LHV \cdot \Phi \cdot m_B \tag{3}$$

Where *LHV* is the lower heating value of the biomass, Φ is energy-to-exergy ratio, evaluated as function of the biomass composition (Mehmood, 2011) and m_B is the biomass flowrate.

3.2 Exergoeconomic evaluation

Thermo-economic or exergoeconomic evaluation is a convenient methodology to assess accurately the cost of a useful system's output by considering non-exergetic and exergetic related costs. It is particularly useful for the cost allocation of multigeneration system. The thermo-economic balance for a component *j* is calculated using the following equation (Bejan *et al.*, 1996):

$$\sum_{in} (c_{in} \cdot \dot{E}_{in})_j + \dot{Z}_j + c_{q,j} \cdot \dot{E}_{q,j} = \sum_{out} (c_{out} \cdot \dot{E}_{out})_j + c_{w,j} \cdot \dot{W}_j \tag{4}$$

$\dot{E}_{in}$, $\dot{E}_{out}$, $\dot{W}_j$, $\dot{E}_{q,j}$ are the exergy rates formerly calculated from the exergy analysis and associated respectively to the inlet material flows, outlet material flows, electricity consumptions or production and heat exchange. c_{in}, c_{out}, $c_{w,j}$ and $c_{w,j}$ are the unit exergy cost related to the aforementioned exergy rates and $\dot{Z}_j$ represent the non-exergetic related costs and is calculated as function of the investment cost (I_j), the operation and maintenance cost ($O\&M_j$), the capital recovery factor (*crf*), and the component's number of hours of operation at nominal conditions per year *(h) :*

$$\dot{Z}_j = \frac{I_j \cdot crf}{h} + \frac{O\&M_j}{h} \tag{5}$$

The boundary of the exergoeconomic analysis as well as the balance and auxiliary relations for the plant's components are shown in Figure 3. Table 2 summarizes the main cost assumptions.

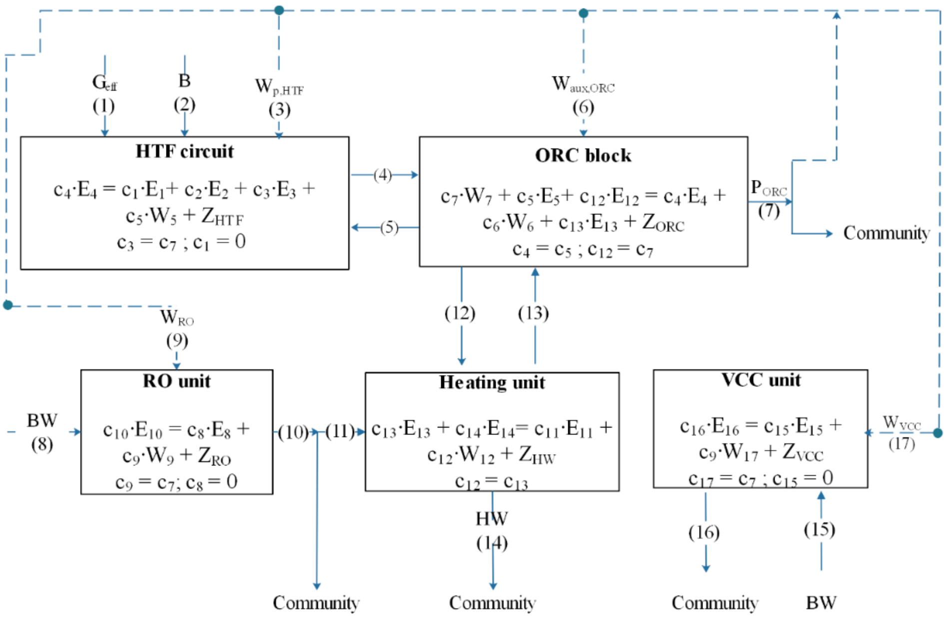


Figure 3: Exergoeconomic model of the plant

Table 2: Cost assumptions for the exergoeconomic analysis

Item	Value
Solar field specific cost, €/m²	250
Biomass boilers cost, €/kW_{th}	300 (Karellas and Braimakis, 2016)
Thermal energy storage cost, €/m^3	1000 (Bellos, 2018)
ORC unit cost, €/kW_e	3000 (Dumont *et al.*, 2018)
RO unit cost, €/m^3/day	435 (Maleki, 2018)
VCC unit cost, €/kW_{th}	400 (Karellas and Braimakis, 2016)
Hot water heat exchanger, €	740
Solar field O&M cost, €/y	1332 (2.5 % of the SF investment cost)
Biomass boilers, ORC and VCC O&M cost, €/y	1020 (1.5 % of the investment cost)
RO O&M cost, €/y	3606
Biomass cost (c_2), €/kWh	0.0115
Lifetime, y	20
Discount rate, %	5

4. RESULTS AND DISCUSSION

4.1 Meteorological data

To assess the performances of the studied system under different weather conditions, simulations were conducted for two typical days, representing both summer and winter periods. Solar irradiation and ambient temperature data measured by a Meteorological High Precision weather station were used as input data for the simulations. Figure 4 represents the hourly variation of the effective solar irradiations, as well as the ambient temperature for the two considered days. As mentioned in the second section, the plant can be operated under two modes (winter and summer modes), depending on the ambient temperature. Figure 5 represents the hourly variation of the ambient temperature at Benguerir and the considered period for each mode.

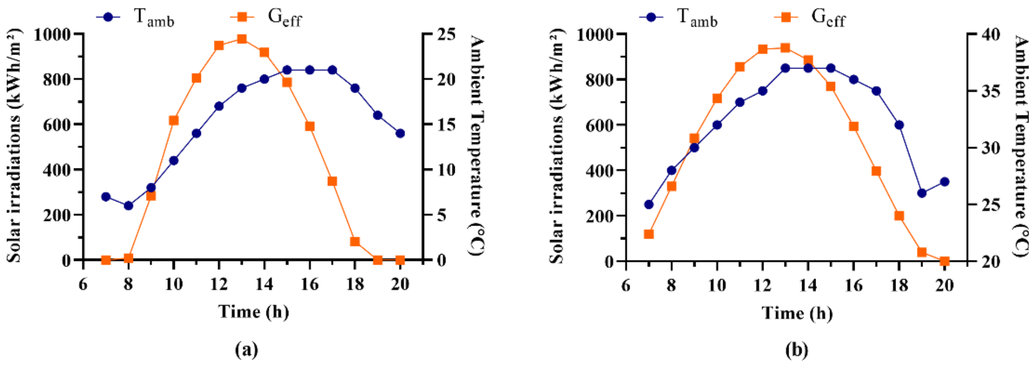


Figure 4: Effective solar irradiations and ambient temperature variation: a) 02/01, b) 08/07

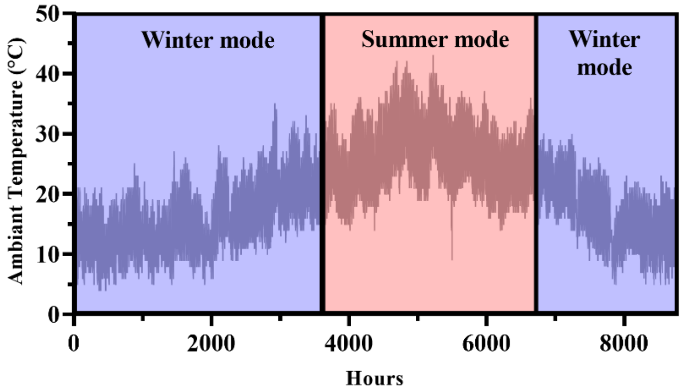


Figure 5: Hourly annual ambient temperature variation at the studied site

4.2 Thermodynamic evaluation

Figure 6 represents the variation of the solar field's exergy efficiency, the plant's overall exergy efficiency and the solar fraction (SF: ratio of the solar field's power to the total power delivered by the solar field and the biomass boilers) for the two considered days. During the winter day (02/01), solar field's production reaches 1088 $kW_{th}h$, representing a daily solar fraction of 35 %. Solar field's exergy efficiency achieves a maximum of 17 %, whereas the plant's overall exergy efficiency varies between 3.37 and 8.89 % during the day and is primarily impacted by the solar fraction: an increase of the solar fraction is generally associated to a decrease of the plant exergy efficiency. During the summer day (08/07), more energy is produced by the solar field (1192,71 $kW_{th}h$) due to the higher solar irradiations received by the CPC collectors, still, even more energy is required to drive the VCC unit, leading thus to an increase of the biomass consumption and a decrease of the daily solar fraction (27.86 %). Solar field's exergy efficiency achieves a maximum of 16.7 %, whereas the overall plant's exergy efficiency is varying in a range between 1.4 and 8.7 %.

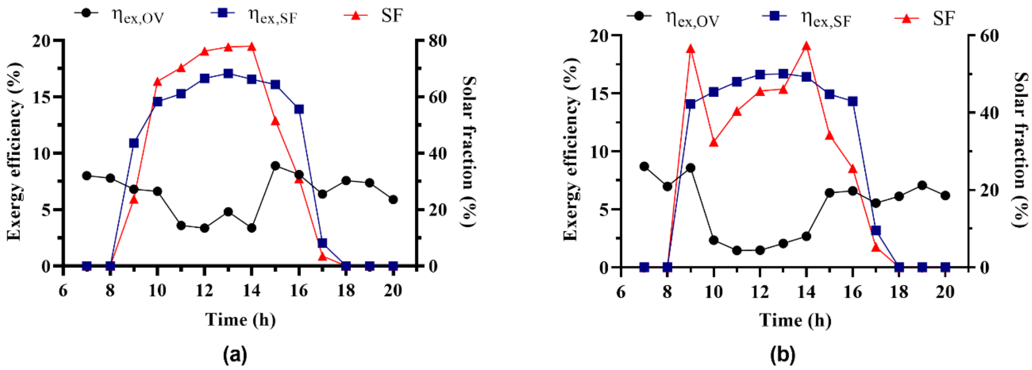


Figure 6: Solar fraction, solar field's and plant's exergy efficiencies: a) 02/01, b) 08/07

4.3 Exergoeconomic evaluation

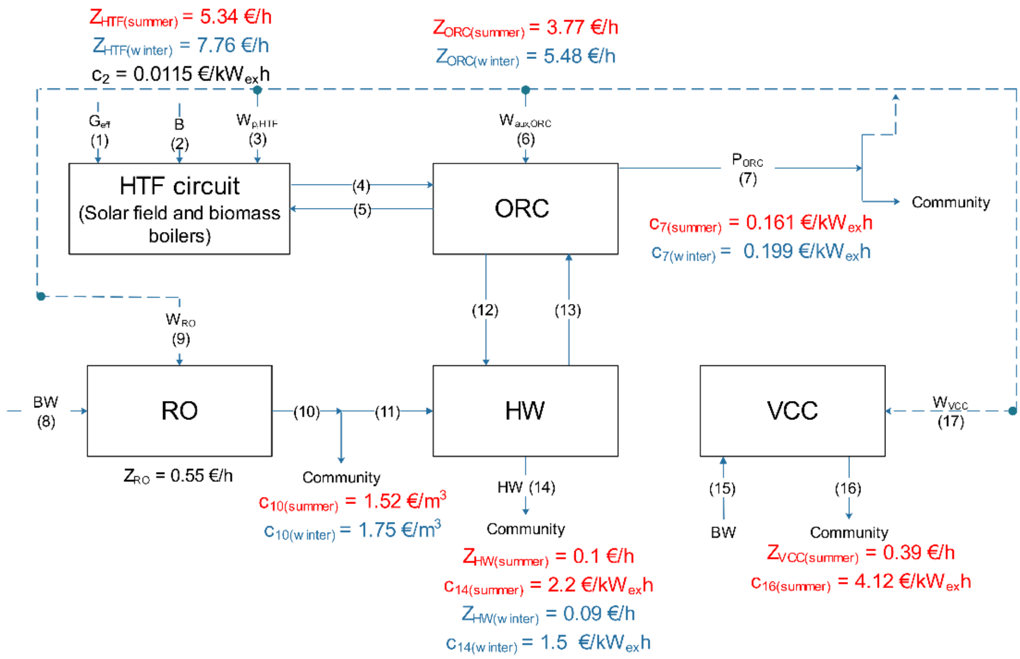


Figure 7: Exergoeconomic analysis results

The exergoeconomic costs of the useful products as well as the plant's components hourly costs are depicted in Figure 7. It can be observed that extending the operation time of a given component allows a reduction of its hourly operational costs and following decreases the useful outputs unitary costs that are highly impacted by the considered component. This can be illustrated by the electricity cost (c_7) which decreases from 0.199 to 0.161 €/kWh when the HTF circuit and the ORC hourly operational costs decreases respectively from 7.76 €/h and 5.48 €/h to 5.34 €/h and 3.77 €/h due to the extended operation time in the summer mode. The achieved generation costs remain relatively higher comparatively to centralized systems; they can be considered however as competitive in the context of isolated communities (Calise *et al.*, 2015).

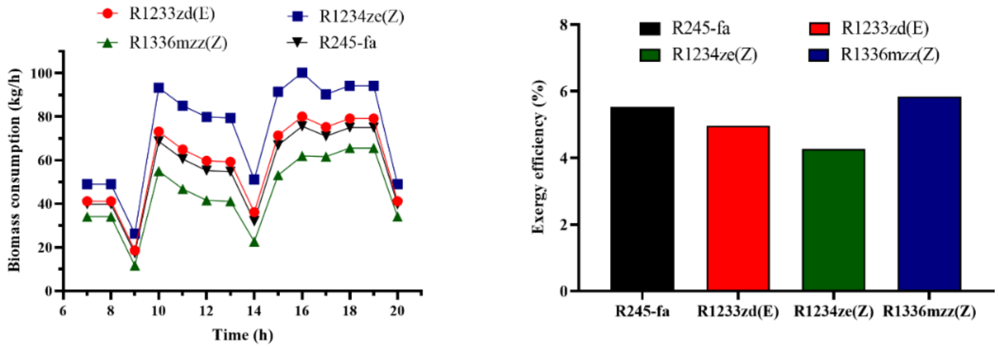
4.4 Sensitivity analysis

4.4.1 ORC working fluids: with the aim to assess the impact of the ORC block working fluid on the plant's performances, a comparative study was conducted considering the low-GWP working fluids R1233zd(E), R1234ze(Z) and R1336mzz(Z). Fluid properties were extracted from REFPROP 10.0 database (Lemmon *et al*, 2018) and were used to evaluate the required energy to be provided by the HTF circuit, in order to produce the same quantities of the useful outputs as in the base scenario (R245-fa as a working fluid). The considered operating conditions for the fluids are given in Table 3.

Sensitivity analysis results for the summer day are illustrated in Figure 8. Figure 8 (a) showed that the use of R1336mzz(Z) allows a noticeable reduction of the biomass consumption, reaching up to 18.5 %, which can significantly impact the cost of the produced outputs when the biomass cost is high. Biomass consumption in the case of R1233zd(E) shows a small increase (6.3 %) in comparison to the base scenario, whereas this consumption is noticeably higher when R1234ze(Z) is used as a working fluid, with a relative increase of 33.8 %. Similar results are obtained for the plant's overall exergy efficiency, hence R1336mzz(Z) allows a relative enhancement of the efficiency by 5.6 %, whereas the use of R1233zd(E) and R1234ze(z) lead to an efficiency reduction of 10.1 and 22.8 %, respectively.

Table 3: Operating conditions of the ORC block for the studied fluids

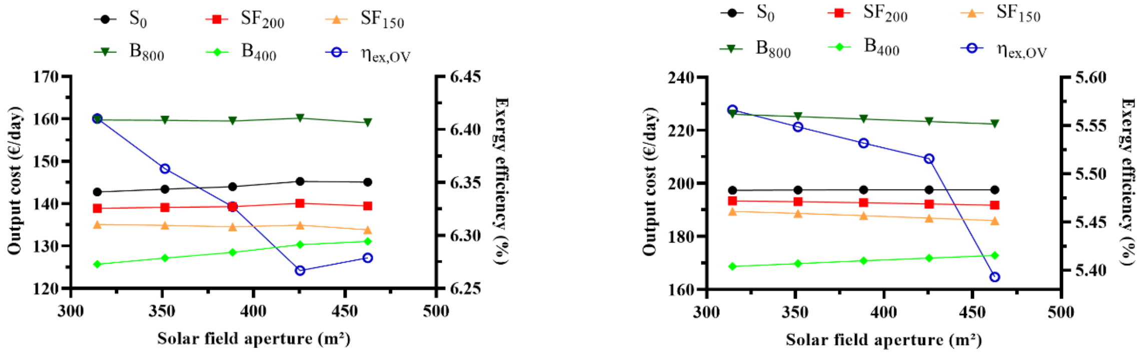
Fluids	High pressure (bars)	Low pressure (bars)	Superheating degree (K)
R1233ze(E)	22	4	5
R1234ze(Z)	22	6.5	5
R1336mzz(Z)	22	2	5



(a) (b)

Figure 8: Working fluids sensitivity analysis results (08/07): a) impact on the biomass consumption, b) impact on the plant exergy efficiency

4.4.2 Solar field aperture and the corresponding storage volume: A sensitivity analysis was also conducted to investigate the impact of the solar field aperture and the thermal storage capacity on the plant's overall exergy efficiency and the exergetic cost of the produced useful outputs. For this puprose, simulations were conducted considering five different solar field's apertures assuming for each case a corresponding thermal storage capacity equivalent to 3 hours of solar field's operation at nominal capacity. Exergoeconomic evaluation was conducted considering different cost scenarios for the solar field (150 and 200 €/m² denoted respectively by SF_{150} and SF_{200}) and the biomass (400 and 800 €/T denoted respectively by B_{400} and B_{800}) specific costs. Figure 9 shows the plant overall exergetic efficiency and the useful outputs daily cost variation as function of the solar field aperture for the studied scenarios. The increase of the solar field aperture leads in general to a decrease of the plant exergetic efficiency, it is however interesting to mention that an increase of the efficiency is observed in the winter mode (from 425.5 to 462.5 m²) when the exergy efficiency increase associated to the biomass consumption reduction exceeded the exergy efficiency reduction due to the increase of the solar contribution. Results showed that an increase of the solar field aperture allows a reduction of the biomass consumption between 1 and 1.6 kg/m² in winter and between 1.51 kg/m² and 1.53 kg/m² in summer. Hence, a solar field specific cost of 150 and 200 €/m² is required respectively in winter and in summer modes to make the solar field aperture increase economically viable. On the other hand, it can be seen that the biomass specific cost has a significant impact on the total exergetic cost of the produced outputs. Ensuring a secure supply of the biomass at an optimized price is therefore essential to guarantee the economic viability of the studied system.



(a) (b)

Figure 9: Solar field aperture impact on the plant's performances: a) 02/01, b) 08/07

5. CONCLUSIONS

In this paper, a hybrid solar/biomass multigeneration system supplying an off-grid community, was investigated based on thermodynamic and exergoeconomic indicators. The main conclusions that can be drawn from this work are as follows:

- Simulation results showed that the plant is able to meet the community requirements with a solar field contribution, a mean solar field exergetic efficiency and a mean overall exergetic efficiency of respectively 35%, 13.67, 6.32% and 27.86% 14,15 %, 5,15 % in winter and in summer days,
- The cost of the produced useful outputs can be considered as competitive in the context of isolated communities,
- The choice of the working fluid can have a significant impact on the thermodynamic and economic performances of the plant, the use of R1336mzz(Z) can reduce the biomass consumption by 18.5 % and improve the overall plant exergetic efficiency by 5.6 % relatively to the use of R245-fa,
- Increasing the solar field aperture is economically viable in winter and in summer if the solar field specific cost is respectively lower than 150 and 200 €/m², on the other hand the biomass cost is a critical parameter having an important effect on the cost of the produced outputs.

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