Evaluation of the performance of hybrid CSP/ biomass power plants

João Soares[1]*, Armando C. Oliveira[1], Simon Dieckmann[2], Dirk Krüger[2]
and Francesco Orioli[3]
[1]CIENER-INEGI, University of Porto, Rua Dr Roberto Frias, 4200-465 Porto, Portugal;
[2]DLR - Institute of Solar Research, Linder Höhe, D-51147 Köln, Germany; [3]Soltigua, Via Roma, 54 47035 Gambettola (FC), Italy

Abstract

The value of renewable energy systems is undeniable since they rely on a free source that will not run out. However, they depend on meteorological conditions, leading to uncertainty on the instantaneous energy supply. An interesting concept consists on the strategic combination. In this article, two 1-MW$_{el}$ concentrated solar power/biomass hybrid power plants are presented and evaluated. One is intended for power generation only, while the other delivers combined heat and power. Technical and economic performances were evaluated through numerical simulation and calculation of the levelized cost of electricity.

Keywords: concentrated solar power; biomass; renewable hybridization; power generation

*Corresponding author:
joaosoares@fe.up.pt

Received 26 March 2018; revised 25 July 2018; editorial decision 19 August 2018; accepted 4 September 2018

1 INTRODUCTION

The fundamental benefit of using renewable energy systems is undeniable since they rely on a free source that will not run out. Nevertheless, they strongly depend on meteorological conditions (solar, wind, etc.), leading to uncertainty on the instantaneous energy supply and consequently to grid connection issues.

Although it is easy to accommodate a small share of unstable renewable generation, larger shares bring new challenges to the electrical sector, contributing to instability and unreliability. Whilst a feasible solution for electrical energy storage is under research, concentrated solar power (CSP) can be a reliable solution due to the easiness to dispatch energy, which is mostly associated to the integration with thermal energy storage (TES) tanks. However, the use of TES implies a larger solar field (SF) and storage tanks and thus additional costs [1]. Bioenergy is the only renewable source that is continuously available on the production side. Nevertheless, the availability and cost of biomass feedstocks hinder large-scale deployment of bioenergy technologies [2].

An interesting alternative concept is renewable hybridization [3]. It consists of the strategic combination of different renewable sources in the power generation portfolio by taking advantage of each technology. Hybridization of concentrating solar energy with biomass denotes a powerful way of assuring system stability and reliability [4]. The main advantage is dispatchability through the extension of the operating range. Furthermore, electrical grid stabilization is promoted due to the hybrid system flexibility, allowing to accommodate fluctuations on the demand side [5].

The interest on CSP/biomass hybrid power plants significantly increased in the last years and different combinations of CSP and biomass technologies have been assessed [3–10]. At commercial level, the first hybrid CSP/biomass power plant (Borges Termosolar) started to operate in December 2012 [11]. Also, distinct concepts have been and are being evaluated in the scope of research projects, e.g. [12–14]. One interesting hybrid concept was assessed in the framework of the REELCOOP project, co-funded by the EU [13]. A 60-kW$_{el}$ small-scale prototype was installed and tested in Tunis. The prototype relies on a combination of concentrating solar energy and biomass sources to drive a Rankine cycle power block (PB). Direct steam generation (DSG) is achieved within the SF, under the recirculation concept. Despite DSG advantages [15], dispatchability has been hindered by latent heat storage technical challenges. In the REELCOOP prototype, a breakthrough alternative concept was demonstrated that consists in using as backup to the SF heat

doi:10.1093/ijlct/cty046

generation, a biogas steam boiler running on food waste (FW), enhancing both system dispatchability and global system efficiency.

In this paper, the technical and economic performance of two 1 MW_{el} hybrid CSP/biomass renewable electricity generation systems are evaluated. Both systems were designed as a scale-up and enhancement of the REELCOOP prototype.

The two case studies are similar and only differ on the purpose. One of them exclusively aims power generation, while the other also delivers useful heat (combined heat and power, CHP). The use of CSP/biomass hybrid power plants for CHP and combined cooling heating and power has been addressed in [16–20]. However, in this paper CHP is achieved through the novel combination of a parabolic trough SF with DSG and FW anaerobic digestion (AD). System technical performances were assessed using a freeware software, Greenius [21]. Annual simulations were carried out, and simulation results were presented and analysed, such as SF annual generated heat and efficiency; boiler efficiency; biogas consumption; PB and system efficiency. The economic performance was evaluated through the calculation of the levelized electricity cost.

2 HYBRID CSP/BIOMASS CASE STUDIES

In this section, the CSP/biomass hybrid case studies are presented, as well as the simulation model and assumptions.

2.1 *The REELCOOP prototype*

The REELCOOP hybrid power plant has a nominal electrical output of 60 kW_{el} and relies on a regenerative ORC as generation system, developed by Zuccato Energia. The SF relies on parabolic trough collector technology and is constituted by three parallel loops of four PTM_x/hp-36 collectors developed by Soltigua, with a net collecting surface of 984 m^2. The SF was designed for DSG with the recirculation concept, i.e. subcooled water is partially evaporated in the solar collectors. Auxiliary energy is provided by a biogas steam boiler [22]. The prototype is installed in Tunis, and a preliminary simulation assessment showed that for a capacity factor of 100% and low solar share (17%), the system annual average efficiency is about 10% [10].

The economic assessment of the prototype is hindered by the system small-scale. Moreover, it would not illustrate the real value of the REELCOOP concept. Therefore, in this paper, the hybrid concept is assessed as a scale-up and enhancement of the REELCOOP prototype, close to a real-life application.

2.2 *Design considerations*

From the experience of the REELCOOP project, four main variables were well defined for the hybrid power plant design: PB, scale, operating conditions and usability of heat.

One of the main advantages of generating steam within the SF is the possibility to use it directly on the PB, i.e. eliminating the heat exchanger between the SF and the PB [23]. Thus, the PB should rely either on a conventional Rankine cycle or a steam engine.

Up to a scale of 100 kW_{el}, the Rankine cycle market is scarce, and steam turbine isentropic efficiencies are significantly low [24]. Accordingly, in order to have a PB with an acceptable efficiency and a reasonable levelized cost of electricity, it was necessary to scale-up the prototype. It is well known that CSP benefits from economies of scale. Centralized generation is usually accomplished with larger capacities, in the MW_{el} power range.

Various steam engines and turbine models were analysed and compared, within the range of 100–2000 kW_{el}. In order to keep up the balance between PB efficiency and system capital expense, a power output of 1 MW_{el} was defined. It is noteworthy that at this scale steam turbines are mostly used for waste heat recovery, and isentropic efficiencies continue to be significantly lower than those of conventional steam power plants. This issue is not crucial when the turbines are driven by heat surplus; however, heat from solar and biomass is costly. On the other hand, the technology is proven and operation reliable.

Steam turbine operation conditions (i.e. pressure and temperature) significantly influence the PB efficiency. Whilst it is possible to enhance PB efficiency by generating steam within the SF and use it in a turbine over 100 bar, it would represent numerous challenges. At a 1 MW_{el} scale, most of the commercial turbines operate under 45 bar, as over this threshold, costs significantly increase.

On the SF side, it is necessary to account for the pressure drop within the collector absorber tubes and pipes, which implies even higher pressures at the SF inlet. Furthermore, superheated steam is essential to assure a low wetness at the last turbine stage outlet. However, higher operating temperatures within the SF imply higher thermal losses. The PB steam inlet conditions were defined as 40 bar and 350°C.

As aforementioned, steam turbines at this scale are still characterized by low isentropic efficiency, which results in a significant amount of wasted heat. To improve the economic balance of the plant, the use of the waste heat is addressed, i.e. CHP. Consequently, it was decided to assess two case studies, one where the hybrid power plant is used solely for power generation and another one with CHP.

2.3 *Power block*

Both turbine/generator sets are based on the SST-110 model from the Siemens manufacturer. This specific model is a dual-casing turbine on one gearbox, with the possibility of being used as backpressure or condensing units, with or without extraction. Other relevant characteristics are quick-start without preheating and commercial use in cogeneration plants.

The PBs were modelled using a commercial software—EBSILON® Professional—considering basic project rules. A 60% design isentropic efficiency was defined for the steam turbines. Case 1 (C1) results in a Rankine cycle efficiency of about 22%, sustained by a steam mass flow rate of 1.77 kg/s (see Figure 1).

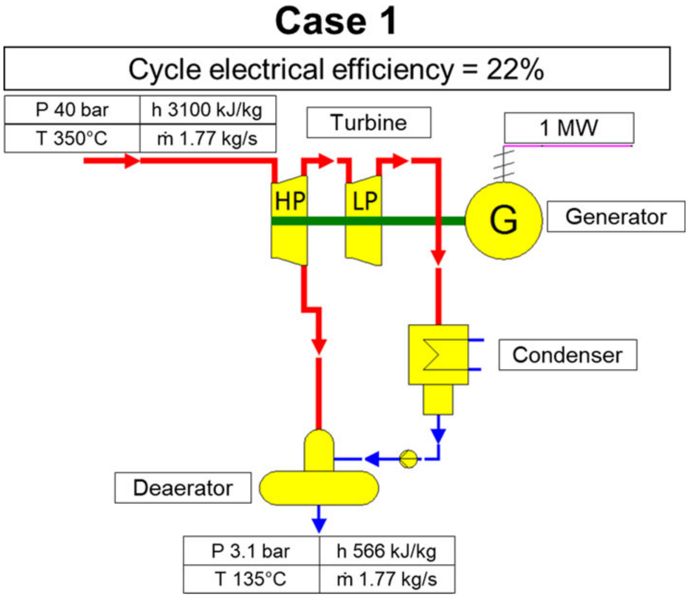

Figure 1. *Case 1 PB.*

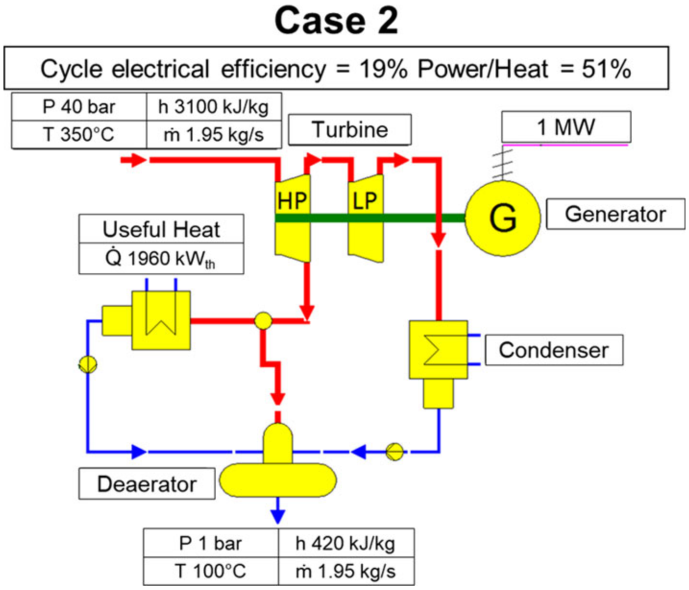

Figure 2. *Case 2 PB.*

For Case 2 (C2), two hypotheses were assessed, i.e. backpressure and condensing units, with a middle extraction. Whilst backpressure results in larger CHP efficiencies, it decreases electrical conversion efficiency. As a consequence, a higher steam flow rate is required, which infers a larger SF and boiler, and a consequent increase in the system capital expense. On the other hand, the use of a condensing turbine with intermediate extraction permits an adequate balance on the power-to-heat ratio, accomplished with a minor decrease on the electrical conversion efficiency. Case 2 PB (see Figure 2) has an electrical conversion efficiency of 19% driven by a steam mass flow rate of 1.95 kg/s. The extraction pressure was set to 1 bar (i.e. 100°C), allowing the use of steam for conventional domestic hot water and also to drive a single-stage absorption chiller. The nominal power-to-heat ratio is about 51%.

Both C1 and C2 key specifications are presented in Table 1.

2.4 *Solar field*

The SF was dimensioned and optimized using a free software developed by the German Aerospace Center: Greenius. In contrast to the original REELCOOP prototype, with a parabolic trough collector by Soltigua, a generic parabolic trough collector with a larger aperture width of 4.6 m and a vacuum receiver was considered, in order to reach outlet temperatures of 350°C with high efficiencies. The optical efficiency of the collector is estimated at 77%.

As in the REELCOOP prototype, the recirculation concept was adopted over the once-through one, to assure both operation stability and controllability under solar radiation transients. It is noteworthy that the operation of a CSP plant at this scale should be automatic, to reduce human resource needs and thus costs. Within this concept, water is preheated and partially evaporated in the evaporator (EVAP) section. Subsequently, at the steam drum, the water content is separated and recirculated, whilst the steam content is superheated in the superheating (SH) section and subsequently used to drive the steam turbine.

Table 1. *PB key specifications.*

	Case 1	Case 2
PB nominal power [kW_{el}]	1000	1000
PB nominal electrical efficiency [%]	22	19
PB nominal heat output [kW_{th}]	0	1960
Nominal power-to-heat ratio [%]	0	51

Case 1 SF is constituted by four loops of four collectors in the EVAP section, and one loop of three collectors in the SH section (see Figure 3), with a total effective solar aperture area of about 10 000 m^2. The recirculation rate was set to 3. At design conditions, Case 1 SF can provide a thermal output of 5761 kW_{th}, i.e. a solar multiple of about 1.3.

On the other hand, to achieve 1 MW_{el} Case 2 requires a larger SF, achieved through an extra loop in the EVAP section and one additional collector in the SH section, increasing the effective solar aperture area to about 12 700 m^2. The nominal thermal output is 7276 kW_{th} (design conditions). A summary of the SF specifications and outputs under design conditions are presented in Table 2.

2.5 *Hybridization*

A significant advantage of CSP plants is the ability to generate power during peak demand (e.g. late afternoon) using TES tanks. Whilst DSG presents several advantages over other CSP fluid technologies, storing energy is a challenging task. Steam

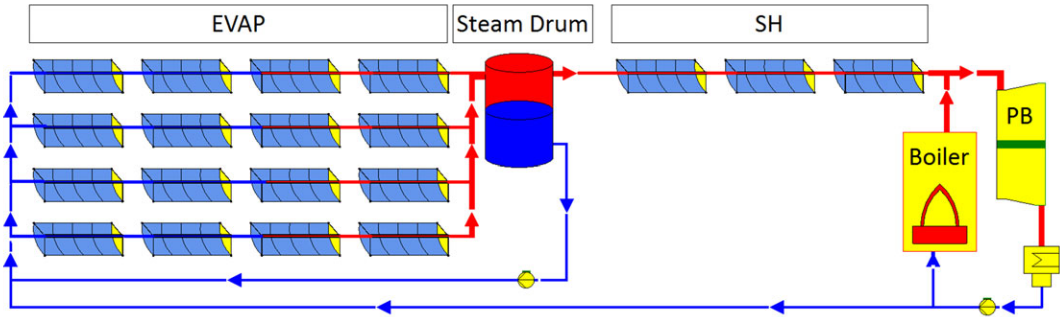

Figure 3. *Case 1 system layout.*

Table 2. *SF key specifications.*

	Case 1	Case 2
Collector type	Parabolic trough, vacuum receiver	Parabolic trough, vacuum receiver
Collector effective area [m^2]	529	529
Reference DNI [W/m^2]	800	800
Evaporator N° of loops	4	5
Evaporator N° of collectors per loop	4	4
Evaporator aperture [m^2]	8464	10 580
SH N° of loops	1	1
SH N° of collectors per loop	3	4
SH aperture [m^2]	1587	2116
SF nominal thermal output [kW_{th}]	5761	7276
Solar multiple	1.3	1.4
SF Inlet temperature [°C]	135	100
SF Outlet temperature [°C]	350	350

Table 3. *Annual key results.*

	Case 1	Case 2
DNI [$kWh/(m^2.y)$]	1922	
Load curve	6:00–22:00 1 MW_{el}	
Annual heat generated SF [MWh_{th}]	7750	9817
Specific thermal field output [kWh_{th}/m^2]	771	773
Mean annual SF efficiency [%]	40.1	40.2
Annual heat generated—boiler [MWh_{th}]	19 840	23 100
Mean annual boiler efficiency [%]	85	85
Annual biogas consumption [km^3]	3.45	4.02
Average biogas consumption [m^3/day]	9500	11 000
Solar share [%]	27.5	28.8
SF dumped heat [MWh_{th}]	232	444
Annual useful heat from SF and boiler [MWh_{th}]	27 400	32 500
Annual power generated [MWh_{el}]	5840	5840
Mean annual PB efficiency [%]	21.3	18.0
Mean annual system electrical efficiency [%]	13.7	11.3
Annual heat output [MWh_{th}]	-	11 600
Mean annual power-to-heat ratio [%]	-	50.3
Mean annual system efficiency [%]	13.7	33.8

latent heat storage requires the use of phase change materials, also addressed under the REELCOOP project framework [25].

In the REELCOOP prototype, another solution was tested that consists of using a steam boiler driven by biogas, to backup SF thermal production and to extend power generation without solar radiation. Therefore, in this assessment, a steam boiler driven by biogas with a nominal efficiency of 85% was considered. The boiler is placed in parallel with the SF (see Figure 3), to either backup SF operation (e.g. winter times) or to work individually (e.g. at night). As that, it is always possible to either drive the PB at nominal power or to accommodate demand.

As in REELCOOP, biogas is produced from AD of FW. The main advantage of FW is that it is a surplus and therefore inexpensive. On the other hand, the system design is complex due to the potential variety of the biomass. An annual average biogas LHV 24.34 MJ/m^3 was defined, and the boiler nominal outputs were 5 and 6 MW_{th}, for C1 and C2, respectively.

2.6 *Simulations*

Annual simulations were carried out in Greenius. The software is a powerful simulation tool for calculation and analysis of renewable power projects. Additionally, it permits the use of water/steam as a heat transfer fluid and thus is suitable for DSG simulations, with calculations being carried out in a few seconds. Likewise, it is possible to simulate hybrid power plants [26].

First, simulations were carried out for the PB under full- and part-load conditions, using EBSILON. Afterwards, the simulation results were used as an input for Greenius by means of a parametric table.

The project site was set to Tunis location (36.83°N and 10.23°E), and TMY weather data obtained from Meteonorm software were used. The annual sum of direct normal irradiation (DNI) is 1922 kWh/m^2. A simple load curve and operation strategy were defined, i.e. full-load capacity from 6:00 to 22:00. Whilst this is not accurate, it is demonstrative of a possible load demand for a 1 MW_{el} scale power plant, with consumption starting in the early morning and ending in the late afternoon.

3 RESULTS

The annual key simulation results for the two case studies are presented in Table 3. In both cases, nominal load operation was assured for the predefined 5840 h. The solar share varies from

27.5% to 28.8%, for C1 and C2, respectively. The solar share is a consequence of the predefined load curve and the absence of TES. The low solar energy share results from the predefined 16 h of full-load operation strategy, and the reduced solar multiple necessary to cut heat dumping rate during summer periods, as storage is absent. The dumping rate for C1 is about 3% and slightly higher for C2 (4.5%). As C2 is designed for CHP, this heat could be useful, but, nevertheless, this hypothesis was not addressed in this study.

In C1, the annual heat produced at the SF is about 7750 $\mathrm{MWh_{th}}$, which results in a specific thermal field output of 771 $\mathrm{kWh_{th}/m^2}$. The larger SF in C2 increases heat production by about 27% (9817 $\mathrm{MWh_{th}}$). The average annual SF efficiency is about 40% for both cases, with a slightly better result for C2 due to the lower SF average temperature.

One advantage of CSP/biomass hybridization is the possibility to operate at nominal load even in low radiation periods. Consequently, the average annual PB efficiencies (21.3% for C1 and 18.0% for C2) are close to design values.

The mean annual system's electrical efficiencies are 13.2 and 11.3%, for C1 and C2, respectively. On the other hand, the CHP efficiency for C2 is 33.8% with an annual average power-to-heat ratio of 50%.

The biogas daily consumption was assessed to estimate the AD system size. This result was required for the energy cost assessment (Section 4). C2 daily average biogas consumption is about 11 000 $\mathrm{m^3}$, with an annual consumption of 4 $\mathrm{km^3}$. C1 biogas consumption is about 14% lower, with a daily average of 9500 $\mathrm{m^3}$ (see Table 3).

Typical daily operation for summer and for winter are shown in Figure 4 for C1. In summer, the turbine is driven solely by biomass at early morning and night, i.e. when solar radiation is not enough to run the SF. On the other hand, from 9:00 to 17:00, power generation is sustained exclusively by the SF. Therefore, in a typical summer day, there could be only two boiler start-ups. In a typical winter day, the boiler operation extends to 16 h. Nevertheless, from 11:00 to 17:00 the boiler is driven at partial load.

C2 operation in typical summer and winter days is similar to C1 (see Figure 5). The main difference is related to heat production, also continuous. A lower heat demand is expected to occur during summer, and therefore the heat can be used to drive an absorption chiller for cooling. Considering a chiller's coefficient of performance of 0.7, it would be possible to produce about 22 400 KWh of colling per day.

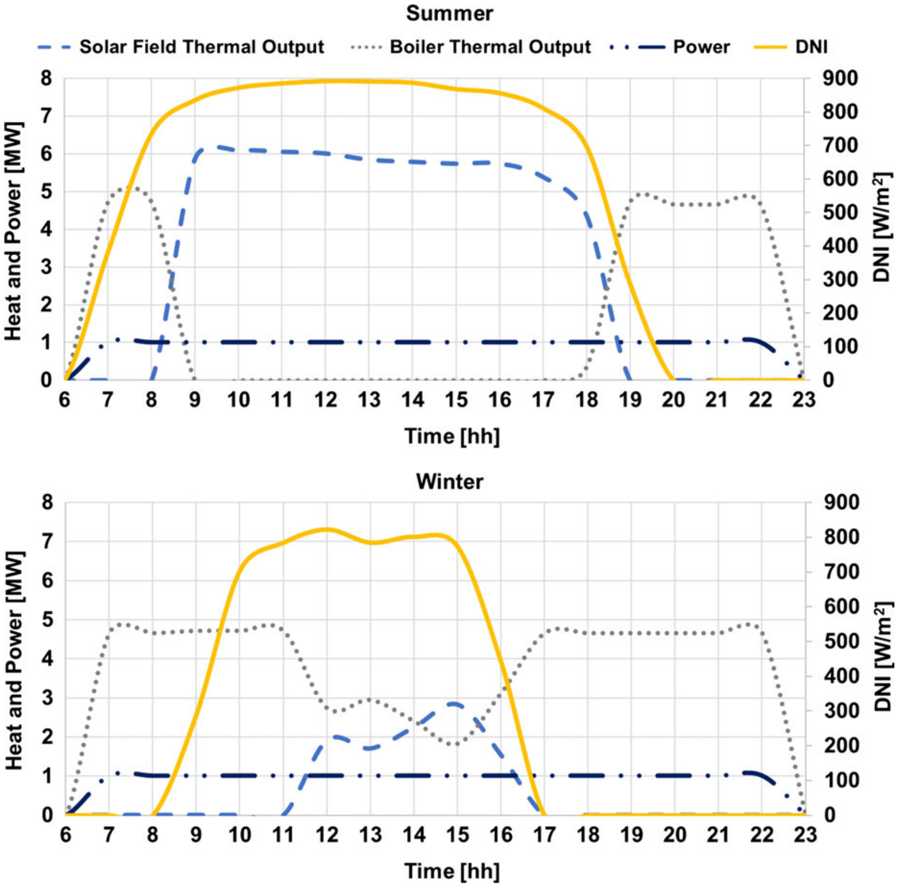

Figure 4. *Case 1 typical daily operation for summer (top) and winter (bottom).*

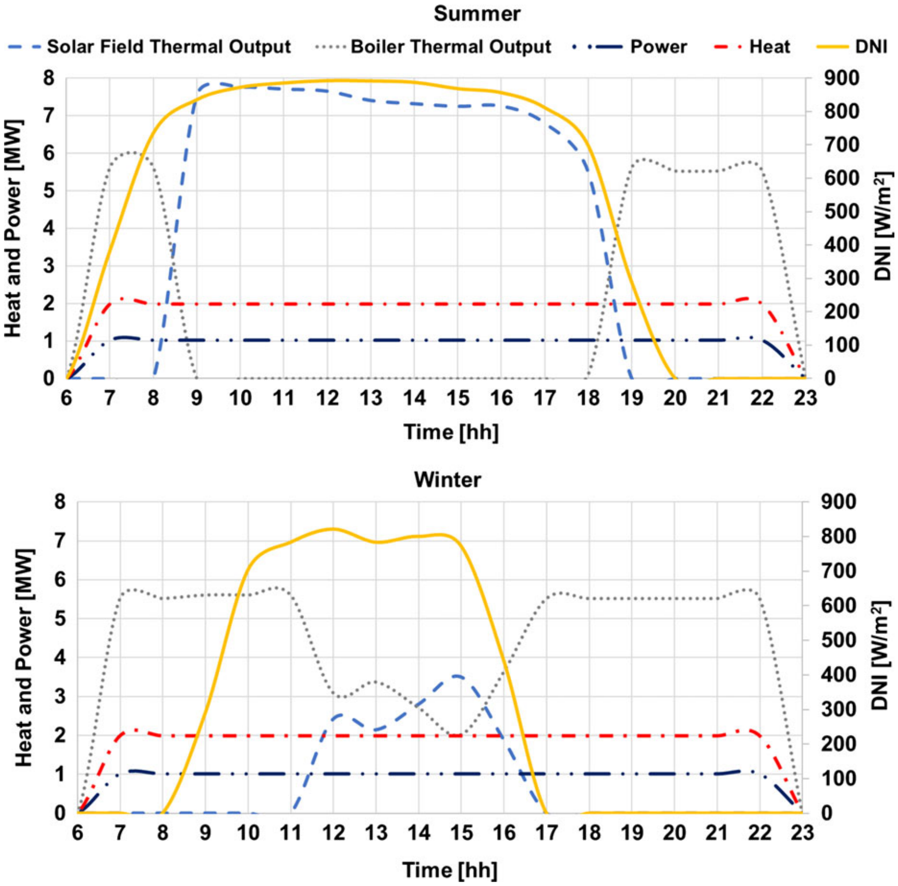

Figure 5. *Case 2 typical daily operation for summer (top) and winter (bottom).*

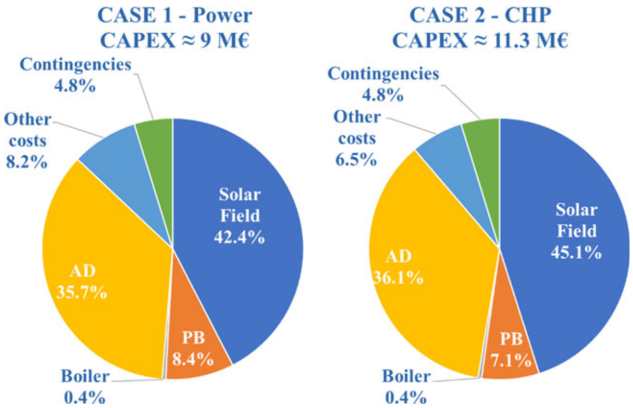

Figure 6. *CAPEX structure for C1 and C2.*

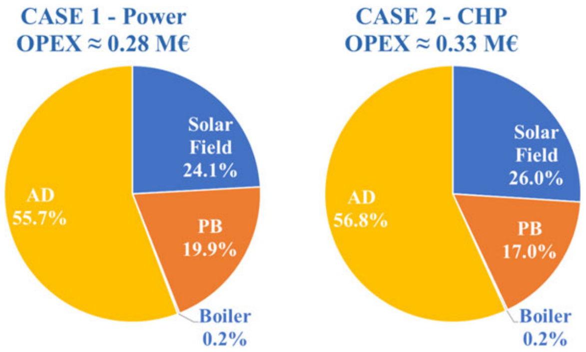

Figure 7. *OPEX structure for C1 and C2.*

4 ENERGY COSTS

For assessing the system capital and operation costs, specific system costs were defined based on the authors' experience, manufacturer information and energy cost reports. For the SF, a value of 400 €/m^2 was defined, which is higher than for conventional CSP plants, due to the small scale of this study. Turbine and boiler specific costs were defined as 800 €/kW$_{el}$ and 8 €/kW$_{th}$, respectively. For the AD system, specific costs were defined according to the average values from the IRENA report on biomass costs for power generation [27]. The capital costs' data include the prime mover (e.g. combustion engine), converter system (e.g. anaerobic digesters), fuel handling, civil works, balance of the plant equipment, owner costs including consultancy. The prime mover and electrical costs were subtracted, as they were already accounted in the PB costs, i.e. biogas will be used to drive a steam boiler, instead of a combustion engine. Also, a capacity factor of 70% was considered. Other costs include project development, insurance during construction, supervision and start-up. Project contingencies were estimated considering 5% of the aforementioned costs.

Cost structures for C1 and C2 are presented in Figure 6. SF and AD system represent about 80% of the capital expenditure (CAPEX) for both cases, of which 55% are related to the SF.

Operational expenditure (OPEX), includes operation and maintenance, replacements and equipment insurance. As expected, AD operation has the highest share (see Figure 7), over 55%. FW pretreatment and on-site handling and processing increase process complexity and thus costs. No costs were considered for FW residues: first, even in countries where subsidies exist (e.g. tipping fees), the values applied for FW are quite low; second, Tunisia faces thoughtful issues concerning waste management, mostly subsided by the state [28]. The hybrid power plant is an option to overcome these issues, and consequently, it was assumed that FW costs would be marginal.

Table 4 includes a summary of equipment specific costs, as well as the associated CAPEX.

One simple and appropriate way to summarize and compare the overall attractiveness of both case studies is the levelized cost of electricity (LCoE),

$$\mathrm{LCoE} = \frac{\mathrm{CAPEX} \times \mathrm{CRF} + \mathrm{OPEX}}{E} \tag{1}$$

where E is the annual electrical generation and CRF the capital recovery factor,

$$\mathrm{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{2}$$

where i is the discount/depreciation rate (6%) and n the plant lifetime (25 years).

Table 4. *Equipment specific costs and CAPEX.*

	Case 1	Case 2
Spec. SF cost [€/m^2]	400	400
Spec. PB cost [€/kW$_{el}$]	800	800
Spec. boiler cost [€/kW$_{th}$]	8	8
Spec. AD cost [€/kW$_{th}$]	678	678
CAPEX SF [€]	4 020 400	5 078 400
CAPEX PB [€]	800 000	800 000
CAPEX Boiler [€]	39 200	44 000
CAPEX AD [€]	3 388 000	4 066 000
Total CAPEX (incl. contingencies) [€]	9 477 115	11 259 217
Total annual OPEX [€]	283 339	331 978

In Case 2, in order to account for the CHP value, heat revenues were subtracted from generation costs [29],

$$\mathrm{LCoE_{CHP}} = \frac{\mathrm{CAPEX} \times \mathrm{CRF} + \mathrm{OPEX}}{E} - \frac{H}{E} * H_{\mathrm{price}} \tag{3}$$

where H is the annual heat produced and H_{price} the price of heat. As the energy market does not include the price for heat, the average cost of natural gas (about 41 €/MWh) in Tunisia [30], divided by a typical boiler efficiency (90%), was assumed for H_{price}.

C1 results in an LCoE of 175.4 €/MWh$_{el}$ (see Table 5), which is favourable considering the relatively small scale of the power plant. This outcome is a consequence of hybrid configurations. Whilst the AD system significantly increases the CAPEX, it improves the capacity factor. Regardless of the PB's low nominal efficiency, annual operation is carried out near design condition, eliminating even lower efficiencies from partial load operation. Moreover, both SF and AD systems share the same PB, diluting the cost.

For C2, despite the higher CAPEX and lower PB efficiency, the LCOE$_{\mathrm{CHP}}$ is 126.3 €/MWh$_{el}$. This value assumes that it is possible to sell all the generated heat at the price of natural gas, which is not evident. The authors are aware that in order to sell the heat it is necessary to be near a consumption centre, and it depends on a match between the heat and electricity demand However, the small scale of the case study places it in the decentralized generation market. Additionally, using FW as a fuel implies that the plant is placed nearby consumers. Therefore, it is reasonable to assume a higher demand for both electricity and heat than the production/supply.

It is noteworthy that Tunisia massively subsidizes natural gas suppliers [30]. If those subsidies were accounted for, the heat revenues would be twice as high, and the LCOE$_{\mathrm{CHP}}$ would be even lower. Additionally, the level of temperature of the heat allows its use for cooling purposes and thus improves the LCOE$_{\mathrm{CHP}}$.

Notwithstanding the attractiveness of the LCOE results, at least when compared with EU average electricity costs, the Tunisian average electricity production cost is about 95 €/MWh$_{el}$ [30]. Furthermore, the average electricity retail price is about 48.7€/MWh$_{el}$, due to substantial direct and indirect subsidies. On the other hand, power consumption is considerably increasing every year (5% rate), and currently Tunisia is a net importer of energy. Thus, an increase in the energy costs is expected in the coming years.

Table 5. *Levelized costs of energy.*

	Case 1	Case 2
Lifetime [years]—annuities	25	25
Discount rate [%]	6.0	6.0
CRF [%]	7.82	7.82
LCOE [€/MWh$_{el}$]	175.4	126.3

5 CONCLUSIONS

In this manuscript, two CSP/biomass hybrid power plant case studies, with 1 MW_{el}, were presented and evaluated. Case studies diverge on the purpose, with one plant for power generation (C1) and the other for CHP (C2). Both systems were modelled as a scale-up and enhancement of a prototype, installed in Tunis under the REELCOOP project.

Simulations were carried out under the assumption of 16 h of continuous load demand per day (6:00 to 22:00). The C1 PB higher efficiency results in an annual average system efficiency of 13.7%, with a solar share of 27%. Despite C2 lower average electrical conversion efficiency (11.3%), the utilization rate is 33.8%, with an average power-to-heat ratio of 50%.

Concerning costs, the SF and AD costs are about 80% of the total CAPEX. C2 CAPEX (11.3 M€) is about 19% higher than C1 (9.5 M€). On the other hand, AD share is above 55% in the OPEX cost structure, justified by the system operation complexity.

C1 LCOE is 175.4 €/MWh_{el}, which is very attractive considering the small scale of the power plant. This outcome is a consequence of hybrid operation, enhancing PB and system efficiency and also reducing costs by equipment sharing (i.e. PB). Results show even better values for C2, with n $LCOE_{CHP}$ of 126.3 €/MWh_{el}.

On the other hand, the Tunisian energy market is heavily subsided, and average electricity production costs and retail prices are about 95 and 48.7 €/MWh_{el}, respectively. With energy consumption increasing at about 5% every year, and as a net energy importer, it is foreseen that costs will increase in the coming years. Also, no subsidies were used for the case studies, which would significantly improve the economic assessment results.

ACKNOWLEDGEMENTS

The REELCOOP project received funding from the European Union Seventh Framework Programme (FP7/2007-2013), under grant agreement no. 608 466 (www.reelcoop.com). All other partners involved in the development of Prototype 3 are greatly acknowledged: CIEMAT (Spain), ENIT (Tunisia), Zuccato Energia (Italy), AES (Tunisia).

REFERENCES

[1] De Luca F, Ferraro V, Marinelli V. On the performance of CSP oil-cooled plants, with and without heat storage in tanks of molten salts. *Energy* 2015; **83**:230–9.

[2] Thomas J, Ashok S, Jose TL. A pricing model for biomass-based electricity. *Energy Source B Econ Plan Policy* 2014;**10**:103–10.

[3] Peterseim JH, White S, Tadros A, *et al.* Concentrating solar power hybrid plants—enabling cost effective synergies. *Renew Energy* 2014;**67**:178–85.

[4] Colmenar-Santos A, Bonilla-Gómez J-L, Borge-Diez D, *et al.* Hybridization of concentrated solar power plants with biogas production systems as an alternative to premiums: The case of Spain. *Renew Sust Energy Rev* 2015;**47**:186–97.

[5] Peterseim JH, Hellwig U, Tadros A, *et al.* Hybridisation optimization of concentrating solar thermal and biomass power generation facilities. *Sol Energy* 2014;**99**:203–14.

[6] Coelho B, Schwarzbözl P, Oliveira A, *et al.* Biomass and central receiver system (CRS) hybridization: volumetric air CRS and integration of a biomass waste direct burning boiler on steam cycle. *Sol Energy* 2012;**86**:2912–22.

[7] Corona B, San Miguel G. Environmental analysis of a concentrated solar power (CSP) plant hybridised with different fossil and renewable fuels. *Fuel* 2015;**145**:63–9.

[8] Peterseim JH, Tadros A, Hellwig U, *et al.* Increasing the efficiency of parabolic trough plants using thermal oil through external superheating with biomass. *Energy Conv Manage* 2014;**77**:784–93.

[9] Peterseim JH, White S, Tadros A, *et al.* Concentrated solar power hybrid plants, which technologies are best suited for hybridisation? *Renew Energy* 2013;**57**:520–32.

[10] Soares J, Oliveira AC. Numerical simulation of a hybrid concentrated solar power/biomass mini power plant. *Appl Therm Eng* 2017;**111**:1378–86.

[11] Cot A, Ametller A, Vall-Lovera J, *et al* (eds). *Termosolar Borges: A thermosolar Hybrid Plant with Biomass. Third International Symposium on Energy from Biomass and Waste*. CISA, Environmental Sanitary Engineering Centre, Italy, 2010.

[12] Servert JF, Cerrajero E, López D, *et al.* Base case analysis of a HYSOL power plant. *Energy Procedia* 2015;**69**:1152–9.

[13] Oliveira A, Coelho B. REELCOOP project developing renewable energy technologies for electricity generation. 12th International Conference on Sustainable Energy Technologies; Hong Kong 2013.

[14] BIOSOL—solar CSP gasification biomass boiler hybrid system 2018. https://www.dbfz.de/index.php?id=1091&L=0.

[15] Eck M, Zarza E, Eickhoff M, *et al.* Applied research concerning the direct steam generation in parabolic troughs. *Sol Energy* 2003;**74**:341–51.

[16] Borello D, Corsini A, Rispoli F, *et al.* A co-powered biomass and concentrated solar power Rankine cycle concept for small size combined heat and power generation. *Energies* 2013;**6**:1478–96.

[17] Khalid F, Dincer I, Rosen MA. Thermoeconomic analysis of a solar-biomass integrated multigeneration system for a community. *Appl Therm Eng* 2017;**120**:645–53.

[18] Nixon JD, Dey PK, Davies PA. The feasibility of hybrid solar-biomass power plants in India. *Energy* 2012;**46**:541–54.

[19] Pantaleo AM, Camporeale SM, Miliozzi A, *et al.* Novel hybrid CSP-biomass CHP for flexible generation: thermo-economic analysis and profitability assessment. *Appl Energy* 2017;**204**:994–1006.

[20] Wang J, Yang Y. Energy, exergy and environmental analysis of a hybrid combined cooling heating and power system utilizing biomass and solar energy. *Energy Convers Manage* 2016;**124**:566–77.

[21] German Aerospace Center (DLR). Greenius—the green energy system analysis tool, http://freegreenius.dlr.de/.

[22] Krüger D, Kenissi A, Dieckmann S, *et al.* Pre-design of a mini CSP plant. *Energy Procedia* 2015;**69**:1613–22.

[23] Giglio A, Lanzini A, Leone P, *et al.* Direct steam generation in parabolic-trough collectors: a review about the technology and a thermo-economic analysis of a hybrid system. *Renew Sust Energy Rev* 2017;**74**:453–73.

[24] Dong L, Liu H, Riffat S. Development of small-scale and micro-scale biomass-fuelled CHP systems—a literature review. *Appl Therm Eng* 2009;**29**:2119–26.

[25] Bayón R, Rojas E. Feasibility study of D-mannitol as phase change material for thermal storage. *AIMS Energy* 2017;**5**:404–24.

[26] Dieckmann S, Dersch J. Simulation of hybrid solar power plants. *AIP Conf Proc* 2017;**1850**:160005.

[27] International Renewable Energy Agency (IRENA). Biomass for Power Generation. 2012.

[28] Bouaoun M. Report on the Solid Waste Management in TUNISIA. 2014.

[29] Alberci S, Boeve S, Breevoort Pv, *et al.* Subsidies and costs of EU energy, Annex 4–5. 2014.

[30] Rafik Missaoui A. *Presentation: Energy Situation in Tunisia*. Alcor, 2014.