Conference Proceedings

EuroSun 2014
Aix-les-Bains (France), 16 – 19 September 2014

Small scale solar-driven CHP system pre-design sensitiveness to solar field and ORC power block components efficiencies

Pedro Horta[1], **José M. Alvarez-Prieto**[1], Jaap Brouwer[2], **Ghennioui Abdellatif**[3], **Hicham Frej**[3], **Souad Lalami**[3], **Bennouna El Ghali**[3], **Carlos Saraiva**[4], **Armando Oliveira**[5], **João Soares**[5]

[1] University of Évora, BES Chair in Renewable Energies, Casa Cordovil, 2º Andar, Rua Dom Augusto Eduardo Nunes, 7, 7000-651 Évora (Portugal) (phorta@uevora.pt)

[2] TERMOCYCLE SP Z O.O., Warsaw (Poland)

[3] Institut de Recherche en Energies Solaires et Energies Nouvelles – IRESEN, Rabat (Morocco)

[4] MCG Solar, Manuel Conceição Graça Ltd, Carregago (Portugal)

[5] University of Porto, Dept. Mechanical Engineering, Porto (Portugal)

Abstract

Within the framework of REELCOOP project, a small scale (10 kWe) solar driven Combined Heat and Power system is being developed and constructed. Using a thermal storage and hybridized with biomass, the system core relies on solar collectors and on a ORC power block under development within the project. The present article addresses a sensitiveness analysis to the overall system design as a function of solar collector and power block components efficiencies. This analysis takes into account a tentative range for such efficiency values as well as design operation conditions on the chosen location for the final installation: Benguerir (Morocco).

Not disregarding further developments of the system model, accounting for variable efficiency conditions and enabling the study of different operation/control strategies, the pre-design results already point some relevant aspects to be accounted for at both component and system development levels, namelly the relation between thermal and optical performance of solar collectors, the impact of expander efficiency in overall power block and system performance.

Keywords: solar-driven ORC; small scale CHP.

1. Introduction (EuroSun_Heading1)

The REELCOOP project (*REELCOOP, 2013*) aims at an enhancement in research cooperation and knowledge creation on renewable electricity generation, involving Mediterranean partner countries (MPC), while at the same time developing and testing new renewable electricity generation systems. Addressing five different topics: photovoltaics (PV), concentrated solar power (CSP), solar thermal (ST), bioenergy and grid integration, the project includes the design and construction of three different electricity generation systems, representative of small and large scale systems: system 1: a 6 kWe BIPV system including air ventilation features; system 2: a 10 kWe solar-driven CHP system based on a Organic Rankine Cycle (ORC) power block; system 3: a 60 kW hybrid solar/bioenergy CSP prototype system. The present article addresses the pre-design of system 2.

© 2015. The Authors. Published by International Solar Energy Society
Selection and/or peer review under responsibility of EuroSun2014 Scientific Committee
doi:10.18086/eurosun.2014.12.02 Available at http://proceedings.ises.org

Having a wider use in waste energy recovery systems, ORC power blocks have also been used in the design of solar-driven CHP systems (*e.g. García-Rodríguez and Blanco-Gálvez, 2007*). Providing power and heat for different applications, such systems have the potential of operating as stand-alone units in isolated off-grid applications, as well as of using low or medium temperature solar collectors with lower operation and maintenance requirements. Furthermore, The decentralized feature of this power generation solution offers the opportunity to utilize the low grade heat of the cycle by the close-by end-user and further improve the efficiency and hence the economics of the system.

The small scale (10 kWe) solar driven CHP system under development and construction in the framework of the project, uses a thermal storage and is hybridized with biomass. Not new in its concept, the system core relies, though, on new developments for both the solar collectors and the ORC power block expander.

As means of assessing the impact of solar collector and power block expander efficiencies in the overall system design, a sensitiveness analysis to the impact of those parameters is presented.

2. CHP system layout and operation mode

The solar driven CHP system layout, illustrated in figure 1, prioritizes the solar field as heat generation system, connected to a thermal storage providing a thermal buffer between the solar field and the power block. The system is hybridized with a 60 kWth biomass boiler acting as secondary (backup) heat source, assuring a constant inlet temperature for the ORC power block, running permanently.

The power block is based on a regenerative Organic Rankine Cycle according to the scheme and T-s diagram presented in figure 1. The working fluid used in the power block is Solkatherm SES36 (*Solvay , 2014*).

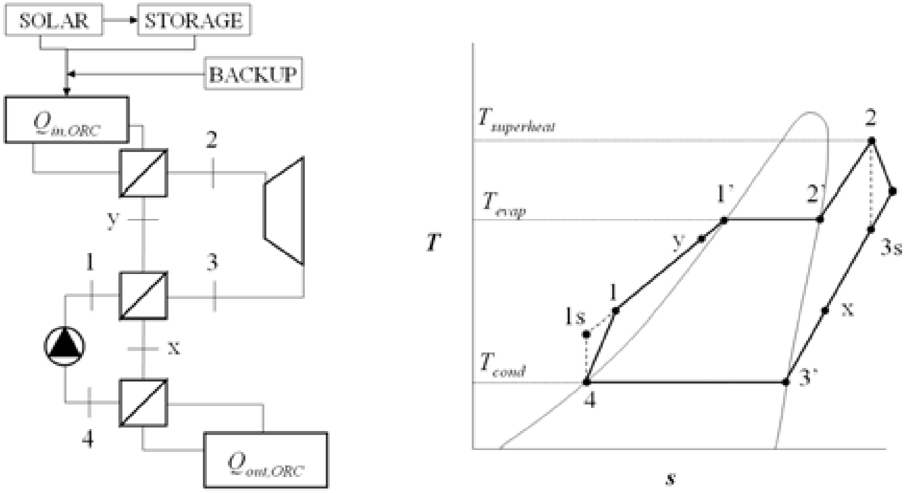


Fig.1 - Regenerative ORC scheme and T,s diagram representation of cycle points

The operative control of the power block is based on the establishment of saturated vapour conditions for a given heat source temperature (point 2' on the T-s diagram of in fig. 8). The control procedure presents the following protocol:

- 1. heat source temperature is acquired, T_{hot};
- 2. evaporation temperature(the cycle is implemented without superheating, expansion from 2') is set to

$T_{evap} = T_{hot} - \Delta T_{heat}$ (eq.1)

(temperature difference accounting for heat exchanger effectiveness and efficiency performances);

- 3. evaporation pressure for T_{evap} is acquired from the working fluid properties table;
- 4. electrical frequency of the pump electric motor is varied until pump outlet reaches $P_1 = P_2 = P_{evap}$.

Such control assures that the working fluid reaches the expander as saturated vapour, preventing the occurrence of liquid phase. The pressure (and working fluid mass flow) is, thus, dependent on the hot source temperature. This stands for a constant temperature/constant flow configuration when a fixed heat input temperature is assured or for a variable temperature/variable flow configuration when this is not the case (as in the case of a solar-only system).

3. System components efficiency range

The solar driven CHP system relies on the assembly of two different types of components:

- commercially available components, in what regards thermal storage, biomass boiler and heat exchangers (HX): ORC power block evaporator, condenser and regenerator - for whose fixed efficiency (thermal storage and boiler) or effectiveness (heat exchangers) are considered, given the constant temperature power block operation framework considered;
- components undergoing new developments within the project framework (solar collectors and ORC power block expander), for whose a range of efficiencies is herein defined.

Efficiency (or effectiveness) parameters for commercially available components are taken as follows:

- boiler efficiency (not used in the present analysis): 0.93;
- ideal thermal storage (thermally insulated, negligible heat losses);
- evaporator HX: effectiveness defined in terms of a heat exchange related temperature difference between hot and cold currents,

  $T_{heat} = 20.0°C$
- condenser HX: effectiveness defined in terms of a heat exchange related temperature difference between hot and cold currents,

  $T_{cool} = 20.0°C$
- regenerator HX:

  $\varepsilon = 0.85$

As for the components being developed within the project, solar collector and expander, efficiency parameters and ranges are related with their present state of development.

3.1. Solar field

The development of the solar collector relies on the use of evacuated tubes with a CPC concentrator. Departing from the technical specifications of tube transmissivity-absorptivity effects and area dependent thermal losses, a range of efficiency curve parameters is defined. Efficiency curve parameters estimations depend on the irrigation factor (linked to the development of the collector inner hydraulic circuit) and concentration factor, the parameters in stake in the collector design process.

At this stage three different concentration factors are considered: C in [2.5, 3.5, 4.5]. Thermal loss coefficients:

$$a_1(ET) = 1.0 \text{ W.m}^{-2}.\text{K}^{-1}$$

and

$$a_2(ET) = 0.01 \text{ W.m}^{-2}.\text{K}^{-2}$$

are considered to the evacuated tube. The absorber area dependence of both thermal loss coefficients is related with the concentration factor, a ratio of aperture and absorber areas, so that:

$$a_1(C) = a_1(ET) / C; \; a_2(C) = a_2(ET) / C \qquad \text{(eq.2)}$$

Optical efficiency values, η_0 were obtained for each concentrator under real material optical properties conditions: absorber absorptivity, $\alpha = 0.935$; glazing transmissivity, $\tau = 0.9$; reflector reflectivity, $\rho = 0.9$. On the other hand, angular acceptance conditions changing with (incidence angle θ and) concentration factor are considered by means of adequate transversal (K_T) and longitudinal (K_L) Incidence Angle Modifier (IAM) values for each of the considered collectors, obtained after ray-tracing simulations (Tonatiuh, 2013). Efficiency curve parameters and IAM values are presented for the three collectors in tables 1 and 2, respectively.

Table 1 – Estimated efficiency curve parameters for CPC with concentration factors C in [2.5, 3.5, 4.5]

C	η_O	a_1	a_2
2.5	0.68	0.400	0.0040
3.5	0.66	0.286	0.0029
4.5	0.65	0.222	0.0022

Table 2 – Transversal and Longitudinal IAM values for CPC with concentration factors C in [2.5, 3.5, 4.5] (within the transversal acceptance range)

C	θ	0º	5º	10º	15º	20º	25º	30.
2.5	K_T	1.000	1.012	1.046	1.105	1.119	0.012	0.000
	K_L	1.000	0.901	0.810	0.755	0.712	0.671	0.630
3.5	K_T	1.000	1.044	1.111	1.145	0.000	0.000	0.000
	K_L	1.000	0.921	0.851	0.791	0.757	0.724	0.660
4.5	K_T	1.000	1.048	1.134	0.001	0.000	0.000	0.000
	K_L	1.000	0.919	0.859	0.820	0.749	0.701	0.602

3.2. ORC power block expander

The development of the power block relies on the use of an innovative rotary lobe expander. The 10 kWe power block is based on a known design benefiting from enhancements not yet fully developed. Based on the base design efficiency estimations and on the estimated improvements, expander isentropic efficiencies are tested within the range η_T in [0.6, 0.65, 0.70, 0.75, 0.80].

4. System pre-design simulations

The system pre-design analysis is based on the results obtained for solar fraction and electricity yearly yield. Considering the system layout, operation is set after the following pre-design conditions:

- constant power block operation (24 h/day);
- biomass hybridization fulfills the heat difference between the thermal storage output and the heat input required by the power block, constrained by boiler maximum power (60 kWth);
- the solar field heats a fixed thermal storage volume (predefined to a 2 m^3 volume) with a limited maximum temperature of 250ºC (related to thermal oil safety/degradation temperatures);
- (in view of the different concentration factors) solar collectors tilt is adjusted seasonally so that: in each period, collector tilt is centered in the range of solar height values (at solar noon); solar height (at solar noon) amplitude in the period fits within the (design) acceptance angle of the collector;
- direct flow (without intermediate heat exchanger) of the heat carrying fluid (thermal oil “BP Transcal N”) between the solar field, thermal storage and boiler;
- maximum power block heat input temperature,

  $T_{heat,in} = 180ºC$;
- evaporation temperature,

  $T_{evap} = T_{heat,in} - \Delta T_{heat}$; (eq.3)
- condensation temperature,

  $T_{cond} = T_{amb} + \Delta T_{cool}$; (eq. 4)
- minimum temperature difference between evaporation and condensation (in view of limited heat source power and variable ambient temperature),

  $\Delta T_{ORC} = 40ºC$;
- optimal thermodynamic cycle conditions for the operating temperatures and working fluid.

Local climatic conditions are defined after TMY data for the system location: Benguerir (Morocco). Average monthly values of the relevant climatic parameters are presented in Table 3.

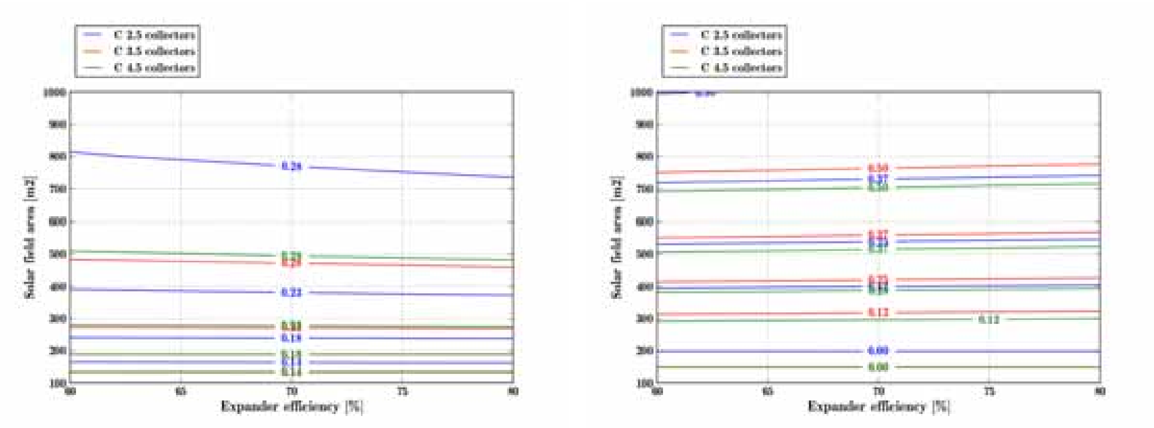
Table 3 – Average monthly values of global (*G*) and diffuse (*G_d*) solar radiation on the horizontal plane (kWh.m^{-2}.day^{-1}) and ambient temperature (ºC) for Benguerir, Morocco

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
G	3.5	4.1	5.6	6.6	7.1	7.4	7.5	6.9	5.6	4.3	3.2	3.0
G_d	1.1	1.3	1.5	1.8	2.0	2.2	2.0	2.0	1.8	1.5	1.3	1.0
T_{amb}	14.7	16.9	16.0	20.7	23.6	25.2	31.4	30.6	27.9	22.0	17.5	17.2

5. Simulation results

Yearly operation simulations were performed for different system compositions: solar field composed by C2.5, C3.5 or C4.5 solar collectors; power block expander efficiencies of η_T in [0.6, 0.65, 0.70, 0.75, 0.80]. To this end, a pre-existing in-house integrated model (*Horta et al., 2008*) was adapted to the present system control and operation conditions. Enabling this pre-design assessment, such model is to be further developed and validated within the project.

The variation of solar fraction values (defined as the ratio between solar heat and total heat provided to the power block) and rejected solar heat fraction (defined as the ratio of solar heat rejected for insufficient storage capacity and total heat provided by the solar field) with solar field area and expander efficiency, for the different solar collectors, is presented in fig. 2.



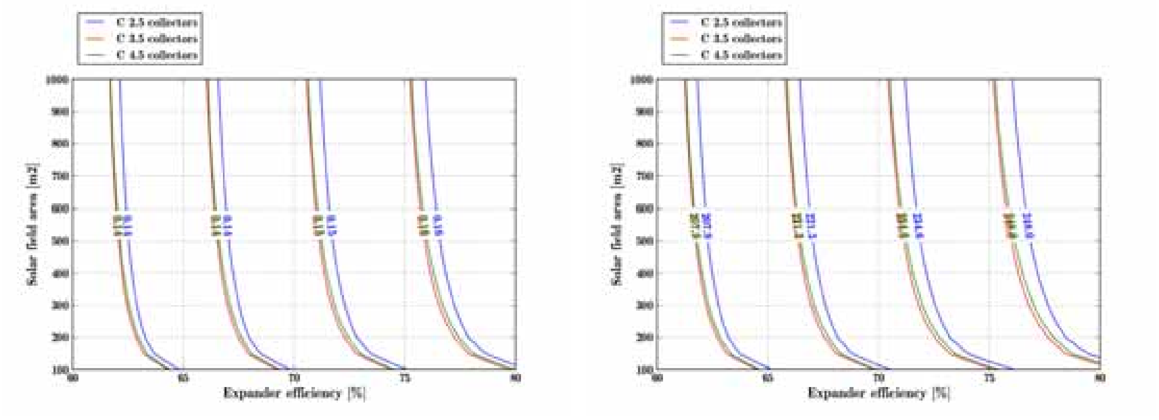
(a)

(b)

Fig.2 – Variation of (a) solar and (b) rejected solar heat fractions values with total solar field aperture area and expander efficiency, for solar collector C2.5, C3.5 and C3.5

The results for solar and rejected solar heat fractions denote that, on the present system design, the thermal storage capacity acts as a bottleneck for solar fraction values. Over 300 m^2 aperture areas significant rejected solar heat fractions are observed. Under those aperture area values, the results show a relative decoupling of solar fraction with expander efficiency. Regarding solar collector results, a clear performance improvement is observed when changing from C2.5 collectors to C3.5 or C4.5 collectors. Between these two, it is important to note a slightly better performance of C3.5 over C4.5, compensating a lower thermal performance with a better optical performance, in view of a wider acceptance.

Results for electrical power yield and ORC cycle efficiency (defined as the ratio of useful electrical power, including consumption at the compressor, and total ORC heat input) are presented in figure 3.



(a) (b)

Fig.3 – Variation of (a) ORC net efficiency and (b) daily yield [kWhe/day] values with total solar field aperture area and expander efficiency, for solar collector C2.5, C3.5 and C3.5

Considering ORC net efficiency results it is possible to conclude for an efficiency variation in line with expander efficiency variation: roughly, the graphic shows a 15% ORC net efficiency increase with a 15% expander efficiency. Yield results are in line with ORC net efficiency results, with a 20% yield increase observed for a 15% expander efficiency increase.

Regarding the impact of solar collector performance on ORC net efficiency, it is possible to observe higher ORC efficiency values for collectors C3.5 and C4.5, which is explained, under the boiler power limitation condition, with average higher evaporation temperatures at the ORC. This effect is also patent in the variation of results with increasing solar field aperture areas, up to the threshold of 300 m2, where solar rejected heat becomes predominant (after thermal storage incapacity).

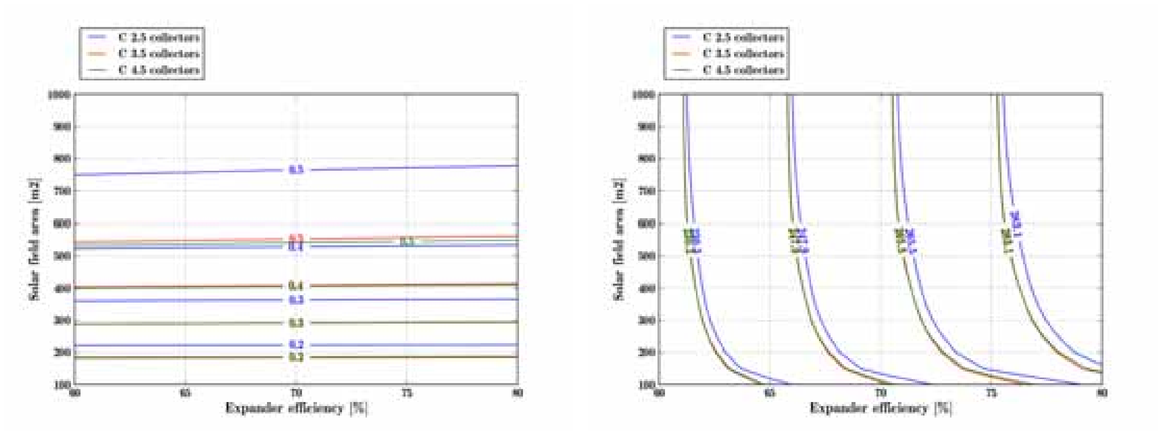
6. Conclusions

Within the framework of REELCOOP project, a small scale (10 kWe) solar driven Combined Heat and Power system, hybridized with a biomass boiler, is being developed and constructed. Considering that the project is currently in the system components development stage, the present article addressed a sensitiveness analysis to the overall system design as a function of solar collector and power block components efficiencies. To this end, system operation simulations within a tentative range for such efficiency values were performed.

Not disregarding further developments of the system model, accounting for variable efficiency conditions and enabling the study of different operation/control strategies, the pre-design results obtained have shown:

- the results show a relative decoupling of solar fraction with expander efficiency;
- an increase in solar concentration is not an assurance of a better solar field performance. An optimized collector design must account for the optical compensation of lower thermal performances, as is reflected in C3.5 and C4.5 results;
- expander efficiency plays an important role in overall system efficiency and power yield results, presenting a variation proportional to that parameter;
- higher solar field performances enable (under a limited boiler power condition) higher average ORC evaporation temperatures, leading to increased ORC efficiencies and yield results;
- thermal storage capacity acts, in the present design, as a bottleneck for increased solar fractions.

As for the later conclusion, the results obtained for solar fraction and power yield with a 10 m^3 thermal storage volume, presented in figure 4, are conclusive and show a 60% increase in solar fraction values and a 10% to 15% yield increase. Also differences on the crossed influences of solar field and expander efficiencies may be observed (e.g. in solar fraction results) with an increased storage volume, which denotes the interconnection of components design in the overall system results.



(a) (b)

Fig.4 – Variation of (a) solar fraction and (b) ORC daily yield (kWhe/day) values with total solar field aperture area and expander efficiency, for solar collector C2.5, C3.5 and C3.5

At the present state of system components development, these results already point some relevant aspects to be accounted for at both component and system development levels, namelly the relation between thermal and optical performance of solar collectors, the impact of expander efficiency in overall power block and system performance.

Furthermore, design of the whole system is to be reassessed after the conclusions regarding the impact of thermal storage capacity on overall system results. Such design optimization has to rely, though, on an economical assessment possible at a later stage, when solar field, power block, boiler and biomass costs are available.

The following developments on the system assessment will further include an analysis of system operation modes and their impact on system results.

Acknowledgements

The presented work was developed within the framework of project "REELCOOP - Research Cooperation in Renewable Energy Technologies for Electricity Generation", co-funded by the European Commission (FP7 ENERGY.2013.2.9.1, Grant agreement no: 608466).

References

REELCOOP - Research Cooperation in Renewable Energy Technologies for Electricity Generation, 2013. FP7 ENERGY.2013.2.9.1, Grant agreement no: 608466.

García-Rodríguez, L., Blanco-Gálvez, J., 2007. Solar-heated Rankine cycles for water and electricity production: POWERSOL project. Desalination 212, 311–318.

Horta P., Mendes J. and Delgado-Torres, A., 2008. Preliminary assessment of a small scale shaft power generation system based on a solar thermal driven Organic Rankine Cycle. Proceedings of ISES/SHC EUROSUN 2008 - 1st International Conference on Solar Heating, Lisbon, Portugal. October 2008.

Solvay Solkatherm SES36, 2014.
(http://www.solvaychemicals.com/EN/products/Fluor/SOLKANE_Specialties/SolkathermSES36.aspx)

Tonatiuh release 2.0.1, 2013. (https://code.google.com/p/tonatiuh/)