Applied Energy 302 (2021) 117600

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Techno-economic and operational assessment of concentrated solar power plants with a dual supporting system

R.E. Gutiérrez [a,b], P. Haro [a,*], A. Gómez-Barea [a]

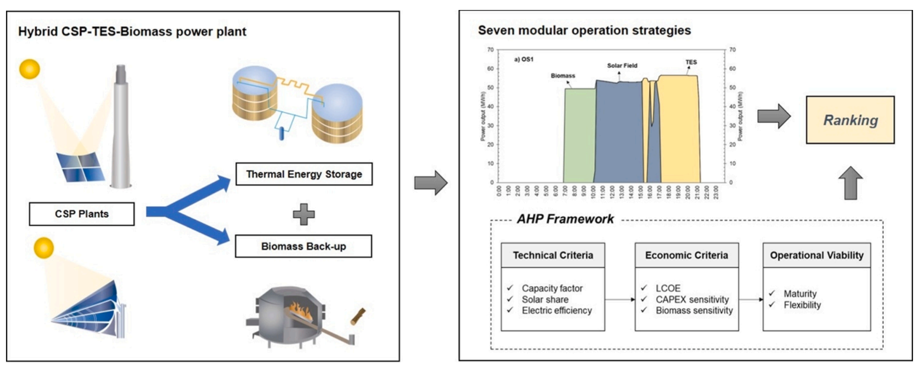
[a] Chemical and Environmental Engineering Department, Escuela Técnica Superior de Ingeniería, Universidad de Sevilla, Camino de los Descubrimientos s/n, 41092 Seville, Spain

[b] Postgraduate Faculty, Universidad de las Américas Quito, Avenida de los Granados E12-41 y Colimes, Quito, Ecuador

HIGHLIGHTS

- A dual TES-biomass supporting system for thermal solar power plants is presented.
- Techno-economic and operational viability criteria are included in the study.
- Seven operation strategies at five TES levels are analysed and compared.
- The benefits of a balanced trade-off between TES and biomass support are explored.
- Limiting biomass support allows a base-load plant operation with a high solar share.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Concentrated solar power
Biomass energy
Hybrid power system
Thermal energy storage
Techno-economic assessment
Dispatch strategy

ABSTRACT

This study evaluates the benefits of integrating a full renewable dual back-up system (biomass and Thermal Energy Storage (TES)) in Concentrated Solar Power (CSP) plants. Two plants of 50 MW_e capacity each are modelled and simulated, based on Parabolic Trough and Solar Tower technologies, with the integration of a biomass grate boiler in parallel to the power island. The Analytic Hierarchy Process is used as a Multi-Criteria Decision Method to compare the performance according to technical, economic, and operational criteria of 7 operating strategies. These strategies have been defined for integrating the biomass block for five levels of TES (No-TES, 5, 10, 15 and 20 h). The results show that the participation of biomass back-up favours the operation of the system as a base-load plant, increasing the capacity factor (CF) up to 71%, the net electric efficiency up to 10%, and reducing the cost of generation down to 56%, compared to stand-alone CSP plants. For the considered solar resource (Seville, Spain), reasonable generation costs (0.153 USD/kWh) can be achieved for a balanced trade-off between biomass and TES while allowing a firm energy supply (CF $\geq$ 80%) and reducing the required flexibility to the boiler. In addition, generation with a high solar share (over 50%) can be achieved with the proposed dual supporting system, favouring access to solar-driven incentives, as well as reducing the sensitivity of the system to the risks associated with biomass supply.

* Corresponding author.
E-mail address: pedrogh@us.es (P. Haro).

https://doi.org/10.1016/j.apenergy.2021.117600
Received 11 April 2021; Received in revised form 26 July 2021; Accepted 9 August 2021
Available online 24 August 2021

Nomenclature

A_{sf}	solar field reflection area (m^2)
C_O	capital costs (USD)
C_n	operation and maintenance costs (USD/year)
CF	capacity factor (%)
CI	consistency index
$d_{nominal}$	nominal discount rate (%)
d_{real}	real discount rate (%)
F_n	biomass costs (USD/year)
$HHV_{Biomass}$	biomass high heating value (MWh_{th}/tonne)
I_{sf}	solar field incident power (MWh/m^2/year)
LCOE	levelized cost of electricity (USD/kWh)
$M_{Biomass}$	biomass feed flow (tonnes/year)
$\eta_{th\ (boiler)}$	biomass boiler thermal efficiency (% HHV)
$\eta_{(boiler)}$	biomass boiler global efficiency to electricity (% HHV)
$\eta_{(PB)}$	power cycle efficiency (%)
$\eta_{(Q)}$	part-load efficiency (%)
$\eta_{(T)}$	temperature variation efficiency (%)
η_e	net electric efficiency (%)
Q_n	plant power output (MWh/year)
Q_{sf}	solar field power output (MWh/year)
Q_{TES}	thermal energy storage power output (MWh/year)
RI	random consistency index
$TGE_{Biomass}$	biomass gross thermal energy (MWh_{th}/year)

Abbreviations

AHP	analytic hierarchy process
BC	base case
CSP	concentrated solar power
CF	capacity factor
CAPEX	capital expenditure
DNI	direct normal irradiation
DSG	direct steam generation
DHI	diffuse horizontal irradiation
FB	fluidised bed
GHI	global horizontal irradiation
HTF	heat transfer fluid
LCOE	levelized cost of electricity
LF	linear Fresnel
NREL	national renewable energy laboratory
OS(i)	operation strategy, i ranges from 1 to 7
O&M	operation and maintenance
ORC	organic Rankine cycle
PD	parabolic dish
PT	parabolic trough
SAM	system advisor model
SCA	solar collector array
SM	solar multiple
ST	solar tower
TES	thermal energy storage
TMY	typical meteorological year

1. Introduction

The supply of clean energy is a key factor in achieving sustainable development goals adopted by the *United Nations General Assembly* in 2015. According to various scenarios, it is projected that by 2050 the share of renewable energy in the total primary energy supplied will be in the range of 43–67% [1–3]. According to the REmap scenario, the share of renewable energy needs to grow from about 25% in 2015 to 60% by 2030 and 85% by 2050 to achieve global energy transition to low-carbon technologies [1]. For electricity generation, 58% of that energy is projected with a 41% share of wind and 31% of solar as the primary sources [1,2].

The conversion of solar energy through photovoltaic (PV) systems has had an essential deployment worldwide, mainly because of the technology's maturity and decreasing generation costs in the last years [4]. However, as a non-dispatchable technology, an increase in the PV installed power tends to generate instability and loss of inertia in the distribution networks. Therefore, back-up systems such as batteries or other energy storage technologies become increasingly necessary to provide (quasi) dispatchable generation, e.g. with high ramp rates [5,6]. Unlike other renewable generation systems, Concentrated Solar Power (CSP) is a flexible and (quasi) dispatchable technology for large Thermal Energy Storage (TES) capacities, providing stability to the grid and favouring the expected penetration of variable renewable energies, such as PV and wind in regions with high direct normal irradiation (DNI).

The limitations due to the degradation temperature of the heat transfer fluids (HTF) used in CSP applications have led plants to operate their power cycles with low-pressure steam, significantly reducing their electric efficiency [7]. On the other hand, because of the intermittency of the solar resource, stand-alone CSP plants operate with reduced capacity factors (CF), in the range of 22–28% depending on the technology, location and solar multiple (SM) [8,9]. These problems affect the economic feasibility of the technology and have limited its deployment to regions located within the so-called sun-belt with levels of DNI higher than 2000 kWh/m^2/year [10].

To face these challenges, commercial CSP plants include solar back-up systems, such as TES, or non-solar back-up systems, generally based on natural gas. TES allows CSP plants to increase their CF up to 29–55%, depending on the storage size [11]. Nevertheless, this performance indicator is still lower than base-load thermal power plants. Besides, the use of natural gas is contradictory with the production of renewable electricity, and it has been limited or banished [12]. As an alternative, electricity generation based on biomass, either through combustion or gasification has the potential to replace natural gas as a supporting system [13–15]. Biomass energy can be considered carbon–neutral (e.g., agricultural residues) and constitutes a local and distributed energy source as it can be stored [16]. However, it must tackle logistic issues resulting from their intermittent availability and low energy density [17].

CSP-biomass boiler hybridisation benefits from using common equipment and infrastructure for heat exchanges, working fluids compression, transport, and expansion, differing only in the heat source to generate steam with similar pressure and temperature levels [18]. These hybridisation sources result in lower installation costs and higher dispatch capacity with 100% renewable back-up [18,19]. Overall, hybrid systems would allow better use of involved resources, especially when they are in limited quantities. Considering hybrid CSP-biomass plants, expansion to regions outside the sun-belt, e.g., with DNI levels above 1800 kWh/m^2/year, would be economically viable [20,21].

Some synergies can be expected from the combined use of TES and biomass as supporting systems to CSP plants. For instance, the solar block (including TES) generation is influenced by the intermittency of the resource, requiring a minimum irradiation level to start the operation: for the solar field to reach a minimum start temperature and for the TES system to establish a charge–discharge strategy looking for a sustained and efficient generation during transients and sun sets [22–24]. Moreover, biomass generation can be adapted to various operation strategies, such as a base-load operation or complementary/variable operation, to adjust plant generation to a specific demand profile [25,26].

The back-up system rated capacity and operation strategy could significantly impact the plant complexity, dispatchability, and performance. Thus, a comparative assessment is necessary to evaluate this effect on the techno-economic and operational viability of the proposed system. In this study, the benefits of integrating a dual back-up system (biomass and TES) in CSP plants are addressed.

1.1. Previous work

The first operational CSP-biomass hybrid project worldwide is the *Borges* plant, located in Lleida, Northeast Spain, with DNI levels around 1800 kWh/m^2/year. The plant has a net installed capacity of 22.5 MW$_e$ with a thermal back-up based on two biomass boilers of 22 MW$_{th}$ each and an additional natural gas boiler for start-up [18]. Biomass back-up allows generation at half load (no sun) and up to 100% load in hybrid mode to cover transients during the day [27]. In addition, the Aalborg CSP plant in Denmark has been successfully operated for heat and electricity generation using an organic Rankine biomass cycle [28,29]. Apart from these power plants, there are several studies evaluating the feasibility of CSP-biomass hybridization in Australia [26,30–32], Brazil [33–35], Europe [8,22,36], India [37,38], Indonesia [39], and Iran [40].

Peterseim et al. [32] evaluated and compared several combinations of CSP technologies with various HTF and biomass back-up system alternatives. Linear Fresnel (LF) with direct steam generation (DSG) hybridised with a biomass fluidised bed (FB) boiler obtained the lowest specific investment cost (3.4 MUSD/MW$_e$). The performance of a 10 MW$_e$ parabolic trough (PT) biomass hybrid plant with natural gas support was studied by Servert et al. [36]. The plant achieved a lower levelized cost of electricity (LCOE) than the stand-alone CSP plants and reduced the biomass demand by 33%. Srinivas et al. [41] evaluated the technical performance of a PT-DSG system hybridised with a biomass boiler, showing an increase in fuel efficiency and a reduction in the plant thermal efficiency when solar share grows from 10% to 50%.

Other studies explored using a biomass FB boiler to superheat the steam from a 50 MW$_e$ PT plant with 7.5 h of storage [10]. Bai et al. [42] evaluated the performance of a 50 MW$_e$ PT-biomass plant with TES. The boiler fulfils a double function, superheating the steam from the solar block and generating it independently. The results showed an increase in the annual solar-to-electricity efficiency of up to 18.3%, while biomass accounts 77.4% of the total generation. Soria et al. [33] evaluated the feasibility of PT-biomass plants for a semi-arid area in Brazil, where configurations with low biomass boiler rated capacity and a SM of 1.2 were able to have high solar shares. Soares et al. [43] find an increase of 6.2% in global electricity efficiency for a mini PT plant hybridised with a biogas boiler to drive an Organic Rankine Cycle (ORC).

Oyekale et al. [44] explored the benefits of biomass retrofitting of an ORC-Fresnel plant in Italy. The results showed a marginal cost of energy of 0.103–0.109 EUR/MWh and an increase in the net electric efficiency of up to 5%. Peterseim et al. [26] evaluated a 30 MW$_e$ solar tower (ST) biomass hybrid plant with 3 h of TES for Griffith, Australia. Generation costs of 0.155 AUD/kWh and a reduction of 43% in investment compared to a stand-alone ST plant was achieved. The analysis of performance and economic benefits of the CSP-Biogas hybridised plant was developed by Petrollese et al. [45] through a case study based on the CSP plant in Ottana (Italy). Hussain et al. [46] found that CSP-biomass-TES hybrid plants achieve a 6% increase in solar share and 3% in electrical efficiency than CSP-biomass plants. However, higher generation costs were incurred.

Table 1 summarises the information from these studies, giving special attention to their operation modes. They demonstrate the feasibility of CSP-biomass hybrid power plants and the growing interest in assessing various combinations of these technologies and hybridisation

Table 1
Summary of literature studies on CSP-Biomass hybridisation, including TES (where applicable).

CSP Technology	TES	Hybridisation Scheme	Capacity (MW$_e$)	Power Cycle	Back-up Operation Strategy	Remarks	Refs.
PT	Yes (with 7.5 h of TES)	Biomass FB boiler in series to power island	50	Rankine	Variable following CSP profile	Frequently start/stop cycles	[10]
ST	Yes (with 3 h of TES)	Biomass boiler in parallel to power island	30	Rankine	Fixed operation at full capacity	Griffith, Australia	[26]
PT Therminol[a]	No	Biomass boiler in parallel to power island	30	Rankine	Cover transients in daytime/ Fixed without DNI	Brazil, 30% biomass fil fraction	[33]
PT, ST, Fresnel	No	Grate, FB, Gasification in parallel to power island	17.3–19.4	Rankine	Continuous operation at full load	Australia, various technological combinations	[32]
PT with Therminol	No	Biomass and NG boiler in parallel to solar field	10	Rankine	biomass fixed and Natural gas to cover transient	Spain, no TES	[36]
PT with DSG	No	Biomass boiler in parallel to power island	50	Rankine	Continuous operation at full load	Solar share is limited to 50% in daytime	[41]
PT	Yes (with indirect TES)	Biomass boiler in parallel to power island	50	Rankine	Variable following CSP profile/ Fixed without DNI	Superheating CPS steam/Direct steam generation	[42]
PT with DSG	No	Biogas boiler in parallel to the solar field	–	ORC	Variable following CSP profile/ Fixed without DNI	Running ORC 12 to 24 h scenarios	[43]
Fresnel with Therminol	No	Biomass boiler in parallel to power island	5	ORC	Modular following CSP profile/ Fixed continuous operation	Ottana, Italy, CSP plant retrofit	[44]
Fresnel with Therminol	No	Biogas boiler in parallel to the solar field	5	ORC	Variable following CSP profile/ Various biogas fractions	Anaerobic digestor linked to biogas storage	[45]
PT	Yes (with indirect TES)	Biomass boiler in parallel to power island	4–6.5	Rankine	Fixed at nights and variable at daytime to cover transients	Biomass only, CSP-biomass and CSP-biomass-TES cases	[46]
PT and ST	*Yes (with up to 20 h of TES)*	*Biomass boiler in parallel to power island*	*50*	*Rankine*	*7 operation strategies, continuous operation, following load and mixed*	*Seville, Spain, Comparative, techno-economic and operational assessment*	**This study**

PT: Parabolic trough, **ST:** Solar tower, **FB:** Fluidised bed, **NG:** Natural gas; **ORC:** Organic Rankine cycle, **DSG**: Direct steam generation.
[a] Mixture of Biphenyl and Diphenyl Oxide.

modes that maximise their integration benefits. Most of these studies assume that biomass and TES are competing and mutually exclusive back-up systems. This study goes beyond this by analysing the synergy of TES and biomass as a dual supporting system. Therefore, aiming to resemble fully renewable base-load power plants. To the best of our knowledge, there is no published work that addresses a detailed comparison of the impact of operation strategies on the overall performance of hybrid power plants. This paper aims to fill this gap by conducting a comparative techno-economic and operational assessment of seven modular operating strategies using the Analytic Hierarchy Process (AHP) as a multi-criteria decision method. This approach provides insights of the benefits and challenges of integrating CSP and biomass in various offsets, as well as expanding the use of these hybrid technologies.

2. Case study description

2.1. Technology and hybridisation scheme

CSP plants can be linear focus, such as parabolic trough collectors and linear Fresnel or point focus, such as solar tower and parabolic dish (PD) systems [9]. PT, LF and ST currently operate with TES from different working fluids, such as thermal oil, molten salts, steam or a combination of them [11]. In this study, the PT and ST technologies are selected, because of their high maturity level, greater commercial deployment, and interest in evaluating the synergy between solar field, thermal storage, and biomass back-up [9]. For the back-up system, a biomass grate boiler is selected, due to its high maturity and less complexity concerning other technologies such as FB boilers or the burning of syngas generated from the gasification process [32]. Although the hybridisation of CSP plants with syngas (produced in a biomass gasifier) boilers could provide greater flexibility [47] than a biomass boiler, it is not considered in this study because of its lower maturity.

The hybridisation modes are defined mainly by the position of the back-up system, which can be parallel, in-series or a combination, both to the solar field and the power island. Parallel schemes allow the back-up system to provide the thermal energy required by the HTF or the working fluid in a decoupled way. In-series hybridisation involves a simultaneous operation of the solar block and the back-up system, either to heat the HTF to nominal conditions or to superheat the working fluid to increase the cycle efficiency [48].

Hybridisation in parallel to the solar field favours greater synergy between the supporting systems, as the biomass boiler directly provides thermal energy to the HTF. However, the location of the biomass boiler next to the power island avoids an additional heat exchange, thus increasing the biomass-to-electricity conversion efficiency. Furthermore, this kind of hybridisation offers greater flexibility in setting operation strategies, as it decouples the biomass block from the heat needs of the storage tanks. Therefore, in this study, a hybridisation mode in parallel to the power island is selected. It allows both a simultaneous operation to complete the required generation profiles and a decoupled operation to extend production during low or no radiation hours. This kind of operation prioritises generation from TES to cover transients and slight load variations, which would reduce the operating pressure on the biomass boiler and the complexity of the whole system [49].

2.2. Solar resource and design capacity

For this case study, a typical meteorological year (TMY) with the solar data of 13 years (2000–2012) at a 10-minute resolution has been used [50]. The series includes measurements of global horizontal irradiation (GHI), DNI, diffuse horizontal irradiation (DHI), ambient temperature, relative moisture, air pressure and wind speed. The DNI design point was set in 850 W/m^2, which refers to 90% of the TMY values (being the design irradiation used in several CSP plants in operation and the scientific literature for Southern Spain) [50–54]. Poplar chips with a higher heating value of 20.18 MJ/kg [55] are used as feedstock for the back-up system. Fig. 1 shows the selected location. More details are shown in the supporting information.

According to the previous experiences in the sector and regulatory limitations, the recommended capacity for newly built plants is at least

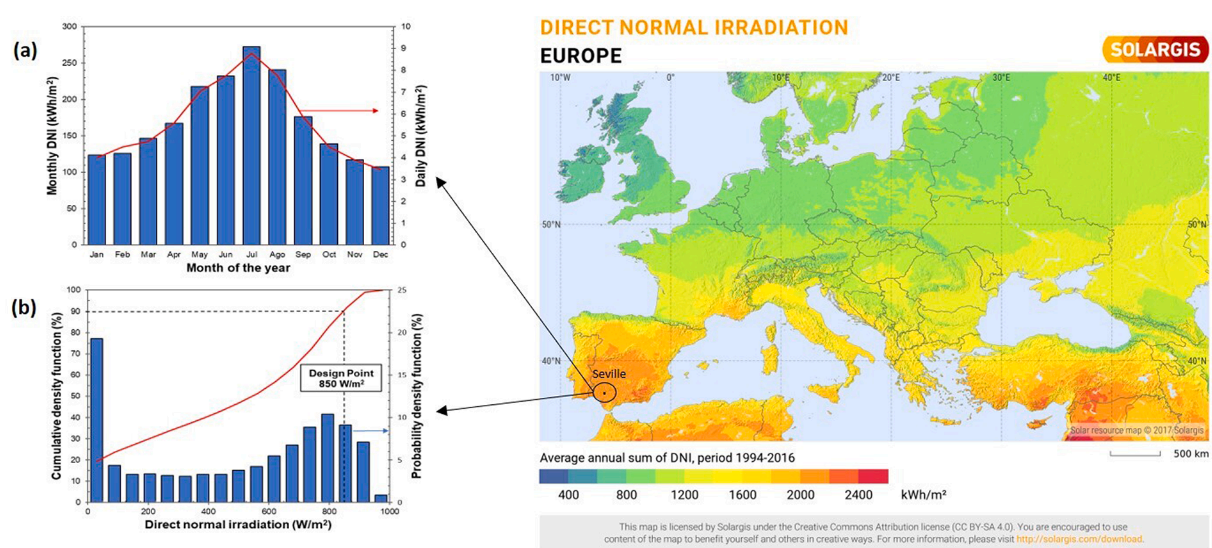


Fig. 1. Description for the selected location (Seville, Spain): (a) Daily and monthly DNI profile; (b) Probability and Cumulative DNI density functions (elaborated from own data and [56]).

50 MW_e [57]. Considering the benefits of scale economy, the investment required for biomass plants decreases as their installed capacity grows. However, at the same time, there is an increase in the uncertainty related to biomass supply. The capital and operating costs of biomass plants are significantly reduced for plant scales in the range of 20–50 MW_e [58]. In this context, we have set hybridised configurations with an overall nominal capacity of 50 MW_e.

In this study, two configurations of CSP-biomass hybridised plants with a net power output of 50 MW_e are assessed: 1) a PT plant with an indirect TES system (Fig. 2); and an ST plant with a direct TES system (two-tank molten-salts) (Fig. 3). A biomass grate boiler with a capacity between 25 and 50 MW_e (depending on the operating strategy) is in parallel to the power island in both configurations. The design of the CSP blocks was carried out considering previous designs operating in Spain. As the main reference for the design of PT, the *Andasol-2* plant (Granada) with 7.5 h of TES capacity and 50 MW_e of installed power was selected. This plant started operation in 2009, with an estimated solar resource of 2136 kWh/m^2/year and an expected annual electricity generation of 158 GWh/year [59]. For ST, the *Gemasolar* plant located in *Fuentes de Andalucía* (Seville) was selected, with a TES capacity of 15 h and an installed power of 19.9 MW_e. *Gemasolar* was the first commercial tower plant to include molten salt thermal storage worldwide. The plant started operation in 2011, with an estimated solar resource of 2100 kWh/m^2/year and an expected generation of 80 GWh/year [60,61].

In the following sections, the selected configurations and the basis for their design and assessment are described, including the technical and economical design parameters, the biomass operating strategies of the boiler, and the criteria for the comparative performance evaluation (Ranking). In the results section, the optimisation analysis between SM and storage capacity is shown. The annualised performance results of the case studies are discussed according to technical, economic, and operational criteria, including the results of the operation strategies ranking. Finally, a set of conclusions is provided.

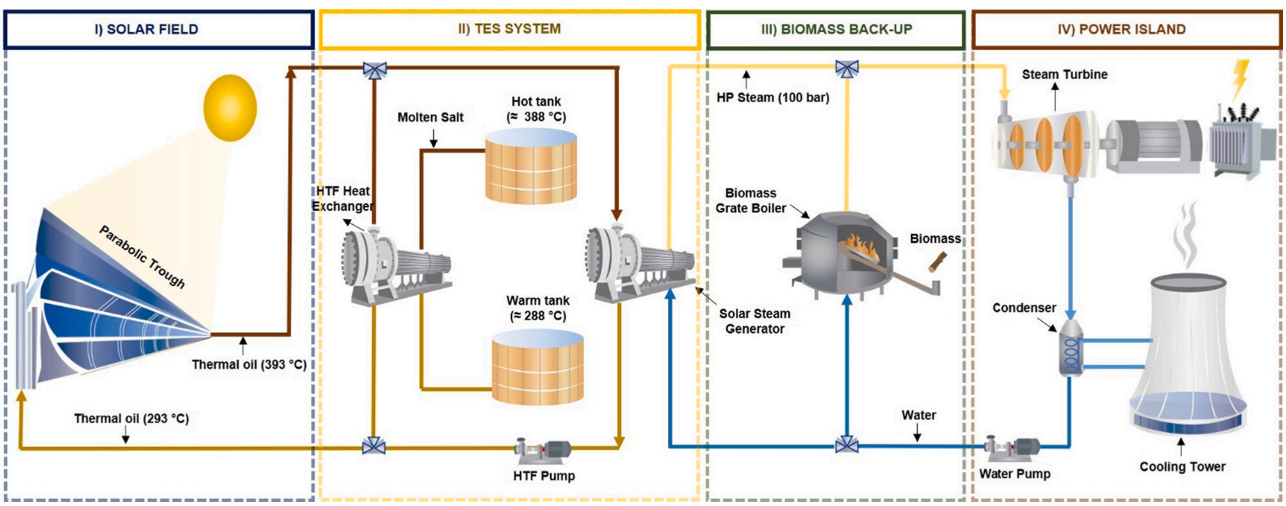


Fig. 2. CSP-Biomass hybrid concept illustration for parabolic trough configuration.

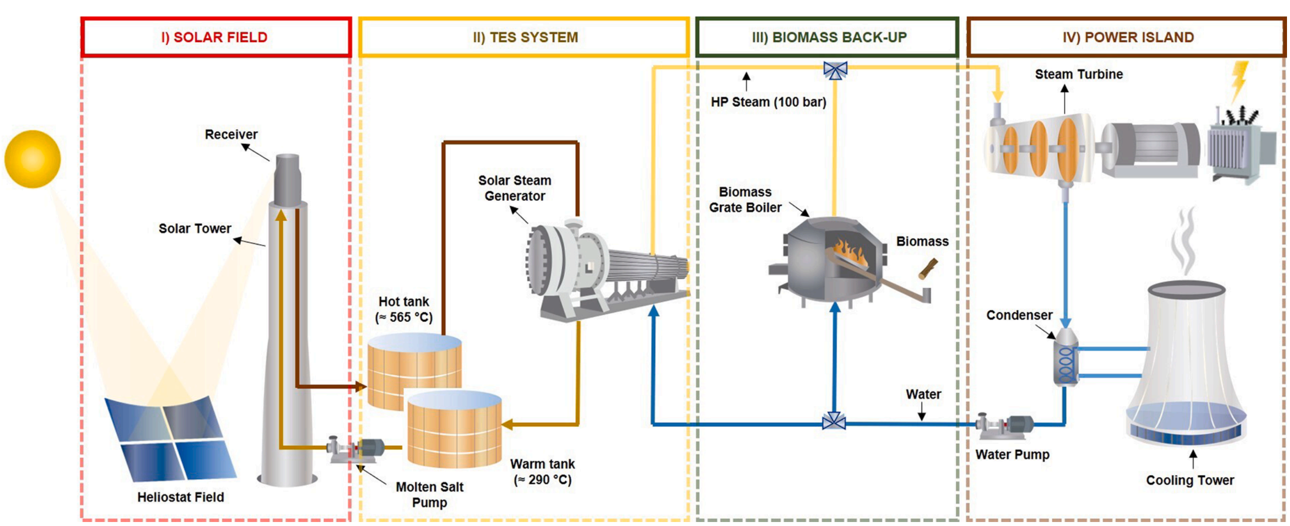


Fig. 3. CSP-biomass hybrid concept illustration for solar tower configuration.

3. Methodology

3.1. Technical design

In the PT-based configuration, the solar field includes several loops located in parallel and formed by four solar collector arrays (SCA) each [59]. Each SCA is made up of 12 solar modules and receiver tubes through which thermal oil (*Therminol VP-1*) circulates, used as HTF. In each loop, the HTF increases its temperature from 293 °C to 393 °C and it is sent to the solar steam generator, or the TES block once the power island requirements have been covered. The *EuroTrough ET150* model has been selected as a solar collector due to its high optical performance and low installation cost [62]. The *Schott PTR70* model has been selected as the receiver tube because of its high reliability, low cost and compatibility with a wide variety of solar collectors [63].

In ST configuration, the solar field is formed by heliostats with a reflection area of 144 m^2 each, with an on-axis inclination, which implies that the vectors corresponding to the solar rays and the receiver are perpendicular to the plane of the heliostat [64]. IDEAL focusing method has been selected, in which focal length is equal to the distance between the centroid of the heliostat and the image plane of the receiver [65]. Heliostats surround the tower with a cylindrical receiver at the top, through which molten salts (60% $NaNO_3$, 40% KNO_3) circulate, operating at temperatures in the range of 290–565 °C [64]. The solar field geometry, tower height, and receiver area were calculated using the National Renewable Energy Laboratory (NREL) *SolarPilot* optimisation algorithm as a function of the SM selected for each case [66].

The TES block is based on two-tanks molten salts, a system widely used for sensible heat storage in CSP plants [9]. In the case of PT, it is an indirect system since the HTF, and the storage fluid are different, which implies an additional step (heat exchange). For ST, it is a direct storage system, with molten salts working as transfer and storage fluid. The relationship between the SM and the thermal storage capacity is crucial in the design of CSP plants. Therefore, it is included in the design of hybrid CSP-biomass plants with TES. A high SM value implies a large solar field reflection area, meaning greater electricity generation [64]. However, as the SM increases, so do installation costs. That may reduce the system profitability if there is no adequate storage capacity, which effectively manages this additional incident power. In this study, the relationship between SM and storage capacity for both technologies base cases (without hybridisation) is obtained through a parametric optimisation analysis (discussed in Section 4.1).

The biomass back-up system is based on a grate boiler, which generates steam of the same quality as in the CSP block. The power island is based on a conventional Rankine cycle that uses water-steam at 100 bar. It consists of a series of heat exchangers that allow the generation and superheating of steam from the thermal oil energy in the PT configuration and molten salts in the ST configuration. The steam expands in a conventional turbine generating a gross power of 55 MW_e with an alternator efficiency of 90%. The electric efficiency of the power block has been set at 39.0% for PT and 41.2% for ST (evaporative cooling system) [64,65]. Efficiency is higher for ST technology than for PT because of the higher exchange temperature of molten salts [67].

The biomass back-up net efficiency is given by the boiler thermal efficiency and the power cycle efficiency (common to the CSP block). The thermal efficiency variation due to boiler operation at different loads is included in the model by a correlation based on [68]. A logarithmic growth of electric efficiency is assumed for operation at loads ranging from 5 to 100 MW_e. This model is consistent with reported efficiency for a similar biomass plant operating in Spain [69]. For further details see Figure S2.1 in the supporting information.

The power yield (10-minute resolution) of the solar field and TES blocks are simulated through System Advisor Model (SAM) version 2018.11.11, a software developed and validated by NREL and used in the scientific literature for the evaluation of new CSP concepts [70–72]. Then, the resulting datasets are exported to an in-house tool, in which the biomass back-up generation is calculated according to the conditions set out for each operation strategy. The resulting performance of the power island integrates the generation from both blocks, including the variation of the turbine efficiency (e.g., part-load operation and ambient temperature). The summary of the technical parameters is shown in Table 2 and further details are provided in the supporting information.

Table 2
Technical parameters of the PT-biomass and ST-biomass configurations [51,59,60,65].

	Parabolic Trough	Solar Tower
Solar Field		
DNI design point (W/m^2)	850	
Solar multiple (SM)	To be calculated[a]	
Solar collector array (SCA) assemblies per loop	4	–
Collector type	*EuroTrough ET150*	–
SCA length (m)	150	–
SCA aperture (m)	5.75	–
SCA reflective aperture area (m^2)	817.5	–
Heliostat reflective area (m^2)	–	144.4
Heliostat focusing method	–	IDEAL
Heliostat canting method	–	On-axis
Heliostat field geometry	–	From optimisation
Tower height	–	“
Receiver area	–	“
Receiver type (geometry)	*Schot PTR70*	Cylindrical
Heat transfer fluid (HTF)	*Therminol VP-1*	Molten salt (60% $NaNO_3$, 40% KNO_3)
HTF hot temperature (°C)	393	565
HTF cold temperature (°C)	293	290
Reference optical efficiency	78%	54 %[b]
Reference thermal efficiency	72%	91 %[b]
Thermal storage		
Full load hours of TES	0–20 (with a step of 5)	
Configuration	Two-Tanks	
Tank height (m)	12	
Dispatch schedule	Summer peak	
Storage fluid	*Hitec solar salt*	Molten salt (60% $NaNO_3$, 40% KNO_3)
Power island		
Design gross output (MW_e)	55	
Gross to net conversion efficiency	90%	
Net output at design (MW_e)	49.5	
Working fluid	Steam	
Boiler operating pressure (bar)	100	
Condenser type	Evaporative	
Cycle conversion efficiency	39.0%	41.2%
Hybridisation		
Technology	Grate boiler	
Net output at design	Depend on the operation strategy	
Hybridisation scheme	Parallel to power island	
Minimum operation load	40% of full load	
Biomass boiler thermal efficiency	81% at full load[c]	

[a] To be calculated trough parametric analysis included in Section 4.1.
[b] Annualized value.
[c] $\eta_{th(boiler)} = 0.134 * ln[operationload(MW)] + 0.285$.

3.2. Economic design

The economic design is based on accepted practices for PT [73] and ST [74,75], considering a conservative scenario (i.e., the substantial reductions projected for 2025 [76] are not considered in this study). When necessary, the 2018 exchange rate of the European Central Bank

Table 3
Economic input parameters for PT-biomass, and ST-biomass configurations [73–75,77–79].

	Parabolic Trough	Solar Tower
Direct capital costs (DCC)		
Site improvement cost (USD/m^2)	25	16
Solar field (USD/m^2)	150	140
HTF system (USD/m^2)	60	–
TES system (USD/kWh_{th})	62	22
Biomass boiler (USD/kW_e)	750	
Biomass handling equipment (USD/kW_e)	330	330
Other equipment related to biomass (USD/kW_e)	270	270
Contingency related to biomass equipment	30%	30%
Fixed solar tower cost (MUSD)	–	3[a]
Solar tower cost scaling exponent	–	0.0113
Receiver reference cost (MUSD)	–	103[b]
Receiver reference area (m^2)	–	1571
Receiver cost scaling exponent	–	0.7
Balance of plant (USD/kW_e)	90	290
Power cycle (USD/kW_e)	910	1040
Contingency (% of DCC)	7	7
Indirect capital costs (ICC)		
EPC and owner cost (% of DCC)	11%	
Total land cost (USD/m^2) [80]	1.145	
Operation and maintenance costs (O&M)		
Fixed cost by capacity (USD/kW_e-year) [73,81]	65[c]	
Variable cost by generation (USD/MWh) [33,81]	5	
Biomass cost (USD/GJ) [55]	3.27	
Financial parameters		
Analysis period (years)	25	
Real discount rate	10%	
Inflation rate	2.5%	

[a] $Cost_{Tower} = Fixedcost_{Tower} \cdot e^{scalefactor \cdot \left[Towerheight - \frac{Receiverheight}{2} - \frac{Heliostarheight}{2}\right]}$.

[b] $Cost_{Receiver} = Referencecost_{Receiver} \cdot \left[\frac{Area_{Receiver}}{Referencearea_{Receiver}}\right]^{scalefactor}$

[c] Base case, for the other cases: $O\&Mfixedcost = -0.078 \cdot (TES_{hours})^2 + 5.36 \cdot TES_{hours} + 65$ (adapted to TES capacities from values reported in [73,81]).

[77] is used. The summary of the economic parameters is shown in Table 3. The direct capital costs related to the biomass block were taken from NREL and the US Environmental Protection Agency reports [78,79]. The potential risk of integrating the biomass back-up is considered by increasing (twofold) the contingency for this block. Land cost of 11,450 USD/ha [77,80] is set for the installation of the plant.

3.3. Operation strategies

The biomass back-up system can adopt strategies ranging from continuous base-load operation (fixed power throughout the year) to modular operation at a variable load that matches the solar generation profile. In this study, 7 modular operation strategies are proposed and assessed, in addition to the base case (BC) that does not include a back-up system (8 cases in total). In operation strategies 1, 2, 5, 6 and 7 (OS1, OS2, OS5, OS6, OS7), the biomass block has the same installed capacity as the CSP system, whereas strategies 3 and 4 (OS3, OS4) have half capacity. OS4 and OS7 allow base-load operation along the year, while the other operation strategies only operate on days when generation from the solar block is expected (forecasted). In all cases, generation will stop when the demanded load is below its minimum operating load.

In OS1 and OS2, the biomass block complements system generation up to nominal power during a preferential schedule (pre-defined). Both strategies differ in OS1, including multiple daily starts, while there is only one for OS2. OS3 and OS4 have a variable load operation with multiple daily start-up of the biomass block, keeping generation for 24 h a day at a minimum of 50% of the system nominal power. Similarly, in OS5 and OS6, the biomass block operates at a variable load with multiple daily start-up, ensuring generation along the whole day. During pre-defined preferential schedules, the biomass block completes and extend the system generation at full load, operating at its minimum load the rest of the time. OS7 has been designed to achieve a firm energy supply (base-load). In this strategy, the biomass block has a continuous operation throughout the year. The summary of these strategies is shown in Table 4.

3.4. Method for ranking operation strategies

The operation strategies ranking consists of 4 consecutive stages:

i) selecting the evaluation main criteria and sub-criteria,
ii) obtaining results,
iii) criteria comparison and weighting, and
iv) alternative scoring for each criterion.

In this comparative analysis, technical, economic, and operational

Table 4
Biomass back-up system operation strategies.

Parameters	OS1	OS2	OS3	OS4	OS5	OS6	OS7
Dominant operation mode	Following load	Sustained	Mixed	Mixed	Following load	Following load	Mixed
Allows all-day generation	–	–	✓	✓	✓	✓	✓
Allows all-year operation	–	–	–	✓	–	–	✓
100% biomass mode (at nights)	–	–	✓	✓	✓	✓	✓
Multiple daily starts	✓	–	✓	✓	✓	✓	✓
Variable load operation	✓	✓	✓	✓	✓	✓	✓
Preferential generation schedule	07:00–21:00	07:00–18:00	–	–	07:00–15:00	07:00–21:00	–
Boiler nominal power (MW_e)	49.5	49.5	25	25	49.5	49.5	49.5
Minimum operating power (MW_e)	19.8	19.8	10	10	19.8	19.8	19.8
Operating power (Preferential schedule) (MW_e)	49.5	49.5	25	25	49.5	49.5	49.5
Operating power (rest of day) (MW_e)	–	–	25	25	19.8	19.8	49.5
Operating power (100% biomass mode) (MW_e)	–	–	25	25	19.8	19.8	49.5

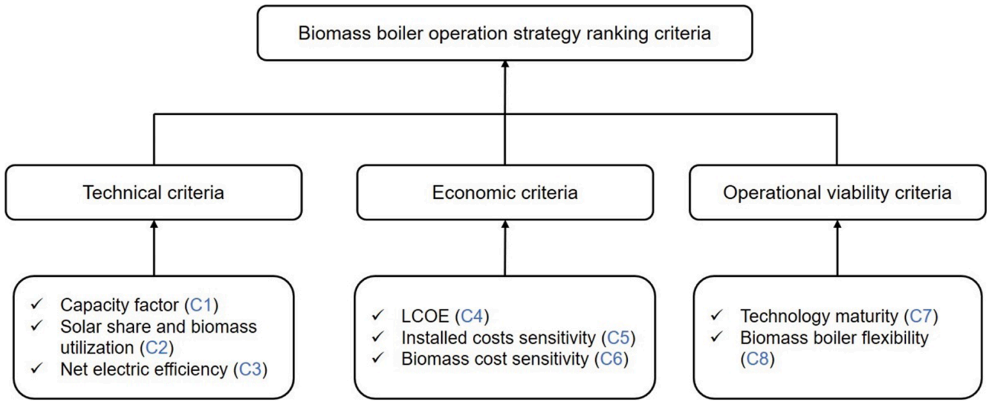


Fig. 4. Operation strategy ranking criteria.

viability evaluation criteria have been included. Each is divided into several sub-criteria, as shown in Fig. 4.

The technical criteria include strategy performance referred to CF (C1), solar share (C2), annual biomass utilisation and net electric efficiency (C3). The CF reflects the time fraction that a plant operates at full load [82]. This criterion is used to evaluate the contribution of the back-up system in the generation of the hybridised plant. The solar share allows determining the portion of electricity generated per year from the solar resource. In reference, the annual demand for biomass is an inverse parameter; the lower the solar share, the higher the use of biomass. The net electric efficiency (η_e) allows evaluating the effect of biomass integration on the conversion performance of the whole system at an annualised scale [32,44,83].

Economic criteria have as a central point the LCOE evaluation (C4) since this parameter includes information related to capital expenditure (CAPEX), operation and maintenance (O&M) and others financial parameters (see supporting information). The sensitivity to variation in the installed costs (C5) and possible fluctuations in the biomass cost (C6) are also analysed. LCOE expressed in USD/kWh is one of the most used parameters in economic performance evaluation for this kind of power plants [84–87]. Technical and economic criteria are calculated according to equations (1) to (5).

$$CF = \frac{Q_n}{PN_{system} \cdot 8760} \quad (1)$$

$$Solarshare = \frac{Q_{sf} + Q_{TES}}{Q_n} \cdot 100 \quad (2)$$

$$M_{Biomass} = \frac{TGE_{Biomass}}{HHV_{Biomass}} \quad (3)$$

$$\eta_e = \frac{Q_n}{M_{Biomass} \cdot HHV_{Biomass} + I_{sf} \cdot A_{sf}} \quad (4)$$

$$LCOE = \frac{C_O + \sum_{n=1}^{N} \frac{[C_n + F_n]}{[1+d_{nominal}]^n}}{\sum_{n=1}^{N} \frac{Q_n}{[1+d_{real}]^n}} \quad (5)$$

Criteria related to operational viability include the technological maturity of the whole system (C7) and the operational flexibility required for the back-up system (C8). The data referring to technological maturity are evaluated according to their use in operating plants, development phase projects or concepts analysed in the literature. The boiler flexibility is analysed according to the generation profiles obtained for different TES capacities and DNI seasonal variations.

AHP is the multi-criteria decision method most used in the analysis of decision problems related to renewable energy systems [88]. Several studies apply it to evaluate solar energy systems, both photovoltaic and CSP [89–92]. The method allows a paired comparison of the decision criteria, to later apply a prioritisation scale on the set of alternatives [93]. For pairwise criteria comparison, a Saaty scale [94] is used with values between 1 and 9, representing the importance of one criterion over another, as shown in Table 5. Equation (6) represents the matrix resulting from the pairwise criteria comparison process.

Table 5
Saaty's discrete 9 value scale [94].

Intensity of importance	Definition	Explanation
1	Equal importance	Two criteria contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favour one criterion over another
5	Essential or strong importance	Experience and judgment strongly favour one criterion over another
7	Very strong or demonstrated importance	A criterion is favoured very strongly over another; its dominance is demonstrated in practice
9	Absolute importance	The evidence favouring one criterion over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between two adjacent scale values	When a compromise between values is needed

$$M_A = \begin{bmatrix} C^{1.1} C^{1.2} \dots C^{1.j} \\ C^{2.1} C^{2.2} \dots C^{2.j} \\ \dots \\ C^{j.1} C^{j.2} \dots C^{j.j} \end{bmatrix} \quad (6)$$

M_A represents the criteria pairwise comparison matrix, j shows the number of comparison criteria, $C^{1.2}$ shows the dominance of criteria 1 over criteria 2, while $C^{2.1}$ shows the reciprocal value. The matrix data is normalised by dividing each deal with the sum of its column, thus obtaining a new matrix M_N. Finally, each criterion's eigenvector is obtained through the average of all the data of each row of M_N.

A dedicated survey with the participation of several external experts in CSP technologies and the authors was carried out to improve the judgment. Participants rated the criteria and completed a form filling the scores of a pairwise matrix. These scores are averaged and converged in a single matrix, from which the criteria weights are obtained. The resulting matrix is considered acceptable when its consistency ratio $\leq$10%; otherwise, the included value judgments were reconsidered. In the evaluation of the alternatives, a specific prioritisation order is established for each criterion. The scale score is defined according to the strategies position in each criterion, assigning values ranging from 0.125 for the worst-located strategy to 1.000 for the best-located strategy and 0.125 increments for each position improvement. Criteria with quantitative results, such as techno-economic parameters (C1-C6), are valued according to the corresponding simulations and economic analyses. For the operational viability criteria (C7, C8), a qualitative assessment is established based on the literature and daily generation profiles.

The total score for each strategy considering all the evaluation criteria is obtained according to equation (7). Finally, the strategy that achieves the highest score is considered the best alternative in this analysis, the rest of the alternatives are ranked according to the same criteria.

$$AHP_{score} = \sum_{j=1}^{n} F_j w_j \quad (7)$$

F_j represents the score assigned to the strategy according to its location in criterion j, n represents the total number of criteria; w_j represents the weight of criterion j. Further details on AHP methodology are included in the supporting information.

4. Results and discussion

4.1. Solar multiple effect

The optimal SM for each TES capacity has been obtained, prioritising the minimum LCOE for plants operating at the maximum CF that can be achieved at that point from the parametric simulations, as has been done in [95]. Parametric optimisation analyses have been performed to

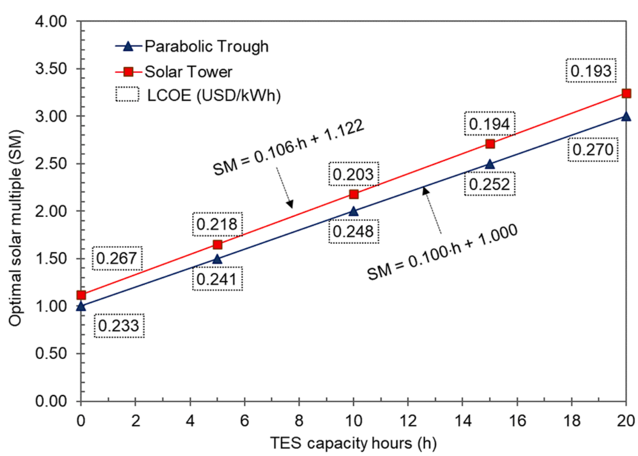


Fig. 5. Optimal solar multiple (SM) values for various TES capacity based on the minimum LCOE and maximum CF.

calculate these values, the SM value has been varied from 1.0 to 3.4 and the TES capacity from 0 to 18 h. The optimal SM ranges between 1.2 and 3.0 for ST and 1.0–2.8 for PT. Although for ST, higher TES capacities imply lower LCOEs. In this study, thermal storage has been limited to 20 h, because from this capacity the LCOE reduction tends to stabilise (as seen in Fig. 5). Moreover, 20 h is an achievable storage capacity according to the current state of molten salt technology (i.e., Atacama-1 project in Chile with 17.5 h of TES [96]). Fig. 5 shows a linear relationship between these parameters, so correlations can be established as input parameters in the design of the configurations to be assessed in the following sections (see further details in the supporting information).

4.2. Annualised performance results

The technical and economic criteria are analysed on an annualised basis for 8 different cases shown in Table 4. The impact of TES is analysed from 0 to 20 h with a 5-hour step (detailed results are shown in the supporting information).

4.2.1. Capacity factor and biomass use

Capacity factor varies between 19% and 21% for No-TES base cases, up to 100% (≈ 435 GWh/year) in the full-biomass strategy (OS7), as shown in Fig. 6. The TES and biomass block specific impacts on electricity generation are more significant when they act as the only back-up and decrease as increasing the other system participation. Results show greater effects of TES in ST and biomass in PT. For instance, when TES capacity increases up to 20 h, CF increases by 36% and 46% for the PT and ST base cases, respectively.

The impact of biomass without TES varies with the operation strategy. For example, for PT with OS7 (full-biomass), CF increases up to 79%, while for OS2 (low-biomass) to 13%. Only OS7 allows delivering a firm power supply to the grid (FC ≥ 80%) at any TES capacity. These generation levels are also achieved for ST configuration in OS4, OS5 and OS6 with TES of 15–20 h.

Not surprisingly, the full-biomass strategy (OS7) obtained the lowest solar share, only reaching a mainly solar generation after 15 h of TES. The rest of the strategies had an intermediate behaviour between BC (100% solar share) and OS7. In this interval, as thermal storage increases, its effect on the solar share decreases. Nonetheless, there is a value of TES that secures solar shares over 50% for ST (≥5 h) and PT (≥10 h). OS7 is the strategy with the highest biomass use. Besides, it also has the largest biomass savings due to TES, with a potential reduction above 100 kt/year at 20 h of capacity.

Literature reports CF between 37% and 51% for CSP-biomass hybrid

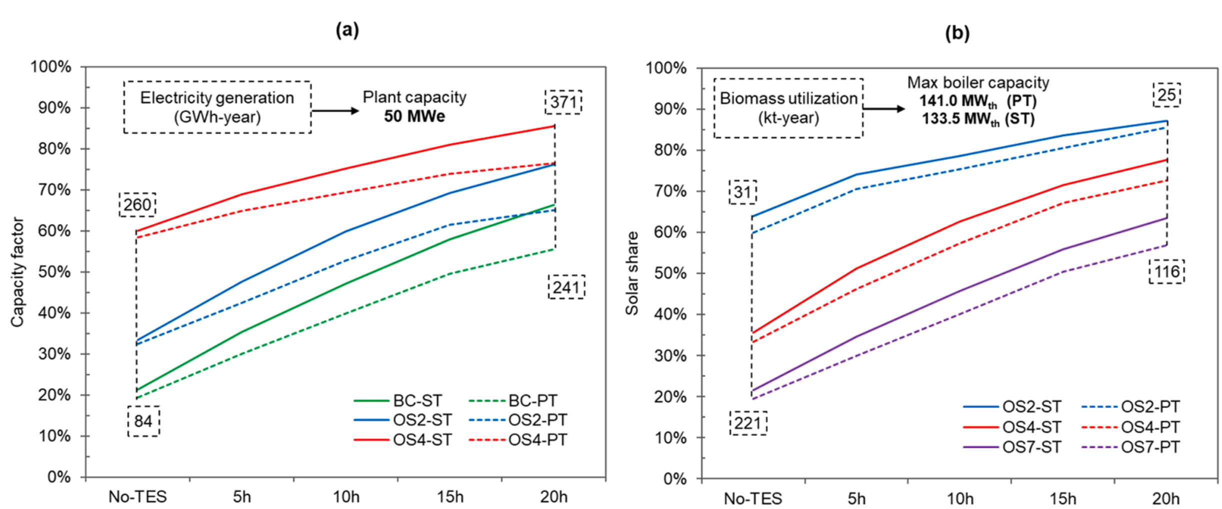


Fig. 6. (a) Capacity factor (CF) and (b) Solar share for various operation strategies at different thermal storage levels (**BC**: Base case, **OS2**: Operation strategy 2, **OS4**: Operation strategy 4, **OS7**: Operation strategy 7, **PT**: Parabolic trough; **ST**: Solar tower).

plants without TES [18,33,97] which coincides with the results obtained in this study for strategies 1 to 6 with CF between 32% and 61%. Similarly, several studies report solar shares less than 30% for CSP-biomass hybridised plants [26,98]. Including thermal storage systems, solar shares up to 88% have been reported [18].

4.2.2. Net electric efficiency

Fig. 7 shows the net electric efficiencies on an annualised basis for the most representative operating strategies. The results show that back-up participation and electric efficiency follow the same trend. OS7 with intensive use of biomass presents the highest efficiency levels, standing at around 24% without thermal storage. These increases could be even higher for biomass boilers with fixed operating strategies, where thermal efficiency is not penalised by part-load operation. TES system reduces overall electric efficiency since it replaces a portion of the biomass back-up electricity generation. However, increases in TES favour a greater convergence of the extreme values while smoothing the effect of the biomass fraction on the overall efficiency of the system.

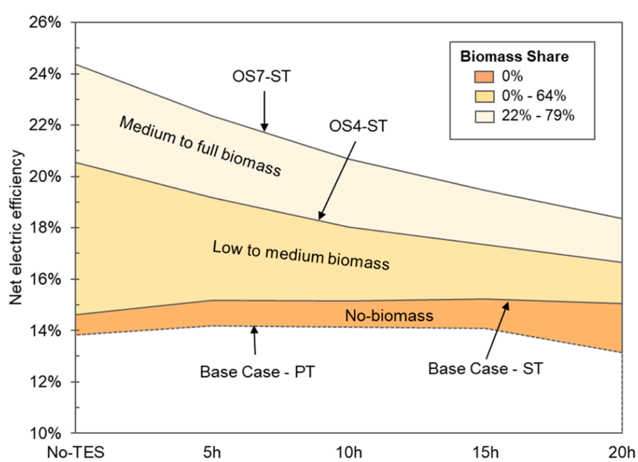


Fig. 7. Net electric efficiency for various levels of biomass utilisation in CSP hybrid configurations. (**OS4**: Operation strategy 4, **OS7**: Operation strategy 7, **PT**: Parabolic trough; **ST**: Solar tower).

Conventional CSP plants present annualised efficiencies between 14% and 15% [9,18], values in agreement to those obtained in this study for stand-alone CSP plants (base cases). Concerning CSP-biomass hybridised systems, to our knowledge, literature mainly reports peak efficiencies rather than average efficiencies on an annual basis, as it has been done in this study [18,30].

4.2.3. Capital costs

Fig. 8 shows the installation costs. Only the options without TES and 20 h are shown to highlight their impact on the specific costs (sizing) of various components (e.g., solar field, HTF). Firstly, base cases investment for PT and ST are shown, followed by the additional investments from the biomass block (25 MW_e: OS3 and OS4; 50 MW_e: rest of strategies). The specific investment for the base cases of PT and ST without TES was 3010 and 3936 USD/kW_e, respectively. Adding 20 h of TES implies an additional investment of 7577 USD/kW_e for PT and 4845 USD/kW_e for ST. For both technologies, the inclusion of the biomass block (25–50 MW_e) implies increasing investment in the range of 1170–2357 USD/kW_e. Thus, a 50 MWe biomass boiler comprises 43% of the total investment for a hybridised PT plant and 37% for ST plant, in both cases excluding TES.

The first PT-biomass hybrid plant in operation since 2012 reported a specific investment of 7786 USD/kW_e [99]. In this study, the investment required for a similar plant (OS4) was 4180 USD/kW_e, even considering the conservative approach used for the economic design. It is interesting to observe that PT plants without TES and medium use of biomass (OS4) reach higher generation levels than stand-alone plants with 20 h of storage, all this with a 61% lower investment.

4.2.4. Levelized cost of electricity

The main impact on LCOE is the biomass price. Therefore, the higher the biomass back-up share, the better the economic performance of hybrid systems, which in general means a reduced TES capacity. The full-biomass non-TES strategy shows the best LCOEs: 0.106 USD/kWh for PT and 0.116 USD/kWh for ST. On the other hand, strategies with a high installed capacity but a low biomass share (e.g., OS1 and OS2) report the highest LCOEs because the limited electricity output from the biomass block does not compensate for such large increases in its

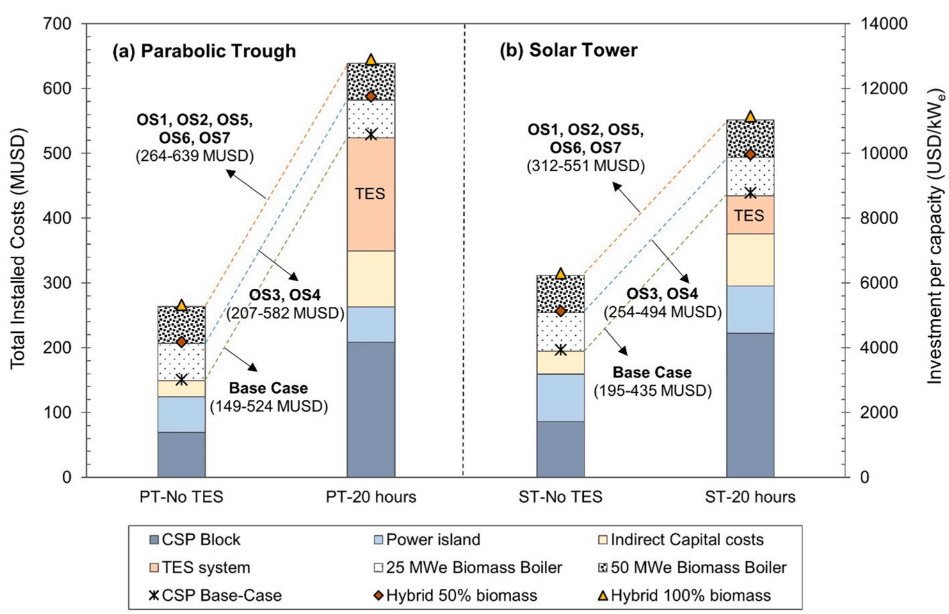


Fig. 8. Detailed installed costs and investment per capacity for a CSP-biomass plant without TES and 20 h of storage capacity: (a) Parabolic trough, (b) Solar tower. (**OS1-OS7**: Operation strategies 1–7).

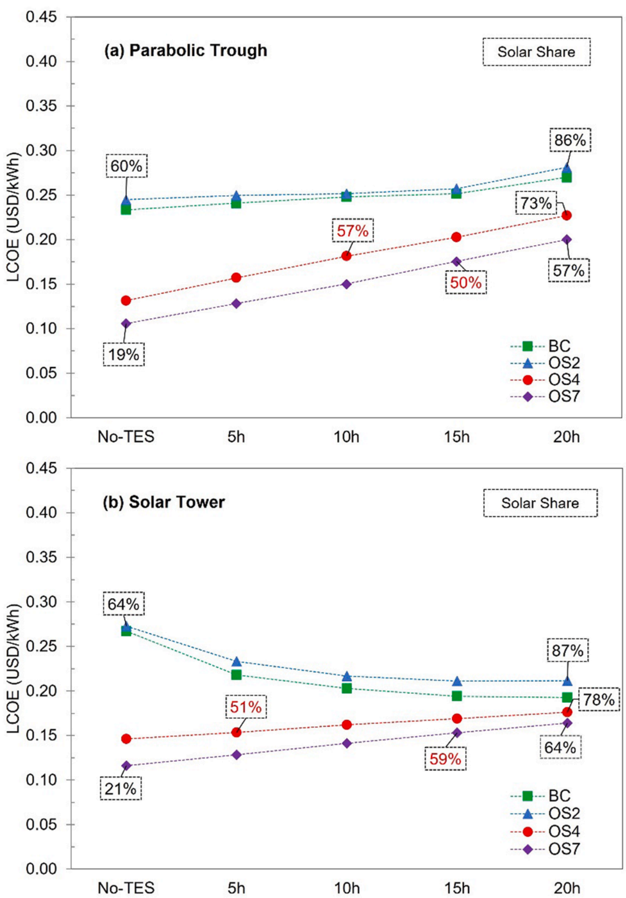


Fig. 9. LCOE for various operation strategies at different levels of thermal storage. (a) Parabolic Trough; (b) Solar Tower. (**BC:** Base case, **OS2:** Operation strategy 2, **OS4:** Operation strategy 4; **OS7:** Operation strategy 7).

installed costs. Fig. 9 shows that while higher thermal storage increases the LCOE, this effect is smoothed out for ST and strategies with low participation of the biomass back-up system (i.e., OS1 and OS2). For the cases without TES, the OS7 LCOEs were 55% and 57% lower than the base cases for PT and ST. For 20 h of TES, these differences were reduced to 26% and 14%, respectively.

Commercial ST plants with 12 to 15 h of TES present LCOEs between 0.17 and 0.24 USD/kWh [9]. A similar PT-biomass plant currently in operation in Spain has an LCOE of 0.309 USD/kWh [77,99]. The improvement in economic performance, considering the involved technologies learning curve, is included in this study through a sensitivity analysis. A reduction in PT and ST plants LCOE by 37% and 43% is expected by 2025 because of the decline in installation costs, mainly solar block components [76].

4.2.5. Sensitivity analysis

The sensitivity of the LCOE to the variation of the installation costs (±40%) and feed biomass cost (- 50, + 100%) is shown in Fig. 10 for the 8 case studies considering 0 h, 10 h, and 20 h TES capacities. Each area corresponds to LCOE variation for a set of strategies with a specific storage capacity. In all areas, the upper limit coincided with OS2 results and the lower limit with OS7; the remaining cases are located in the inner zone. Among the higher solar share operation strategies (OS2), a greater LCOE sensitivity to installed costs variation is observed. Similarly, low solar share plants (OS7) present a greater sensitivity to the variation of biomass feed costs. Even considering a more extensive range for biomass cost variation, its effect on the LCOE was considerably lower than that of the installed costs.

The inclusion of TES systems has the potential to alleviate both effects, especially for ST cases. As biomass costs and storage capacity increase, the base cases (conventional CSP plants) become increasingly attractive. As thermal storage increases, the differences between strategies sensitivities are reduced while their order of location is maintained. The areas included in the figures show the different TES effects on the LCOE, depending on the analysed technology. For all PT cases, greater storage implies a greater LCOE, while for ST, this is only true for medium to high biomass share.

4.3. Technology maturity and biomass boiler flexibility

Technological maturity for energy systems can be assessed according to the worldwide number of plants and installed capacity considering both commercial operation and commissioning. Since the two considered supporting systems in this study can work independently, their maturity is assessed separately, leaving the complexity associated with their integration as a separate factor. As part of the dedicated survey, the biomass block installed capacity and the generation profiles are discussed and rated according to the defined operating strategy.

For the operational flexibility analysis, December 2nd has been selected as the reference day, with an accumulated DNI of 6.31 kWh/m^2, representing the 50% percentile of the TMY series in Seville. For this day, the cases without TES and 10 h of capacity are analysed, as shown in Figs. 11 and 12. Operation flexibility is analysed based on the biomass boiler requirement to achieve short response times, high ramp rates, and multiple daily starts to complete the required generation profiles. Strategies with boiler sustained generation present a lower operating complexity (OS2) since steam generation is constant, allowing base-load operation. On the other hand, strategies aimed at following the CSP generation profile (OS1, OS5, OS6) require multiple daily starts and high ramp rates, which are considered to penalise their efficiency and increase their complexity.

OS3, OS4 and OS7 present a constant load operation most of the time, with multiple starts and load variations of different intensity during the day transients. The required ramp rates depending on the DNI variability. Therefore, they are considered mixed strategies in this study. Due to their lower installed capacity, OS3 and OS4 present lower operating requirements. The inclusion of large TES capacities reduces the boiler operation intensity for all operation strategies, as shown in Fig. 12.

4.4. Ranking of operational strategies

Evaluation criteria weights were obtained as a result of the pairwise comparison process. Table 6 shows greater relevance for technical and economic parameters. LCOE and CF stand out as the main criteria, with a weight of 26.1% and 16.7%, respectively. In comparison, the biomass

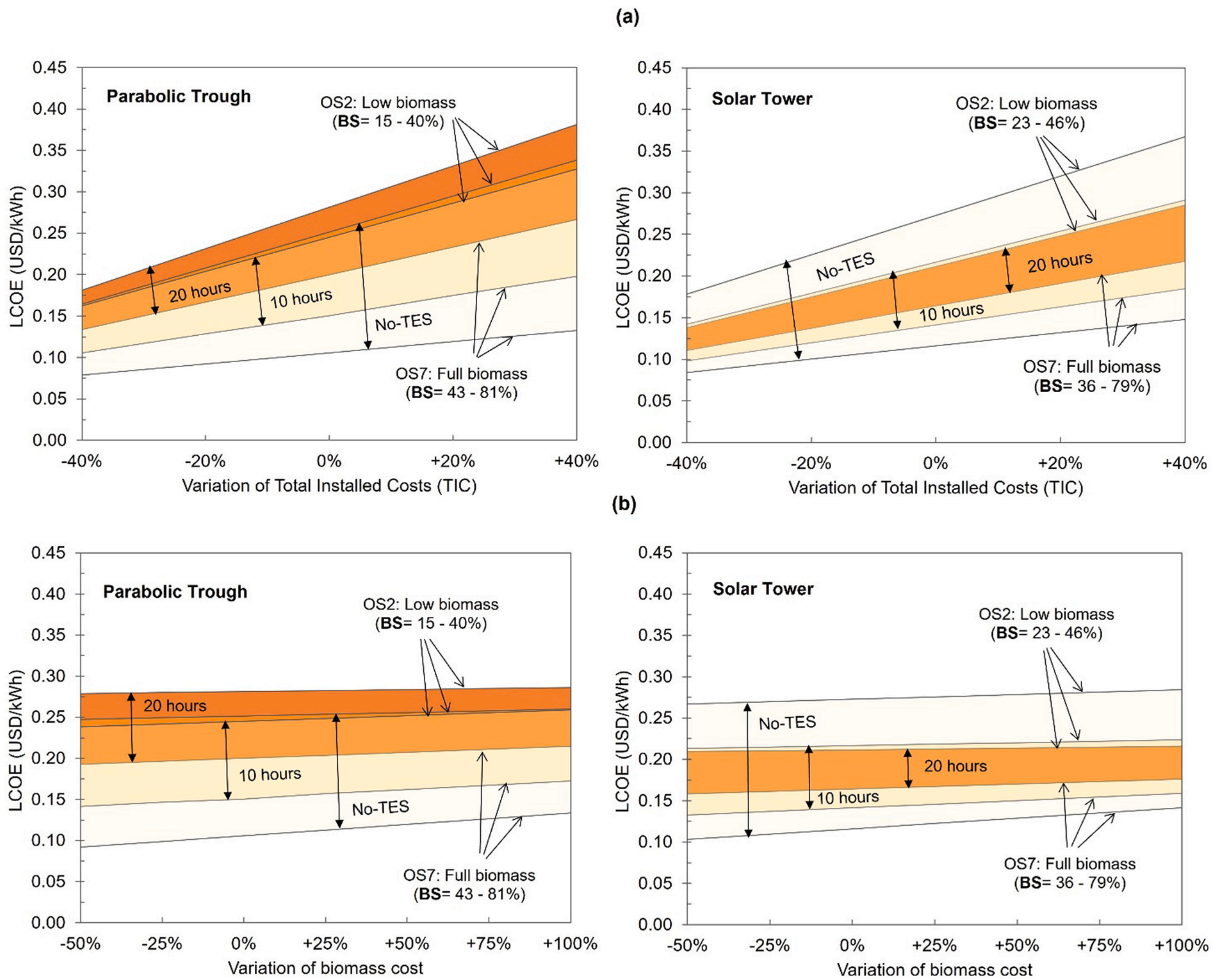


Fig. 10. LCOE sensitivity of Parabolic trough and Solar tower hybrid configurations for various operation strategies at different TES capacity levels: (a) ± 40% uncertainty in total installed costs, (b) −50%, +100% uncertainty in biomass cost. (**BS:** Biomass share, **OS2:** Operation strategy 2; **OS7:** Operation strategy 7).

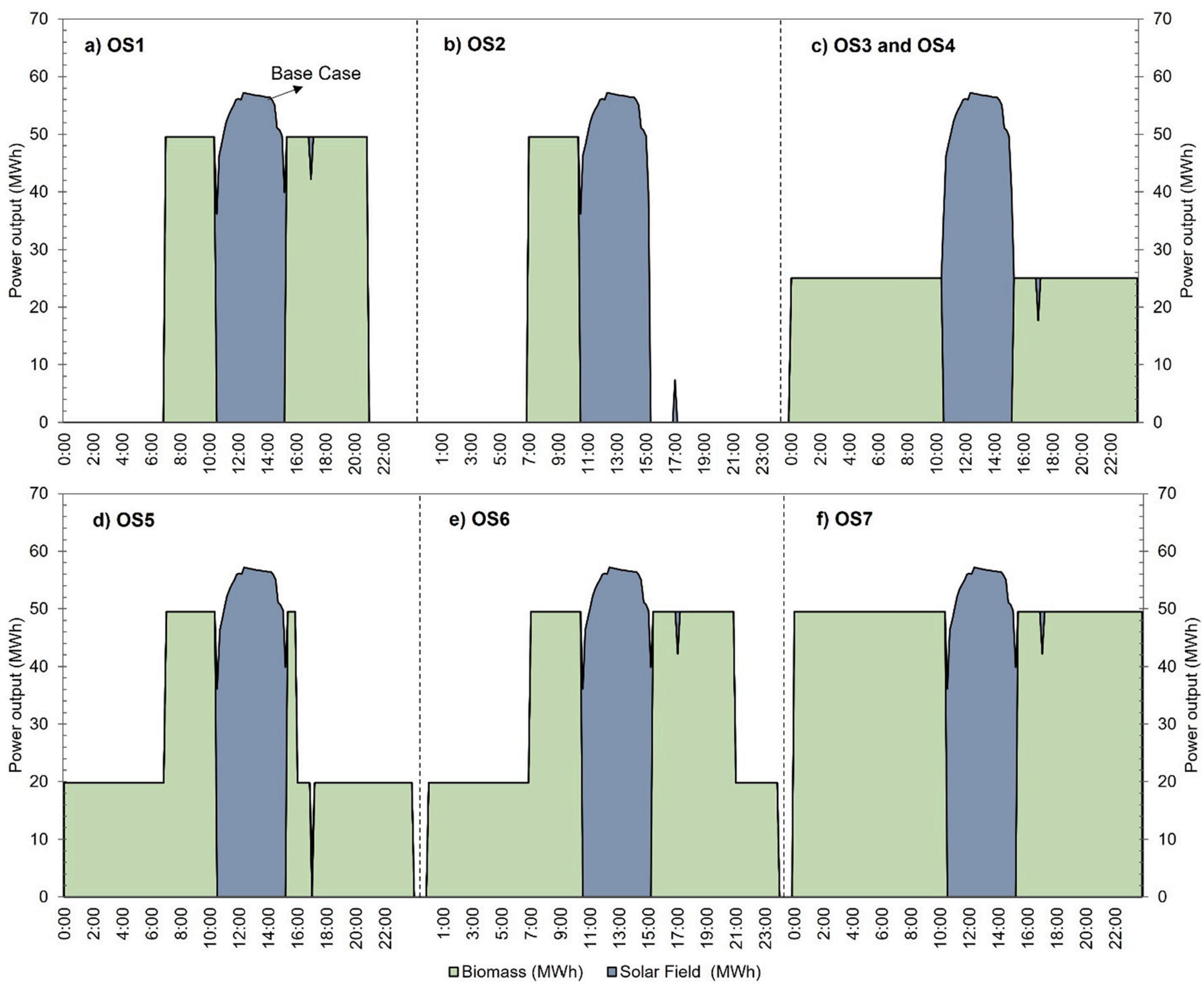


Fig. 11. Power output profile for ST-biomass plant without thermal storage (P50% day based on DNI). a) OS1, b) OS2, c) OS3 and OS4, d) OS5, e) OS6; f) OS7. (**OS1-7**: Operation strategies 1–7).

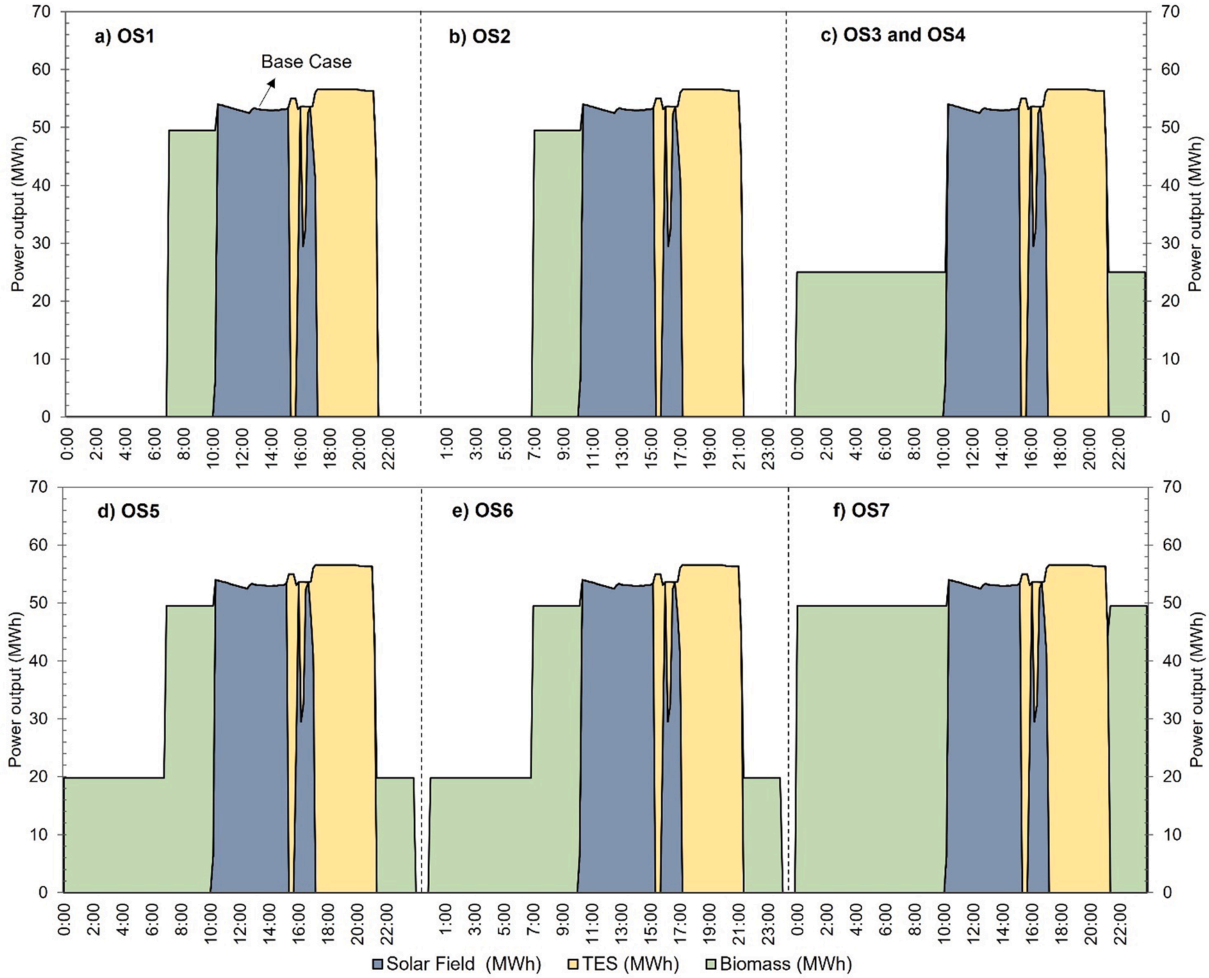


Fig. 12. Power output profile for ST-biomass plant with 10 h of TES (P50% day based on DNI). a) OS1, b) OS2, c) OS3 and OS4, d) OS5, e) OS6; f) OS7. (**OS1-7:** Operation strategies 1–7).

Table 6
Main criteria and criteria weights.

Main Criteria (MC)	MC Weights (%)	Ranking Criteria (C)	Criteria Weights (%)
MC1: Technical performance	34.9%	C1: CF	16.7%
		C2: Solar share and biomass utilisation	9.3%
		C3: Net electric efficiency	8.9%
MC2: Economic performance	47.2%	C4: LCOE	26.1%
		C5: Installed costs sensitivity	11.5%
		C6: Biomass cost sensitivity	9.6%
MC3: Operational viability	17.9%	C7: Technology maturity	13.1%
		C8: Biomass boiler flexibility	4.8%

boiler flexibility was considered the least relevant criterion with 4.8%. The consistency of the judgments expressed in the pairwise matrix was verified by obtaining a consistency ratio of 7.2%, less than the 10% limit recommended for this kind of study. The ranking of operation strategies for CSP-biomass is shown in Fig. 13. The detailed results of the evaluation of criteria, rankings of strategies by criteria and the associated scores are included in the supporting information.

Alternatives with a medium or intensive biomass share (OS3, OS4, OS5, OS6 and OS7), achieve the highest scores in criteria such as CF, net electric efficiency and LCOE. On the other hand, as the biomass share decreases (BC, OS1, OS2), the strategies present a better performance in criteria such as solar share, greater positive sensitivity to the variation of investment costs and less negative sensitivity to the variation in the biomass cost. The operational viability criteria favour strategies with less operational complexity and greater technological maturity. The base cases stand out due to their large deployment at a commercial level, OS2 because of a smoother operation of the back-up system and OS4 due to its operational similarity with the only commercial CSP-biomass plant in the world.

OS4 and OS7 were the best-scored strategies in the ranking, because of high performance in technical and economic parameters. Nevertheless, OS4 was favoured by higher solar shares and greater operational

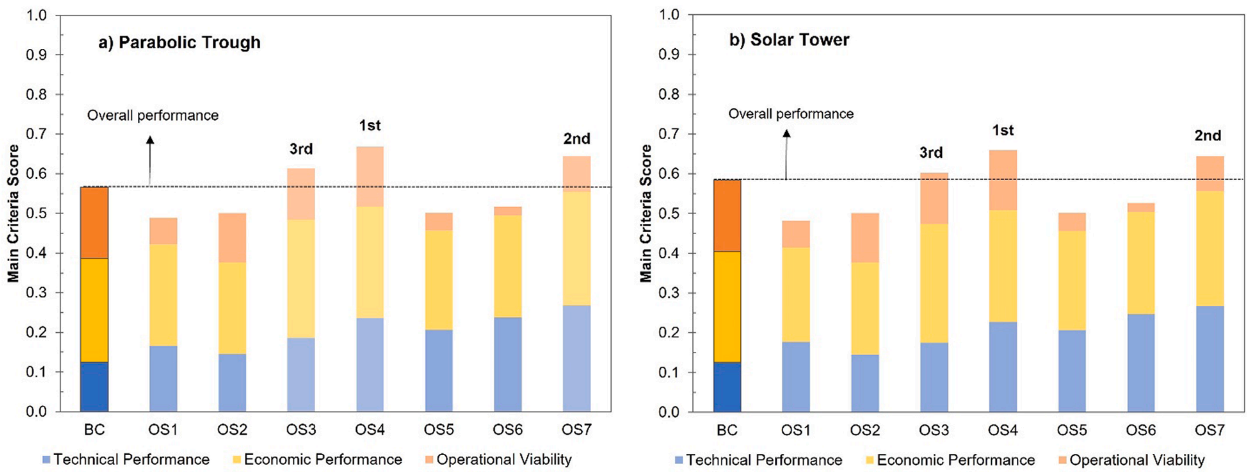


Fig. 13. Operation strategies scores by Main Criteria. a) Parabolic Trough; b) Solar Tower. **BC:** Base case, **OS1-7:** Operation strategies 1–7.

viability, thanks to its lower installed capacity and lower operating intensity on the biomass boiler, especially at large TES capacities. OS3 and BC were placed with a balanced performance in most of the criteria, highlighting for BC the highest operational viability and the best economic performance of OS3 among all the cases. OS4, OS7 and OS3 were the CSP-biomass hybridised cases in which a higher overall performance is observed compared to a conventional CSP plant (BC).

OS6, OS5, OS2 and OS1 occupy the last positions in the ranking. For these operation strategies, hybridised plants achieve lower performance than conventional CSP plants (BC). OS6 and OS5 present a rather positive performance in technical criteria. However, they are penalised in operational viability, because of their following load mode. All these strategies, especially OS2 and OS1 score low in economic performance, because of the investment associated with a high-capacity biomass boiler and the added generation, which does not justify its high installation costs.

5. Conclusions

Two configurations of concentrated solar power (CSP) plants with a dual supporting system (biomass back-up and thermal energy storage, TES) were modelled and assessed with 7 operation strategies (OS1-7). Additionally, base cases without biomass back-up system were assessed for comparison. Relevant synergies were identified between solar and non-solar back-up systems for a 100% renewable generation, considering technical, economic, and operational performance. The main findings are summarised below:

- The biomass supporting system contributes to increasing the capacity factor (CF) of a conventional CSP plant ($19\% > CF \leq 21\%$), bringing it closer to a base-load plant. Firm energy supply ($CF \geq 80\%$) can be achieved for biomass blocks with the same installed capacity as that of the CSP plant and a full-biomass strategy (OS7). However, this is also feasible for medium biomass strategies (OS4, OS5, OS6) provided that it is combined with large TES capacities (≥15 h),
- The thermal storage supporting system (TES) increases the solar share of the hybridised plant, mainly for biomass-intensive strategies. Nevertheless, except for the full-biomass strategy (OS7), all cases reached a solar share above 50% with 5 h of TES. Up to 51% of biomass reduction can be achieved at very large TES capacities (20 h). A higher TES share also implies a reduction in the annualised net electric efficiency of up to 6%.
- The higher the biomass share, the lower the levelized cost of electricity (LCOE) because of the lower operating cost of the biomass system compared to TES. This effect is favoured in the strategies aiming at base-load operation. OS7 without TES achieved the best economic performance, with LCOEs of 0.106 USD/kWh for parabolic trough (PT) and 0.116 USD/kWh for solar tower (ST). Moreover, very large TES capacities (20 h) implies an increase in generation costs in hybridised plants up to 89% for PT and 41% for ST.
- Medium and full biomass strategies (OS4 and OS7, respectively) ranked among the best strategies. OS7 performs better on most of the considered technical and economic criteria. However, the smaller size of the biomass supporting system in OS4 favours the solar share, lowering the uncertainty of biomass supply while improving its operational viability. On the contrary, strategies with an extensive biomass support system and limited operation (i.e., OS1, OS2) achieve the worst performance because the limited additional generation to the CSP plant did not balance the additional capital investment.

To sum up, biomass-intensive operation strategies achieve firm energy supplies, resulting in the lowest generation cost and highest electric efficiency. However, a high biomass load increases the risks associated with supply. The interest of having a dual supporting system (biomass + TES) lies on the possibility of overcoming these limitations while ensuring a firm supply at a reasonable cost (e.g., 0.15 USD/kWh) with a high solar share (>50%). Therefore, the proposed dual supporting system can be particularly interesting for locations where solar and biomass resources are moderately available.

CRediT authorship contribution statement

R.E. Gutiérrez: Conceptualization, Methodology, Data curation, Writing – original draft. **P. Haro:** Conceptualization, Methodology, Supervision, Writing – review & editing. **A. Gómez-Barea:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the Spanish National Plan I+D+i (Project CTM2016-78089-R) and the Junta de Andalucía through the project P18-RT-4512 (Co-funded by European Regional Development Fund/European Social Fund “A way to make Europe”).

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2021.117600.

References

[1] IRENA. Global Energy Transformation: A Roadmap to 2050 (2019 Edition). Abu Dhabi: International Renewable Energy Agency; 2019.
[2] Gielen D, Boshell F, Saygin D, Bazilian MD, Wagner N, Gorini R. The role of renewable energy in the global energy transformation. Energy Strateg Rev 2019;24:38–50. https://doi.org/10.1016/j.esr.2019.01.006.
[3] IEA. Perspectives for the Energy Transition: The Role of Energy Efficiency; 2018.
[4] LAZARD. Lazard's levelized cost of energy analysis — version 13.0. 2019.
[5] Duan Jun, van Kooten G Cornelis, Liu Xuan. Resources, Conservation & Recycling Renewable electricity grids, battery storage and missing money. Resour Conserv Recycl 2020;161:105001. https://doi.org/10.1016/j.resconrec.2020.105001.
[6] Akbari Hoda, Browne Maria C, Ortega Anita, Huang Ming Jun, Hewitt Neil J, Norton Brian, et al. Efficient energy storage technologies for photovoltaic systems. Sol Energy 2019;192:144–68. https://doi.org/10.1016/j.solener.2018.03.052.
[7] Peterseim JH, White S, Tadros A, Hellwig U. Concentrated solar power hybrid plants, which technologies are best suited for hybridisation? Renew Energy 2013;57:520–32. https://doi.org/10.1016/j.renene.2013.02.014.
[8] Hussain CMI, Norton B, Duffy A. Technological assessment of different solar-biomass systems for hybrid power generation in Europe. Renew Sustain Energy Rev 2017;68:1115–29. https://doi.org/10.1016/j.rser.2016.08.016.
[9] Islam T, Huda N, Abdullah AB, Saidur R. A comprehensive review of state-of-the-art concentrating solar power (CSP) technologies: current status and research trends. Renew Sustain Energy Rev 2018;91:987–1018. https://doi.org/10.1016/j.rser.2018.04.097.
[10] Peterseim JH, Tadros A, Hellwig U, White S. Increasing the efficiency of parabolic trough plants using thermal oil through external superheating with biomass. Energy Convers Manag 2014;77:784–93. https://doi.org/10.1016/j.enconman.2013.10.022.
[11] Kuravi Sarada, Trahan Jamie, Goswami D Yogi, Rahman Muhammad M, Stefanakos Elias K. Thermal energy storage technologies and systems for concentrating solar power plants. Prog Energy Combust Sci 2013;39(4):285–319. https://doi.org/10.1016/j.pecs.2013.02.001.
[12] Baharoon DA, Rahman HA, Omar WZW, Fadhl SO. Historical development of concentrating solar power technologies to generate clean electricity efficiently – a review. Renew Sustain Energy Rev 2015;41:996–1027. https://doi.org/10.1016/j.rser.2014.09.008.
[13] Hall J Peter. Sustainable production of forest biomass for energy. For Chron 2002;78(3):391–6. https://doi.org/10.5558/tfc78391-3.
[14] Saidur R, Abdelaziz EA, Demirbas A, Hossain MS, Mekhilef S. A review on biomass as a fuel for boilers. Renew Sustain Energy Rev 2011;15(5):2262–89. https://doi.org/10.1016/j.rser.2011.02.015.
[15] Ahtikoski Anssi, Heikkilä Jani, Alenius Virpi, Siren Matti. Economic viability of utilizing biomass energy from young stands-the case of Finland. Biomass Bioenergy 2008;32(11):988–96. https://doi.org/10.1016/j.biombioe.2008.01.022.
[16] Shabani N, Akhtari S, Sowlati T. Value chain optimization of forest biomass for bioenergy production: a review. Renew Sustain Energy Rev 2013;23:299–311. https://doi.org/10.1016/j.rser.2013.03.005.
[17] Asadullah M. Barriers of commercial power generation using biomass gasification gas: a review. Renew Sustain Energy Rev 2014;29:201–15. https://doi.org/10.1016/j.rser.2013.08.074.
[18] Pramanik S, Ravikrishna RV. A review of concentrated solar power hybrid technologies. Appl Therm Eng 2017;127:602–37. https://doi.org/10.1016/j.applthermaleng.2017.08.038.
[19] Powell KM, Rashid K, Ellingwood K, Tuttle J, Iverson BD. Hybrid concentrated solar thermal power systems: a review. Renew Sustain Energy Rev 2017;80:215–37. https://doi.org/10.1016/j.rser.2017.05.067.
[20] German Aerospace Center (DLR). Concentrating solar power for the Mediterranean region. Stuttgart; 2005.
[21] Abdelhady S, Borello D, Tortora E. Design of a small scale stand-alone solar thermal co-generation plant for an isolated region in Egypt. Energy Convers Manag 2014;88:872–82. https://doi.org/10.1016/j.enconman.2014.08.066.
[22] Pantaleo AM, Camporeale SM, Sorrentino A, Miliozzi A, Shah N, Markides CN, et al. Hybrid solar-biomass combined Brayton/organic Rankine-cycle plants integrated with thermal storage: techno-economic feasibility in selected Mediterranean areas. Renew Energy 2020;147:2913–31. https://doi.org/10.1016/j.renene.2018.08.022.
[23] Poghosyan V, Hassan MI. Techno-economic assessment of substituting natural gas based heater with thermal energy storage system in parabolic trough concentrated solar power plant. Renew Energy 2015;75:152–64. https://doi.org/10.1016/j.renene.2014.09.025.
[24] Geissbühler L, Mathur A, Mularczyk A, Haselbacher A. An assessment of thermocline-control methods for packed-bed thermal- energy storage in CSP plants, Part 2: Assessment strategy and results. Sol Energy 2019;178:351–64. https://doi.org/10.1016/j.solener.2018.12.016.
[25] Pantaleo AM, Camporeale SM, Miliozzi A, Russo V, Shah N, Markides CN. Novel hybrid CSP-biomass CHP for flexible generation: thermo-economic analysis and profitability assessment. Appl Energy 2017;204:994–1006. https://doi.org/10.1016/j.apenergy.2017.05.019.
[26] Peterseim JH, Tadros A, White S, Hellwig U, Landler J, Galang K. Solar tower-biomass hybrid plants - maximizing plant performance. Energy Procedia 2013;49:1197–206. https://doi.org/10.1016/j.egypro.2014.03.129.
[27] Morell D. CSP BORGES The World's First CSP plant hybridized with biomass. CSP Today USA 2012 - 6th Conc Sol Therm Power Conf; 2012.
[28] 16.6MWth CSP for combined heat and power generation, Denmark n.d. https://www.aalborgcsp.com/projects/166mwth-csp-for-combined-heat-and-power-generation-denmark/ [accessed September 28, 2020].
[29] Aalborg CSP-Brønderslev CSP with ORC project | Concentrating Solar Power Projects n.d. https://solarpaces.nrel.gov/aalborg-csp-bronderslev-csp-orc-project [accessed September 28, 2020].
[30] Peterseim JH, White S, Tadros A, Hellwig U. Concentrating solar power hybrid plants - Enabling cost effective synergies. Renew Energy 2014;67:178–85. https://doi.org/10.1016/j.renene.2013.11.037.
[31] Peterseim JH, Herr A, Miller S, White S, O'Connell DA. Concentrating solar power/alternative fuel hybrid plants: annual electricity potential and ideal areas in Australia. Energy 2014;68:698–711. https://doi.org/10.1016/j.energy.2014.02.068.
[32] Peterseim JH, Hellwig U, Tadros A, White S. Hybridisation optimization of concentrating solar thermal and biomass power generation facilities. Sol Energy 2014;99:203–14. https://doi.org/10.1016/j.solener.2013.10.041.
[33] Soria R, Portugal-pereira J, Szklo A, Milani R, Schaeffer R. Hybrid concentrated solar power (CSP) – biomass plants in a semiarid region: a strategy for CSP deployment in Brazil. Energy Policy 2015;86:57–72. https://doi.org/10.1016/j.enpol.2015.06.028.
[34] Milani R, Szklo A, Hoffmann BS. Hybridization of concentrated solar power with biomass gasification in Brazil's semiarid region. Energy Convers Manag 2017;143:522–37. https://doi.org/10.1016/j.enconman.2017.04.015.
[35] Soria Rafael, Lucena André FP, Tomaschek Jan, Fichter Tobias, Haasz Thomas, Szklo Alexandre, et al. Modelling concentrated solar power (CSP) in the Brazilian energy system: a soft-linked model coupling approach. Energy 2016;116:265–80. https://doi.org/10.1016/j.energy.2016.09.080.
[36] Servert J, San Miguel G, López D. Hybrid solar - biomass plants for power generation. GlobalNEST 2012;13:266–76.
[37] Nixon JD, Dey PK, Davies PA. The feasibility of hybrid solar-biomass power plants in India. Energy 2012;46(1):541–54. https://doi.org/10.1016/j.energy.2012.07.058.
[38] Sahoo U, Kumar R, Pant PC, Chaudhary R. Resource assessment for hybrid solar-biomass power plant and its thermodynamic evaluation in India. Sol Energy 2016;139:47–57. https://doi.org/10.1016/j.solener.2016.09.025.
[39] da Fonseca MB, Poganietz WR, Gehrmann HJ. Environmental and economic analysis of SolComBio concept for sustainable energy supply in remote regions. Appl Energy 2014;135:666–74. https://doi.org/10.1016/j.apenergy.2014.07.057.
[40] Mohammadi K, Khorasanizadeh H. The potential and deployment viability of concentrated solar power (CSP) in Iran. Energy Strateg Rev 2019;24:358–69. https://doi.org/10.1016/j.esr.2019.04.008.
[41] Srinivas T, Reddy BV. Hybrid solar-biomass power plant without energy storage. Case Stud Therm Eng 2014;2:75–81. https://doi.org/10.1016/j.csite.2013.12.004.
[42] Bai Z, Liu Q, Lei J, Wang X, Sun J, Jin H. Thermodynamic evaluation of a novel solar-biomass hybrid power generation system. Energy Convers Manag 2017;142:296–306. https://doi.org/10.1016/j.enconman.2017.03.028.
[43] Soares J, Oliveira AC. Numerical simulation of a hybrid concentrated solar power/biomass mini power plant. Appl Therm Eng 2017;111:1378–86. https://doi.org/10.1016/j.applthermaleng.2016.06.180.
[44] Oyekale J, Heberle F, Petrollese M, Brüggemann D, Cau G. Biomass retrofit for existing solar organic Rankine cycle power plants: conceptual hybridization strategy and techno-economic assessment. Energy Convers Manag 2019;196:831–45. https://doi.org/10.1016/j.enconman.2019.06.064.
[45] Petrollese M, Cocco D. Techno-economic assessment of hybrid CSP-biogas power plants. Renew Energy 2020;155:420–31. https://doi.org/10.1016/j.renene.2020.03.106.
[46] Hussain CM Iftekhar, Norton Brian, Duffy Aidan. Comparison of hybridizing options for solar heat, biomass and heat storage for electricity generation in Spain. Energy Convers Manag 2020;222:113231. https://doi.org/10.1016/j.enconman.2020.113231.
[47] Suárez-Almeida M, Gómez-Barea A, Ghoniem AF, Nilsson S, Leckner B. Modeling the transient response of a fluidized-bed biomass gasifier. Fuel 2020;274:117226. https://doi.org/10.1016/j.fuel.2020.117226.
[48] Barea JM, Ordoñez I. Análisis cualitativo de diversas posibilidades de configuración en una central termosolar híbrida. 2012.
[49] Liu Ming, Steven Tay NH, Bell Stuart, Belusko Martin, Jacob Rhys, Will Geoffrey, et al. Review on concentrating solar power plants and new developments in high temperature thermal energy storage technologies. Renew Sustain Energy Rev 2016;53:1411–32. https://doi.org/10.1016/j.rser.2015.09.026.
[50] Moreno-Tejera S, Silva-Pérez MA, Lillo-Bravo I, Ramírez-Santigosa L. Solar resource assessment in Seville, Spain. Statistical characterisation of solar radiation at different time resolutions. Sol Energy 2016;132:430–41. https://doi.org/10.1016/j.solener.2016.03.032.
[51] Garcia Garrido S. Centrales Termosolares CCP Volumen 1: Fundamentos Técnicos, Principales Equipos y Sistemas; 2013.
[52] Amelio M, Beraldi P, Ferraro V, Scornaienchi M, Rovense F. Optimization of heliostat field in a thermal solar power plant with an unfired closed Joule-Brayton cycle. Energy Proc 2016;101:472–9. https://doi.org/10.1016/j.egypro.2016.11.060.
[53] Montes MJ, Rovira A, Muñoz M, Martínez-Val JM. Performance analysis of an Integrated Solar Combined Cycle using Direct Steam Generation in parabolic

trough collectors. Appl Energy 2011;88(9):3228–38. https://doi.org/10.1016/j.apenergy.2011.03.038.
[54] Schenk H, Hirsch T, Feldhoff JF, Wittmann M. Energetic comparison of linear Fresnel and parabolic trough collector systems. J Sol Energy Eng Trans ASME 2014;136. https://doi.org/10.1115/1.4027766.
[55] Haro P, Ollero P, Villanueva Perales AL, Gómez-Barea A. Thermochemical biorefinery based on dimethyl ether as intermediate: Technoeconomic assessment. Appl Energy 2013;102:950–61. https://doi.org/10.1016/j.apenergy.2012.09.051.
[56] Mapas de recursos solares y datos GIS para más de 180 países | Solargis n.d. https://solargis.com/es/maps-and-gis-data/download/spain [accessed March 5, 2021].
[57] Martín H, De La Hoz J, Velasco G, Castilla M, García De Vicuña JL. Promotion of concentrating solar thermal power (CSP) in Spain: performance analysis of the period 1998–2013. Renew Sustain Energy Rev 2015;50:1052–68. https://doi.org/10.1016/j.rser.2015.05.062.
[58] Searcy Erin, Flynn Peter. The impact of biomass availability and processing cost on optimum size and processing technology selection. Appl Biochem Biotechnol 2009;154(1-3):92–107. https://doi.org/10.1007/s12010-008-8407-9.
[59] SolarPACES. Andasol-2 | Concentrating Solar Power Projects n.d. https://solarpaces.nrel.gov/andasol-2 [accessed January 14, 2020].
[60] SolarPACES. Gemasolar Thermosolar Plant | Concentrating Solar Power Projects n.d. https://solarpaces.nrel.gov/gemasolar-thermosolar-plant [accessed January 14, 2020].
[61] Amadei CA, Allesina G, Tartarini P, Yuting W. Simulation of GEMASOLAR-based solar tower plants for the Chinese energy market: influence of plant downsizing and location change. Renew Energy 2013;55:366–73. https://doi.org/10.1016/j.renene.2012.12.022.
[62] Geyer M, Osuna R, Esteban A, Schiel W, Schweitzer A, Zarza E, et al. EURO TROUGH - Parabolic Trough Collector Efficient Solar Power Generation. In: 11th SolarPACES Int Symp Conc Sol Power Chem Energy Technol Zurich, Switz; 2002. p. 1–7.
[63] Burkholder F, Kutscher CF. Heat loss testing of Schott's 2008 PTR70 parabolic trough receiver; 2009.
[64] Hirbodi Kamran, Enjavi-Arsanjani Mahboubeh, Yaghoubi Mahmood. Techno-economic assessment and environmental impact of concentrating solar power plants in Iran. Renew Sustain Energy Rev 2020;120:109642. https://doi.org/10.1016/j.rser.2019.109642.
[65] National Renewable Energy Laboratory. System advisor model (SAM); 2019.
[66] SolarPILOT Released as Open Source; Tool Used to Optimize Solar Power Towers | News | NREL n.d. https://www.nrel.gov/news/program/2018/solarpilot-released-open-source.html? [accessed March 31, 2021].
[67] Franchini G, Perdichizzi A, Ravelli S, Barigozzi G. A comparative study between parabolic trough and solar tower technologies in Solar Rankine Cycle and Integrated Solar Combined Cycle plants. Sol Energy 2013;98:302–14. https://doi.org/10.1016/j.solener.2013.09.033.
[68] Kumar A, Kumar N, Baredar P, Shukla A. A review on biomass energy resources, potential, conversion and policy in India. Renew Sustain Energy Rev 2015;45:530–9. https://doi.org/10.1016/j.rser.2015.02.007.
[69] FuturEnergy. Biollano: a 50 MW biomass plant in Puertollano owned by ENCE 2020:23–35. https://futurenergyweb.es/wp-content/uploads/2020/05/FuturEnergy_Marzo_2020-23-35-biollano.pdf.
[70] Kost C, Flath CM, Möst D. Concentrating solar power plant investment and operation decisions under different price and support mechanisms. Energy Policy 2013;61:238–48. https://doi.org/10.1016/j.enpol.2013.05.040.
[71] Wagner SJ, Rubin ES. Economic implications of thermal energy storage for concentrated solar thermal power. Renew Energy 2014;61:81–95. https://doi.org/10.1016/j.renene.2012.08.013.
[72] Ezeanya Emeka K, Massiha Gholam H, Simon William E, Raush Jonathan R, Chambers Terrence L, Mago Pedro. System advisor model (SAM) simulation modelling of a concentrating solar thermal power plant with comparison to actual performance data. Cogent Eng 2018;5(1):1524051. https://doi.org/10.1080/23311916.2018.1524051.
[73] Kurup P, Turchi CS. Parabolic Trough Collector Cost Update for the System Advisor Model (SAM). Tech Rep NREL/TP-6A20-65228 2015:1–40.
[74] Turchi CS, Heath GA. Molten Salt Power Tower Cost Model for the System Advisor Model (SAM). Tech Rep NREL/TP-5500-57625 2013:1–53.
[75] Turchi C. Concentrating Solar Power : Current Cost and Future Directions. Oral Present; 2017.
[76] Dieckmann S, Dersch J, Giuliano S, Puppe M, Lüpfert E, Hennecke K, et al. LCOE reduction potential of parabolic trough and solar tower CSP technology until 2025. AIP Conf Proc 2017;160004. https://doi.org/10.1063/1.4984538.
[77] European Central Bank. ECB euro reference exchange rate: US dollar (USD) n.d. https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html [accessed May 12, 2020].
[78] U.S. Environmental Protection Agency Combined Heat and Power Partnership. Biomass Combined Heat and Power Catalog of Technologies. Biomass CHP Cat 2007:122. https://doi.org/10.1126/science.214.4523.864.
[79] Bain WP, Downing M, Perlack RLA. Biopower Technical Assessment: State of the Industry and the Technology. National Renewable Energy Laboratory; 2003.
[80] Valoración Fincas. What are the agricultural land prices in Spain? Moved up 3,2% on 2015. 2016. https://valoracionfincas.es/land-prices-in-spain/ [accessed May 12, 2020].
[81] Fichter T, Soria R, Szklo A, Schaeffer R, Lucena AFP. Assessing the potential role of concentrated solar power (CSP) for the northeast power system of Brazil using a detailed power system model. Energy 2017;121:695–715. https://doi.org/10.1016/j.energy.2017.01.012.
[82] Izquierdo Salvador, Montañés Carlos, Dopazo César, Fueyo Norberto. Analysis of CSP plants for the definition of energy policies: the influence on electricity cost of solar multiples, capacity factors and energy storage. Energy Policy 2010;38(10):6215–21. https://doi.org/10.1016/j.enpol.2010.06.009.
[83] Liu Q, Bai Z, Wang X, Lei J, Jin H. Investigation of thermodynamic performances for two solar-biomass hybrid combined cycle power generation systems. Energy Convers Manag 2016;122:252–62. https://doi.org/10.1016/j.enconman.2016.05.080.
[84] Bonyadi N, Johnson E, Baker D. Technoeconomic and exergy analysis of a solar geothermal hybrid electric power plant using a novel combined cycle. Energy Convers Manag 2018;156:542–54. https://doi.org/10.1016/j.enconman.2017.11.052.
[85] Giostri A, Binotti M, Sterpos C, Lozza G. Small scale solar tower coupled with micro gas turbine. Renew Energy 2020;147:570–83. https://doi.org/10.1016/j.renene.2019.09.013.
[86] Achkari O, El Fadar A. Latest developments on TES and CSP technologies – energy and environmental issues, applications and research trends. Appl Therm Eng 2020;167:114806. https://doi.org/10.1016/j.applthermaleng.2019.114806.
[87] Yilmazoglu MZ. Effects of the selection of heat transfer fluid and condenser type on the performance of a solar thermal power plant with technoeconomic approach. Energy Convers Manag 2016;111:271–8. https://doi.org/10.1016/j.enconman.2015.12.068.
[88] Mardani A, Jusoh A, Zavadskas EK, Cavallaro F, Khalifah Z. Sustainable and renewable Energy: an overview of the application of multiple criteria decision making techniques and approaches. Sustain 2015;7:13947–84. https://doi.org/10.3390/su71013947.
[89] Tahri M, Hakdaoui M, Maanan M. The evaluation of solar farm locations applying Geographic Information System and Multi-Criteria Decision-Making methods: case study in southern Morocco. Renew Sustain Energy Rev 2015;51:1354–62. https://doi.org/10.1016/j.rser.2015.07.054.
[90] Doljak D, Stanojević G. Evaluation of natural conditions for site selection of ground-mounted photovoltaic power plants in Serbia. Energy 2017;127:291–300. https://doi.org/10.1016/j.energy.2017.03.140.
[91] Aly A, Jensen SS, Pedersen AB. Solar power potential of Tanzania: Identifying CSP and PV hot spots through a GIS multicriteria decision making analysis. Renew Energy 2017;113:159–75. https://doi.org/10.1016/j.renene.2017.05.077.
[92] Waewsak Jompob, Ali Shahid, Natee Warut, Kongruang Chuleerat, Chancham Chana, Gagnon Yves. Assessment of hybrid, firm renewable energy-based power plants: Application in the southernmost region of Thailand. Renew Sustain Energy Rev 2020;130:109953. https://doi.org/10.1016/j.rser.2020.109953.
[93] Vargas Luis G. An overview of the analytic hierarchy process and its applications. Eur J Oper Res 1990;48(1):2–8. https://doi.org/10.1016/0377-2217(90)90056-H.
[94] Saaty Thomas L. How to make a decision: the analytic hierarchy process. Eur J Oper Res 1990;48(1):9–26. https://doi.org/10.1016/0377-2217(90)90057-I.
[95] Sharma C, Sharma AK, Mullick SC, Kandpal TC. Identifying optimal combinations of design for DNI, solar multiple and storage hours for parabolic trough power plants for Niche Locations in India. Energy Procedia 2015;79:61–6. https://doi.org/10.1016/j.egypro.2015.11.478.
[96] SolarPACES. Atacama-1 | Concentrating Solar Power Projects n.d. https://solarpaces.nrel.gov/atacama-1 [accessed November 20, 2020].
[97] Suresh NS, Thirumalai NC, Dasappa S. Modeling and analysis of solar thermal and biomass hybrid power plants. Appl Therm Eng 2019;160:114121. https://doi.org/10.1016/j.applthermaleng.2019.114121.
[98] Soares J, Oliveira AC, Dieckmann S, Krüger D, Orioli F. Evaluation of the performance of hybrid CSP/ biomass power plants. Int J Low-Carbon Technol 2018;13:380–7. https://doi.org/10.1093/ijlct/cty046.
[99] SolarPACEs. Borges Termosolar | Concentrating Solar Power Projects n.d. https://solarpaces.nrel.gov/borges-termosolar [accessed November 10, 2020].