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Title: Evaluation of the performance of hybrid CSP/Biomass Power Plants

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Abstract: The fundamental benefit of using renewable energy systems is undeniable since they rely on a 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.

An interesting alternative concept is renewable hybridisation. It consists in the strategic combination of different renewable sources in the power generation portfolio by taking advantage of each technology. Hybridisation of concentrating solar energy with biomass denotes a powerful way of assuring system stability and reliability. The main advantage is dispatchability through the extension of the operating range.

In this article, two 1 MW_{el} hybrid power plants are presented and assessed. In case 1 the purpose is only power generation and in case 2 the use of Combined Heat and Power. Both systems were designed as a scale up and enhancement of a prototype, installed in Tunis under the REELCOOP project. Technical and economic performance were evaluated trough numerical simulation and levelised cost of electricity calculation.

Simulations were carried out under the assumption of 16 hours of continuous load demand per day (6 to 22 h). Case 1, with a power block higher efficiency, leads to an annual average system efficiency of about 13.7%. The use of heat in case 2, increases system efficiency to 33.8%. Capital expenditure varies from 9.5 M€ (case 1) to 11.3 M€ (case 2).

Despite the lower electrical conversion efficiency of case 2, and its higher capital expense, the levelised cost of electricity is lower (126 €/MWh_{el}) than in case 1(173.1 €/MWh_{el}). Both results are attractive considering the small scale of the power plant. This outcome is a consequence of hybrid operation, enhancing power block and system efficiency, and also reducing cost by equipment sharing (i.e. power block).

Keywords: CSP, Biomass, Hybridisation, Generation

1. INTRODUCTION

The fundamental benefit of using renewable energy systems is undeniable since they rely on a 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 within 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.

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

This concept is being assessed in the framework of the REELCOOP project, co-funded by the EU (Oliveira, 2013). A 60 kW_{el} prototype was installed in Tunis and is currently being tested. 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 REELCOOP prototype.

Case studies are similar, and only differ in the purpose. One of the case studies aims exclusively power generation, and in the other the use of heat is assessed, i.e. Combined Heat and Power (CHP). Both systems rely on a combination of concentrating solar energy (CSP) and biomass sources to drive a Rankine cycle power block (PB). Direct Steam Generation (DSG) is achieved within the solar field (SF). As backup to the SF heat generation, a biogas steam boiler running on food waste is used, enhancing both system dispatchability and global system efficiency.

System technical performance was assessed using a freeware software, Greenius. Annual simulations were carried out and simulation results are presented and analysed, such as: SF annual generated heat and efficiency, boiler efficiency and biogas consumption, PB and system efficiency. Economic performance was evaluated through calculation of the levelised electricity cost.

2. HYBRYD 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 mini power plant has a nominal electrical output of 60 kW, 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 3 parallel loops of 4 PTM_x/hp-36 collectors developed by Soltigua, with a net collecting surface of 984 m^2. DSG is achieved within the SF. Auxiliary energy is provided by a biogas steam boiler (Krüger, 2015). The prototype is installed in Tunis, and a preliminary simulation assessment shows that for a capacity factor of 100% and low solar share (17), system annual average efficiency is about 10% (Soares, 2017).

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.

2.2. Design considerations

From the experience of the REELCOOP project, four main variables were well-defined for the hybrid power plant design: power block, scale, operation conditions and the 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. Thus, the PB should rely either on a conventional Rankine cycle or on a steam engine.

Up to a scale of 100 kW, the Rankine cycle market is scarce, and steam turbine isentropic efficiencies are significantly low. Accordingly, in order to have a PB with an acceptable efficiency, and a reasonable levelised cost of electricity, it was necessary to scale up the prototype. It is well known, that CSP benefits from economies of scale. Centralised generation is usually accomplished with larger capacities, in the MW power range.

Various steam engines and turbine models were analysed and compared, within the range of 100 kW_{el} to 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 the ones used in conventional steam power plants. This issue is not important 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 collectors´ 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. Though, higher operation temperatures within the SF imply higher thermal losses. PB steam inlet conditions were defined for 40 bar and 350°C.

As aforementioned, steam turbines at this scale are still characterised 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. Combined Heat and Power (CHP). Consequently, it was decided to assess two case studies, one where the hybrid power plant is used solely for power generation and another with CHP.

2.3. Power block

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

The power blocks 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 about 1.77 kg/s (see figure 1).

For case 2 (C2), two hypotheses were assessed, i.e. backpressure or 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.

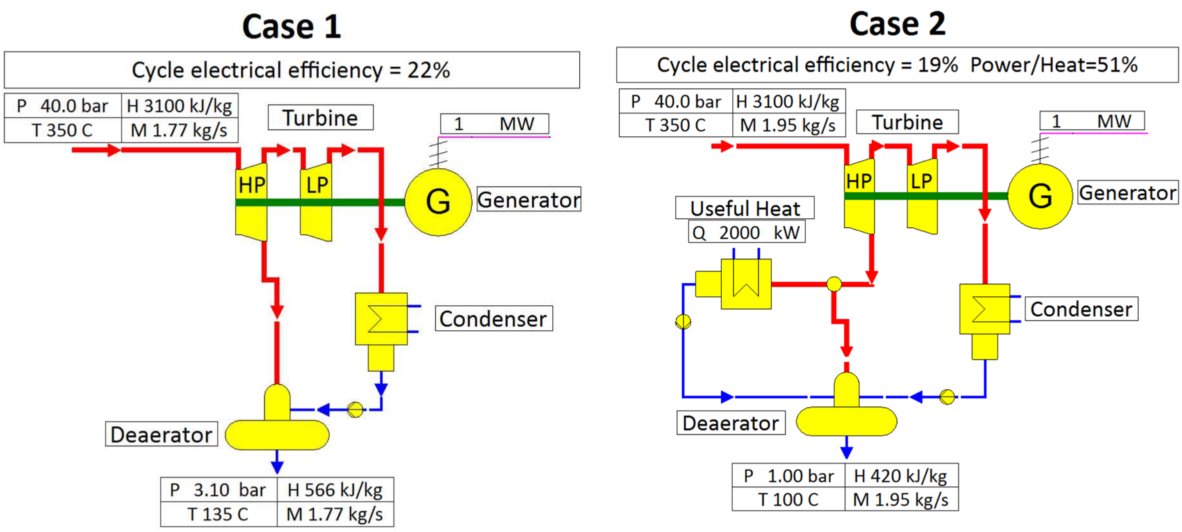

Figure 1 – Case 1 and 2 power blocks.

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. C2 (see figure 1) PB has an electrical conversion efficiency of 19 % driven by a steam mass flow rate of about 1.95 kg/s. Extraction pressure was set up to 1 bar (i.e. 100ºC) 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.

Table 1 – Power block key specifications.

	Case 1	Case 2
PB Nominal Power [kW_{el}]	1000	1000
PB Nominal Electrical Efficiency [%]	22.32%	19.15%
PB Nominal Heat Output [kW_{th}]	0	1960
Nominal Power to Heat ratio [%]	0	51%

2.4. Solar Field

The SF was dimensioned and optimised using a free software: Greenius. In contrast to the original REELCOOP prototype with a parabolic trough collector by Soltigua, a generic parabolic trough collector with larger aperture width of 4.6 m and a vacuum receiver, 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.

The Case 1 SF is constituted by 4 loops of 4 collectors in the evaporator (EVAP) section, and one loop of 3 collectors in the superheating (SH) section (see figure 2), with a total effective mirror area of about 10000 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.

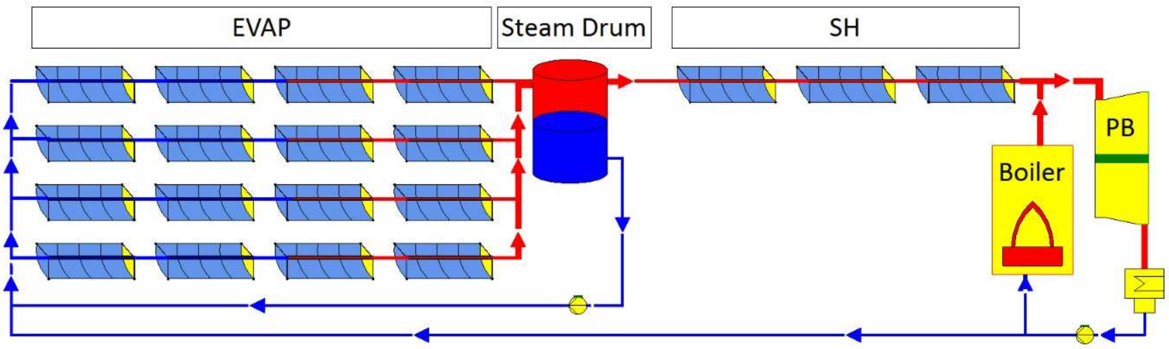

Figure 2 – Case 1 system layout.

On the other hand, to achieve 1MW_{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 mirror area to about 12700 m^2. Nominal thermal output is 7276 kW_{th} at design conditions. A summary of the SF specifications and outputs at design conditions are presented in table 2.

Table 2 – Case 1 and 2 solar field specifications.

	Case1	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 Nº of loops	4	5
Evaporator Nº of collectors per loop	4	4
Evaporator Aperture [m^2]	8464	10580
SH Nº of loops	1	1
SH Nº 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

2.5. Hybridisation

A major 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 latent heat storage requires the use of Phase Change Materials (PCM), also addressed under the REELCOOP project framework (Bayón, 2017).

In the REELCOOP prototype another solution is being 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 2), 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 anaerobic digestion (AD) of food waste (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 output is 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 heat transfer fluid, and therefore is suitable for DSG simulations with calculations being carried out in a few seconds. Likewise, it is possible to simulate hybrid power plants (Dieckmann, 2016).

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

The project site was set to Tunis location (36.83ºN and 10.23ºE) 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 was defined, i.e. full load capacity from 6 to 22 h. Whilst this is not accurate, it is demonstrative of a possible load demand for a 1MW_{el} scale power plant, with consumption starting in the early morning and ending in 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 predefined 5840 hours. The solar share varies from 27.5% to 28.8%, for C1 and C2 respectively. 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.

C1 annual heat produced at the SF is about 7750 MWh_{th}, which results in a specific thermal field output of 771 kWh_{th}/m^2. The larger SF in C2 increases heat production by about 27% (9817 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 hybridisation is the possibility to operate at nominal load even in low radiation periods. Consequently, average annual PB efficiencies (21.3% for C1 and 18.0% for C2) are close to design values. Mean annual system 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%.

Biogas daily consumption was assessed to estimate the anaerobic digestion system size. This result was required for the energy cost assessment (section 4). C2 daily average biogas consumption is about 11000 m^3, with an annual consumption of 4 km^3. C1 biogas consumption is about 14% lower, with a daily average of 9500 m^3 (see table 3).

Table 3 – Annual key results

	Case 1	Case 2
DNI [kWh/(m^2.y)]	1922	1922
Load Curve	6h-22h 1MW$_{el}$	6h-22h 1MW$_{el}$
Annual Heat Generated S.F. [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$_{th}$]	19840	23100
Mean Annual Boiler Efficiency [%]	85%	85%
Annual Biogas Consumption [km^3]	3.45	4.02
Average Biogas Consumption [m^3/day]	9500	11000
Solar Share [%]	27.5%	28.8%
SF Dumped Heat [MWh$_{th}$]	232	444
Annual Useful Heat from SF and Boiler [MWh$_{th}$]	27400	32500
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$_{th}$]	-	11600
Mean Annual Power to Heat ratio [%]	-	50.3%
Mean Annual System Efficiency [%]	13.7%	33.8%

Typical day operation for summer and winter are shown in figure 3 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 h to 17 h, power generation is sustained exclusively by the SF. Therefore, in a typical summer day, boiler start-ups can be only 2. In a typical winter day, the boiler operation extends to 16 hours. Nevertheless, from 11 h to 17 h the boiler is driven at partial load.

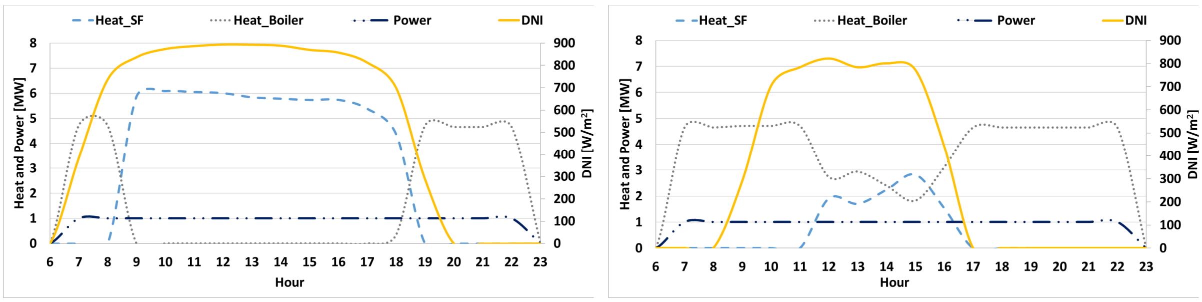

Figure 3 – Case 1 typical daily operation for summer (left) and winter (right).

C2 operation in typical summer and winter days, is similar to C1 (see figure 4). The main difference is related with heat production, also continuous. It is expected to occur a lower heat demand during summer, and therefore the heat can be used to drive an absorption chiller for cooling. Considering a Coefficient of Performance (COP) of 0.7, it would be possible to produce about 22400 KWh$_{COOLING}$ per day.

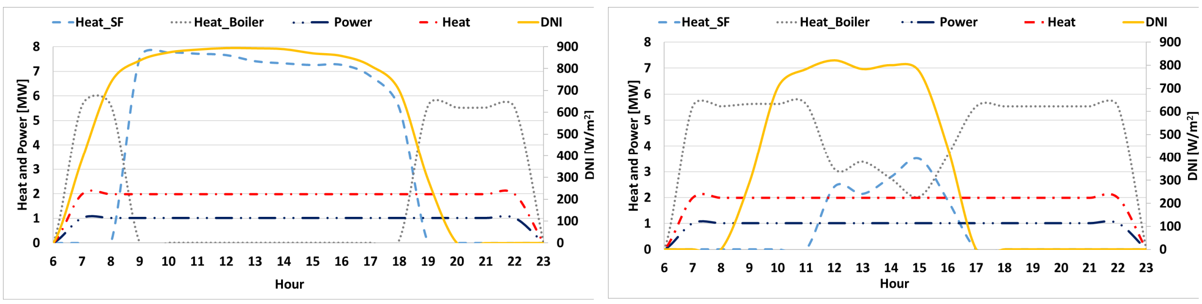

Figure 4 - Case 2 typical daily operation for summer (left) and winter (right).

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, 400 €/m² was defined, which is higher than 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 anaerobic digestion system, specific costs were defined according to the average values from the IRENA report on biomass costs for power generation (IRENA,2012). Considering that biogas will be used to drive a steam boiler, instead of a combustion engine, prime mover and electrical costs were subtracted. 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 5. SF and AD system represent about 80% of the capital expenditure (CAPEX) for both cases, of which 55% are related to the SF.

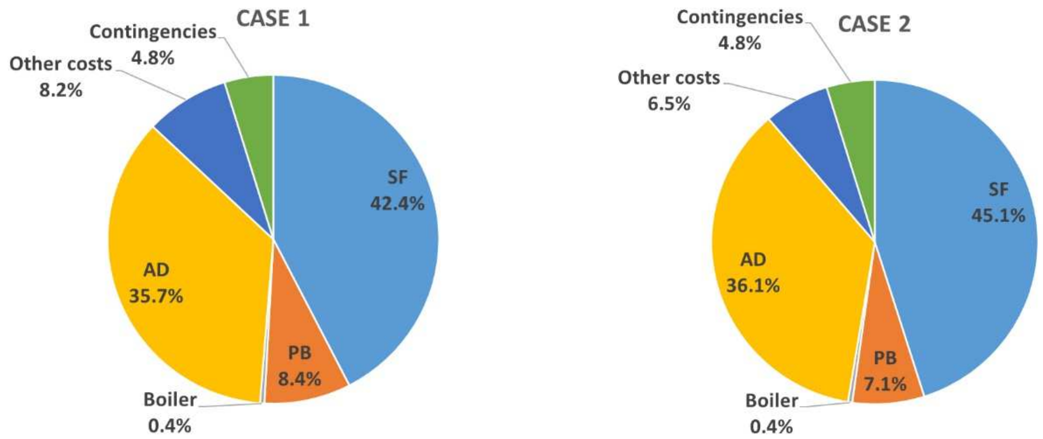

Figure 5 – CAPEX structure for C1 and C2.

Operational expenditure (OPEX), include operation and maintenance, replacements and equipment insurance. As expected, AD operation has the highest share (see figure 6), over 55%. Food waste pre-treatment and on-site handling and processing increase process complexity and thus costs. No costs were considered for food waste 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 (Bouaoun, 2014). The hybrid power plant is an option to overcome this issue, and consequently it was assumed that FW costs would be marginal.

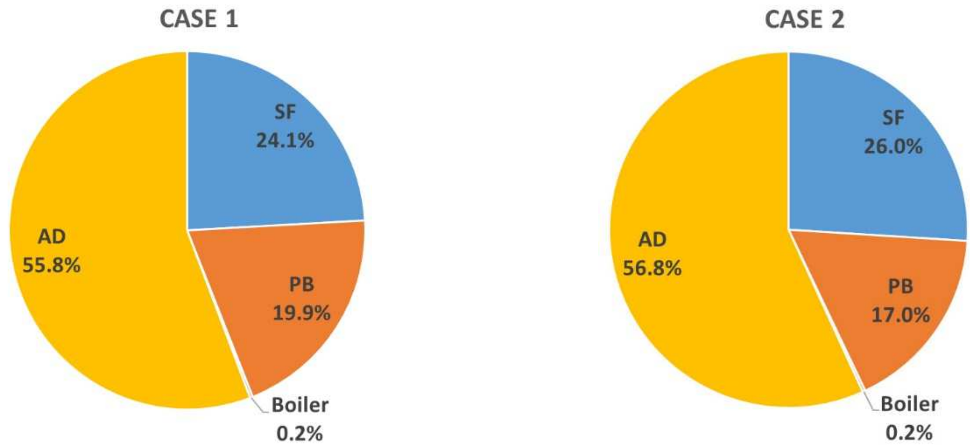

Figure 6 – OPEX structure for C1 and C2.

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

Table 4 – Equipment specific costs and CAPEX.

	Case 1	Case 2
Spec. SF Cost [€/m²]	400.00	400.00
Spec. PB Cost [€/kW_{el}]	800.00	800.00
Spec. Boiler Cost [€/kW_{th}]	8.00	8.00

Spec. AD Cost [€/kW_{th}]	678.00	678.00
CAPEX SF [€]	4,020,400.00	5,078,400.00
CAPEX PB [€]	800,000.00	800,000.00
CAPEX Boiler [€]	39,200.00	44,000.00
CAPEX AD [€]	3,388,000.00	4,066,000.00
Total CAPEX (incl. Contingencies) [€]	9,477,115.00	11,259,217.00
Total Annual OPEX [€]	283,339.00	331,978.00

One simple and appropriate way to summarise and compare the overall attractiveness of both case studies, is the Levelised Cost of Electricity (LCoE),

$$LCoE = \frac{CAPEX \times CRF + OPEX}{E} \quad (1)$$

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

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

where *i* is the interest rate (6%) and *n* the plant life-time (25 years). In case 2, in order to account for the CHP value, heat revenues were subtracted from generation costs (Alberici, 2014).

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

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 (Missaoui, 2014)., divided by a typical boiler efficiency (90%), was assumed for H_{price}.

C1 results in a LCoE of 173.1 €/MWh_{el} (see table 5), which is favourable considering the 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 low nominal efficiency, annual operation is carried out near design condition, eliminating even lower efficiencies from partial load operation. Moreover, both SF and AD system share the same PB, diluting the cost.

For C2, despite the higher CAPEX and lower PB efficiency, the $LCOE_{CHP}$ is 126.3 €/MWh_{el}. This value assumes that it is possible to sell all the produced heat at natural gas price, which is not evident. The authors are aware that for selling the heat it is necessary to be near a consumption centre. First, the small scale of the case study place it in the decentralised generation market. Second, using FW as fuel implies that the plant is placed nearby the consumers.

It is noteworthy that Tunisia massively subsidises natural gas suppliers (Missaoui, 2014). If those subsidies were accounted for the heat revenues would be twice as high and the $LCOE_{CHP}$ would be even lower. Additionally, the level of temperature of the heat allows its use for cooling purposes, and thus improves the $LCOE_{CHP}$.

Notwithstanding the attractiveness of the LCoE results, at least when compared with EU average electricity costs, Tunisia average electricity production cost is about 95 €/MWh_{el} (Missaoui, 2014). 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 increasing considerably every year (5%), and currently Tunisia is a net importer of energy. Thus, an intensification of the energy costs is expected in the coming years.

Table 5 – Levelised cost of energy.

	Case 1	Case 2
Life time [years] – Annuities	25	25
Interest rate [%]	6.0%	6.0%
CRF [%]	7.82%	7.82%
LCOE or $LCOE_{CHP}$ [€/MWh_{el}]	173.1	126.3

5. CONCLUSIONS

In this manuscript two CSP/Biomass hybrid power plant case studies, with $1MW_{el}$, were presented and assessed. Case studies diverge on the purpose, one for power generation (C1) and the other for Combined Heat and Power (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 hours of continuous load demand per day (6 to 22 h). C1 power block higher efficiency results in an annual average system efficiency of about 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 173.1 €/MWh_{el}, which is very attractive considering the small scale of the power plant. This outcome is a consequence of hybrid operation, enhancing power block and system efficiency and also reducing cost by equipment sharing (i.e. PB). Results show even better values for C2, with a $LCOE_{CHP}$ of 126.3 €/MWh_{el}.

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

6. ACKNOWLEDGMENTS

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