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Effect of collector self-shading on the performance of a Biomass/Solar Micro-CHP system

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Abstract

This paper describes an exhaustive study concerning solar geometry and the effect of shading between collectors in the overall performance of a new biomass/solar micro-CHP system. The system is a new prototype of a 6 kWe plant, based on a micro-cogeneration Organic Rankine Cycle (ORC) system, driven by a combination of solar thermal and biomass sources. Both sources may be used separately or combined. The solar thermal energy is obtained through medium-temperature concentrating compound parabolic solar collectors (CPC) with evacuated tubes. The system simultaneously produces electrical energy and low/medium temperature heat. In this study, five scenarios are presented: no shading; shading when the collector tilt is seasonally adjusted; and shading when the collector tilt is fixed in three positions during the year. Results of system simulation under the different operating modes are presented. Namely, a comparison of solar fractions and global electrical efficiencies of the system, with and without shading, is carried out.

Keywords: *collector shading, organic Rankine cycle, micro-cogeneration, solar energy, biomass*

1. Introduction

Micro-generation is the decentralised production of electricity, through different means with an electrical power output up to 50 kW. Micro-cogeneration, or micro-CHP, is the combination of micro-generation with useful heat (Pehnt et al., 2006). Among the several existing technological solutions for micro-cogeneration, Organic Rankine Cycle (ORC) systems are an interesting solution in cases where the heat demand is significantly larger than electricity needs, which is the case of residential and also other buildings (Oliveira et al., 2014). Micro-ORC systems driven by renewable energy sources have attracted the attention of many researchers. Either theoretical or experimental works have been carried out, including developments and improvements in system components (Facão et al., 2008), (Palmero-Marrero and Oliveira, 2009), (Quoilin et al., 2011), (Qiu et al., 2011), (Twomey et al., 2013), (Jradi et al., 2014).

A micro-cogeneration ORC system driven by a combination of solar thermal and biomass sources was simulated by the authors (Palmero-Marrero et al., 2015), (Oliveira et al, 2014). In the simulations, high efficiency vacuum-CPC solar collectors were used, and the power cycle used a highly efficient rotary lobe expander. The results obtained allowed the prediction of system annual performance. The system is under development and the prototype will be installed and tested in Benguerir (Morocco) during this year, in the framework of the REELCOOP project, funded by the EU (REELCOOP, 2015). For solar resource assessment purposes, Meteonorm software was used to generate climatic data of Benguerir.

The previous simulation of the overall system was performed considering no shading between the collectors. However, limitations in the available space may recommend shorter distances between collectors. Taking into account the dimensions of the vacuum-CPC collectors and the layout of the solar field, an extensive study about shading effects was developed.

The performance of the overall system is analyzed, taking into account the shading effects between collectors. Namely, a comparison of solar fractions and global electrical efficiencies of the system, with and without shading, is carried out. Five scenarios are presented: no shading; shading when the collector tilt is seasonally adjusted; and shading when the collector tilt is fixed in three positions during the year. When shading occurs, the reduction in incident solar radiation must be compensated by an increase in the boiler input energy. With

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that in mind, the biomass consumption for all scenarios was also calculated for different operating periods. In the next sections, detailed numerical simulations for specific climatic and operational conditions are presented.

2. Description of the system and numerical model considering shading

2.1 System description

A computer model of the overall system was developed by combining EES (Engineering Equation Solver) with TRNSYS software. EES was used for the power cycle calculations and TRNSYS for simulating the solar circuit and overall system. The system, including its main components, is schematically represented in Figure1 (Oliveira et al., 2014).

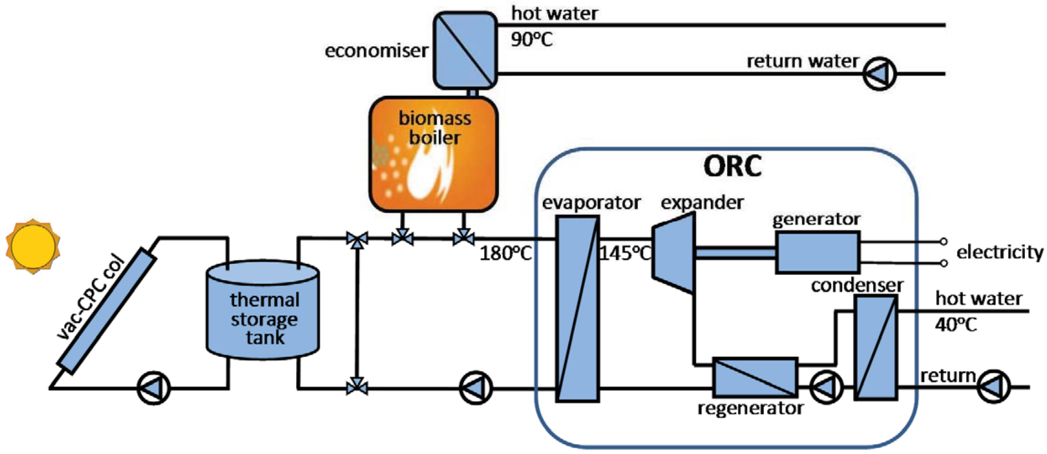

Fig. 1: System schematic representation.

The ORC/power cycle model consists of a set of algebraic equations representing the thermodynamic behavior of each ORC component. The ORC simulated by EES includes the following main components: evaporator, expander, generator, regenerator, condenser and pump. For an electrical output equal to 6 kW, a maximum temperature for the solar circuit of 180ºC is assumed. It is expected that the ORC operates under almost steady-state conditions, as the cycle driving temperature is kept approximately constant. However, the simulations in TRNSYS are transient, as they reflect changes in solar radiation and ambient temperature. The solar circuit simulated by TRNSYS includes the following main components: solar collector, boiler with economizer, thermal storage, pumps and control system. Different working fluids are used in the system: thermal oil for the solar sub-system, water for the condenser, and Solkatherm (SES36) fluid for the ORC.

The inputs of TRNSYS components and EES components are shown in Table 1.

Table 1: Definition of the inputs for each component

Programs	Components	Inputs
TRNSYS	Climatic data (Meteonorm)	Local: Benguerir (Morocco); Latitude = 32.13ºN, Longitude = 7.98ºW.
	Vacuum-CPC collectors (vac-CPC)	A_{coll} = 145.92 m^2; 32 modules (4 in series, 8 in parallel) Concentration factor (C) =2.573 Efficiency curve parameters: η_0=0.623; a_1=0.59 Wm^{-2}K^{-1}; a_2=0.004 Wm^{-2}K^{-2} Tested flow rate = 0.0274 kg s^{-1}m^{-2} Maximum total flow rate = 0.557 kg/s Collector tilt: seasonally adjusted at **51º** (from October to February), **29º** (March, April and September) and **8º** (from May to August), optimised according to period of the year and manufacture. Collector azimuth = 0º Fluid specific heat = 2620 J/kgºC (oil TERMOL 5HT) IAM data: file created through the numerical simulation of the novel CPC collector
	Thermal storage	Tank volume = 8000 l Thermal stratification modelled with 6 fully-mixed equal volume layers Tank losses: negligible Cold-side temperature (from Evaporator) = 140ºC Cold-side flowrate (from Evaporator) = 0.412 kg/s
	Boiler	Rated capacity = 60 kW Set point temperature = 180ºC Boiler efficiency = 0.9
	Pump	Maximum power = 0.6 kW
EES	Evaporator	Useful heat: 40 kW Outlet temperature = 145ºC Superheating = 5ºC
	Expander	Efficiency (η_{exp}): 0.75
	Generator	Efficiency = 0.95 Net electrical power = 6 kW
	Regenerator	ΔTmin = 10ºC Efficiency = 0.82
	Condenser	Condenser temperature = 45ºC

2.2 Climatic data

For solar resource assessment purposes METEONORM (Meteotest, 2015) was used to generate data of Global Horizontal Irradiation, GHI, solar azimuth and height, and ambient temperature (Ta), on an hourly basis for a typical year. The chosen location was Benguerir (Morocco), with a latitude = 32.13ºN and a longitude = 7.8ºW. For this city, the data from Meteonorm and local data were compared - see Fig. 2. In this case, the Meteonorm data were obtained with interpolation from nearby meteorological stations.

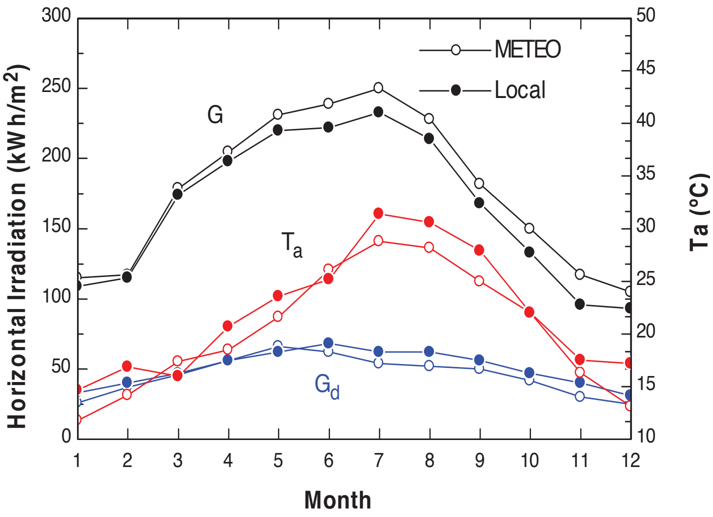

Fig. 2: Global (G) and diffuse (Gd) solar radiation on horizontal surface and ambient temperature (Ta) with Meteonorm data and local data for Benguerir.

The major differences between Meteonorm and local data concern horizontal global irradiation (G) and ambient temperature (Ta) for July, August and September (difference lower than 10% for these months).

2.2 Solar geometry analysis

A solar geometry analysis was carried out, considering the collector dimensions together with the location. Figure 3 shows the dimensions used to calculate the shading effect between the evacuated-CPC collectors, where L_{aper} is the collector aperture (L_{aper} = 0.437 m), d is the collector row separation (d = 0.7 m), tilt is the collector tilt ($tilt$ = 51°, for the most unfavourable situation) and h_{sun} is the solar altitude angle.

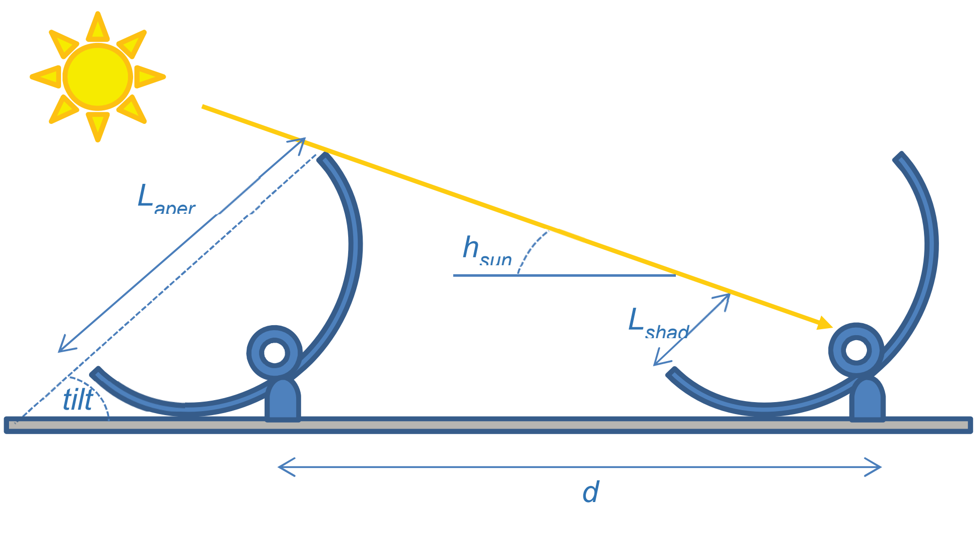

Fig. 3: Schematic view of the evacuated-CPC collectors with some parameters used for the solar geometry analysis.

Using the geometric relationship between a plane of any orientation and the incoming beam solar radiation for the specific latitude (Benguerir's latitude = 32.13ºN), it is possible to calculate the relations of the position of the sun relative to that plane. Considering the worst scenario for shading, when the solar altitude angles are lower (winter period) and the collector tilt is 51°, the shading effects were analysed, and the results will be shown in the next section.

3. Simulation results

Figure 4 shows the shaded length on the collector (L_{shad}) and the percentage of insolated length ($\%insolated$) for each solar altitude angle, defined as (see eq. 1):

$$\%insolated = 100 \cdot (L_{aper} - L_{shad})/L_{aper} \qquad \text{(eq.1)}$$

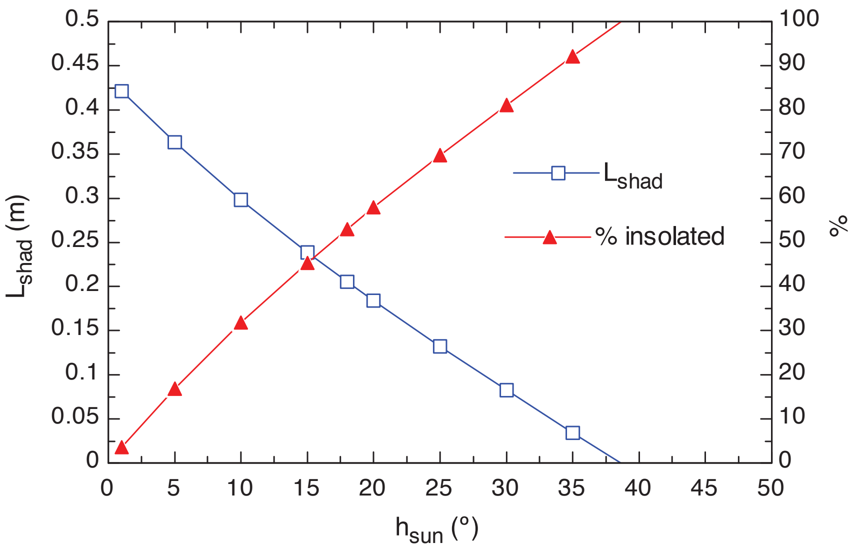

Fig. 4: Shaded length and insolated percentage on the CPC collector depending on solar altitude angle (h_{sun})

As can be seen, for the considered dimensions, the collector surface is completely insolated for a solar altitude angle above about 40º. To know in which months and hours shading occurs, it is necessary to combine the information with a solar chart (solar altitude angle and solar azimuth angle for different days and hours).

Figure 5 shows the solar chart for Benguerir, using an average day for each of the months, and results when the collector tilt is equal to 51º (from October to February).

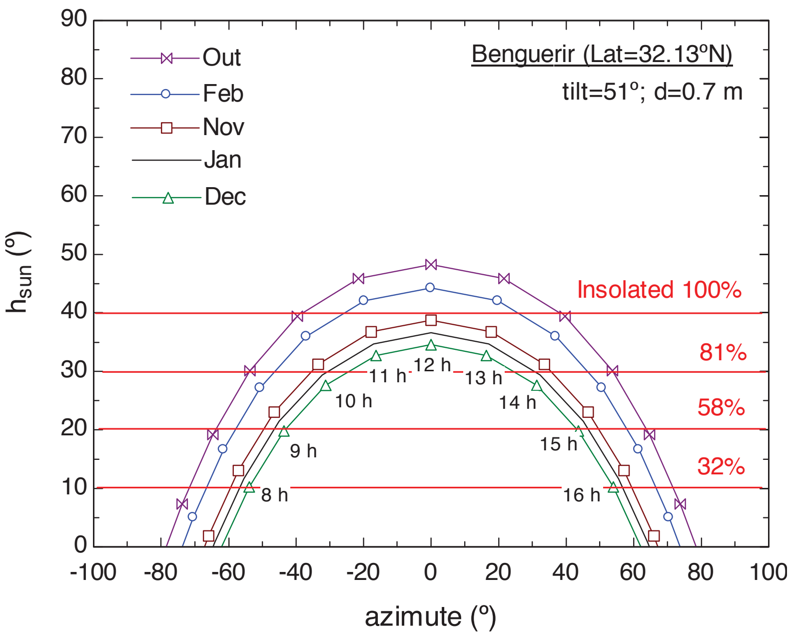

Fig. 5: Solar chart for Benguerir (months when the collector tilt is equal to 51º)

As can be seen, during the average day of November, December and January, part of the collectors behind the first row are always shaded.

Now, it is necessary to evaluate the performance of the system when the shading effect is considered. In the next section, the overall system performance is analysed.

3.1 Overall system performance

The monthly and annual performances, with and without shading, are shown in Table 2.

The table contains values of solar radiation incident on the collector surface (G_{coll}), useful heat gain on the solar collectors (Q_{usef_coll}), energy supplied by the boiler (Q_{aux}), and solar fraction (f), considering that no shading occurs and when the effect of shading is taken into account. The solar fraction can be defined as (see eq. 2):

$$f = Q_{usef\_coll} / \left(Q_{usef\_coll} + Q_{aux}\right) \quad \text{(eq. 2)}$$

Table 2: Monthly and annual performance results

Month (tilt)	G_{coll} (MWh)		Q_{usef_coll} (MWh)		Q_{aux} (MWh)		*F*	
	no shading	Shading	no shading	shading	no shading	shading	no shading	Shading
Jan (51º)	29.23	24.03	6.12	4.99	23.64	24.77	0.21	0.17
Feb (51º)	24.35	21.45	4.61	4.05	22.63	22.83	0.17	0.15
Mar (29º)	30.93	29.46	5.58	5.22	24.18	24.54	0.18	0.18
Apr (29º)	30.95	29.77	5.19	4.83	23.61	23.97	0.17	0.17
May (8º)	33.70	33.59	6.01	5.96	23.75	23.80	0.20	0.20
Jun (8º)	34.57	34.52	6.48	6.45	22.32	22.35	0.23	0.22
Jul (8º)	36.23	36.16	6.82	6.78	22.94	22.98	0.23	0.23
Aug (8º)	33.88	33.72	5.28	5.22	24.48	24.54	0.18	0.18
Sep (29º)	29.56	28.20	5.47	5.12	23.33	23.68	0.18	0.18
Oct (51º)	28.65	25.68	4.74	4.15	25.02	25.61	0.16	0.14
Nov (51º)	27.77	23.69	5.36	4.85	23.44	23.95	0.19	0.17
Dec (51º)	28.11	22.13	5.84	4.53	23.92	25.23	0.20	0.15
Annual	**367.91**	**342.40**	**67.48**	**62.15**	**282.92**	**288.25**	**0.19**	**0.18**

The annual thermal performance can be related to the annual net electricity generation of the power block. Assuming that the solar driven CHP plant is running non-stop throughout the year (helped by the boiler), the annual generated electricity value is 52.6 MWh, with an operating period of 24 h/day. The annual global electrical efficiency ($\eta_{electr,annual}$) is defined as the total electrical energy generated during one year (E_{elec}), divided by the sum of all annual energy inputs – boiler input energy (Q_{boiler}) plus incident solar radiation (G_{coll}), as can be seen in eq. 3:

$$\eta_{electr.annual} = E_{elec} / \left(Q_{boiler} + G_{coll}\right) \quad \text{(eq. 3)}$$

Figure 6 shows the annual solar fraction (f_{annual}) and annual global electrical efficiency for 5 scenarios: no shading, with shading when the collector tilt is seasonally adjusted (3 tilts), and when the collector tilt is fixed during the whole year at 51º, 29º and 8º.

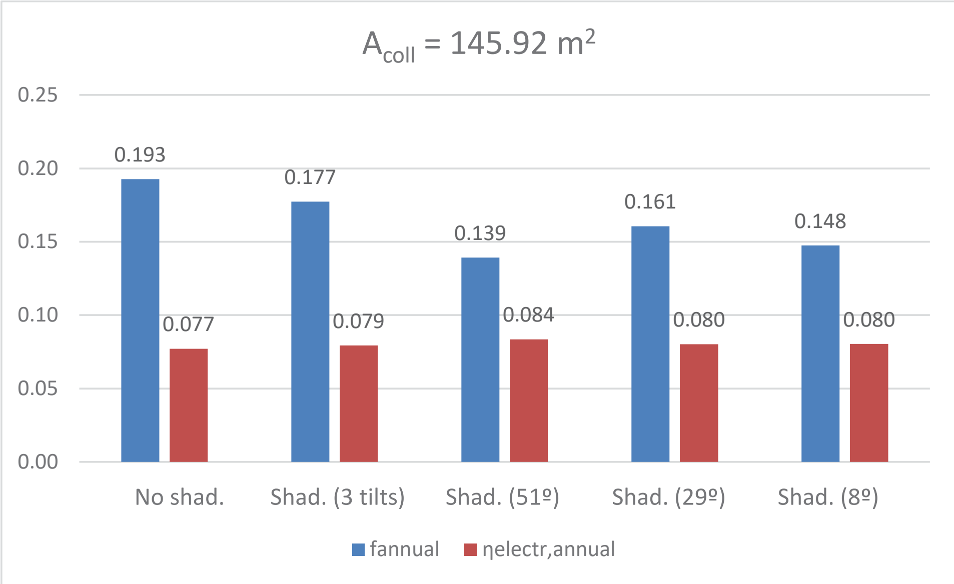

Fig. 6: Annual solar fraction and annual global electrical efficiency for the 5 scenarios.

Shading reduces the annual solar fraction from 0.193 to 0.177 (a relative reduction of 8%). When shading and solar fractions are analysed, the best scenario is when the collector tilt is seasonally adjusted (three times per year): the annual solar fraction with 3 tilts is equal to 0.177. If a single constant tilt of 29º is used, the resulting solar fraction is equal to 0.161, which means a relative reduction of 9%. This will be the best tilt for a constant inclination throughout the year.

A higher solar fraction does not imply a higher global electricity efficiency, since the reduction in incident solar radiation is compensated with an increase in the boiler input energy (with a higher efficiency). On the other hand, biomass consumption increases with the increase in boiler input energy. For that, the biomass consumption for all scenarios was also calculated. For 24 hours/day operation, the biomass consumption will be equal to 69.41 tons/year (3 tilts), 72.62 tons/year (tilt=51º), 70.82 tons/year (tilt=29º) and 71.92 tons/year (tilt=8º).

4. Conclusions

In the present paper, an exhaustive study concerning solar geometry and the effect of shading between collectors in the overall performance of a new biomass/solar micro-CHP system was presented. The performance of the overall system was analyzed, taking into account the shading effects between collectors and the location where the prototype will be installed and tested (Benguerir, Morocco). Five scenarios were considered: no shading, with shading when the collector tilt is seasonally adjusted (3 tilts), and when the collector tilt is fixed during the whole year at 51º, 29º and 8º.

Considering the worst scenario for shading, when the solar altitude angles are lower (winter period) and the collector tilt is 51º, the study shows that the collector surface is completely insolated for a solar altitude angle above about 40º. Then, during the average days of November, December and January, part of the collectors behind the first row are always shaded. To evaluate the performance of the system when shading is considered, annual solar fractions (f_{annual}) and annual electrical efficiencies ($\eta_{electr,annual}$) were assessed. The best performance corresponds to a collector tilt that is seasonally adjusted (three times per year): f_{annual} with 3 tilts is equal to 0.177 and $\eta_{electr,annual} = 0.08$. When shading occurs, the reduction in incident solar radiation must be compensated by an increase in boiler input energy, and so the $\eta_{electr,annual}$ remains practically constant for the different scenarios analysed. Biomass consumption increases with the increase in boiler input energy: for an operating period of 24 hours/day, biomass consumption will be equal to 69.41 tons/year (3 tilts), 72.62 tons/year (tilt=51º), 70.82 tons/year (tilt=29º) and 71.92 tons/year (tilt=8º). After the results, if a single constant tilt throughout the year is used, the best tilt is 29º.

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