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Biomass–solar Thermal Hybridization using Carnot Batteries for s-CO_2 Brayton Cycles

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Abstract. Carnot batteries represent state-of-the-art technology in the fields of thermal energy storage and dispatchable electricity generation. The thermal energy usually comes from solar thermal power plants. The present study analyzes and optimizes a hybrid biomass–solar thermal central tower power plant coupled with a carbon dioxide cycle in a supercritical state and thermal energy storage, known as a Carnot battery system. Thermal and economic optimization were carried out for the power cycle, thermal storage, biomass, and the power plant's main parameters to obtain the current available minimum levelized cost of energy, LCOE.

INTRODUCTION

Current global climate conditions require the implementation of electricity generation technologies that are free of greenhouse gas emissions. Renewable energies appear to be an alternative to null (or near neutral) generation of carbon dioxide (CO_2). However, there are many challenges to harnessing and storing renewable energy. The biggest problem can be unmanageable power generation.

Nonetheless, there are some promising methods. Perhaps the most obvious is the biomass plant, which allows the burning of biomass fuel. However, in such plants, working with high electrical power (i.e., >30 MW) is very complicated because biomass resources are not sufficiently abundant to supply a plant with enough capacity and tend to be expensive. Another alternative is the solar thermal power plant. In particular, such plants can easily be coupled with thermal storage systems to develop well-dimensioned modality. In addition, they can be operated for up to 24 h with controllable electricity generation, and with zero fuel cost. However, it requires constant input of solar radiation, and implementing a thermal storage system can make the installation considerably more expensive.

Considering the advantages and disadvantages of each of these technologies, hybridization between the two is of particular interest. Hybridization makes it possible to reduce the amount of biomass necessary to operate a plant while reducing its size, and thus also its cost. In this way, when there is little solar radiation, biomass is burned to make up for the lack of energy.

However, both of these technologies, being thermal, require a power cycle that transforms the thermal energy into electrical energy. Conventionally, thermal power plants employ Rankine steam cycles. In this work, we describe an alternative method, namely, the use of a supercritical CO_2 Brayton power cycle, which shows excellent performance at a comparatively lower cost.

Several studies have analyzed solar–biomass hybridization systems, including solar tower–solid biomass plants with a Rankine cycle [1], parabolic trough–biomass gasification plants with a combined cycle [2], and solar tower–solid biomass plants with no thermal storage but with cascaded supercritical CO_2 cycles [3]. Herein, we analyze a solar

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tower–solid biomass plants with only one supercritical CO_2 cycle and a thermal storage system, configuring the so-called "Carnot battery" [4].

OBJECTIVES

The following objectives have been defined:

- Given that the plant will operate with a supercritical CO_2 power cycle, something new and unconventional, it is necessary to carry out an exhaustive study of this technology and design and optimize different configurations.
- For thermal energy generation, it is necessary to design the biomass and solar thermal groups and thermal storage.
- The final optimization process of the plant is carried out based on the LCOE.
- According to the results, it may be determined whether it is necessary to implement a thermal storage system in this type of hybrid facility, taking into account the biomass's manageable nature.

METHODOLOGY

The methodology follows:

1. It is necessary to define the reference hybrid power plant and its parameters and operational characteristics.
2. To produce electricity from a thermal source, it is necessary to design the supercritical CO_2 power cycle, which will make it possible to determine the thermal efficiency and thermal power required by the cycle. This process is carried out in the computer program Supercritical Concentrated Solar Power Plant (SCSP) [5].
3. Using data on the thermal power determined previously, the biomass, solar, and thermal storage groups can be designed, based on correlations obtained from SAM [6] and self-developed equations detailed later.
4. Next, these groups are combined to determine the overall production and costs for a typical year, using an in-house algorithm developed in MATLAB [7].
5. In this way, 600 hybrid plants can be designed. We used these to introduce the corresponding cost functions to allow the economic optimization of the plant, based on the LCOE.

Reference Hybrid Plant

The main parameters of the reference hybrid power plant are indicated in Table 1.

TABLE 1. Main parameters of the reference hybrid power plant.

Parameter	Nomenclature	Value	Units
Nominal power	P_N	50	MW
Net nominal power	P_e	45	MW
Cycle thermal power	P_{th}	Optimized	MW_{th}
Thermal efficiency	η_{th}	Optimized	%
Recuperator conductance	UA	Optimized	MW/K
Hours of thermal storage	h	Optimized	hours
Solar field area	A_{SF}	Optimized	m^2
Solar multiple	SM	Optimized	-
Receiver maximum power	P_{rc}	Optimized	MWth
Tower height	H_{tower}	Optimized	m
Receiver area	A_{rc}	Optimized	m^2
Biomass boiler power	P_b	Optimized	MWth
Levelized cost of electricity	LCOE	Optimized	$/MWh

As operational characteristics, the solar thermal systems and biomass groups will work with solar salt [8] as heat transfer fluid and thermal storage. The main advantages of this choice are:

- Excellent thermal properties for energy storage (summarized in Table 2).
- The temperature of the molten salt is consistently held above its melting point, at 220ºC [8], there is no need to implement temperature-monitoring systems or heaters, either gas or electric.
- The working temperature of the molten salt is consistently under, but very close to, the maximum temperature (565ºC) [8], nitrate salts do not undergo thermal decomposition and avoid thermal stress when the plant is not operating.
- The starts and stops of the solar receiver and the biomass boiler can be carried out more quickly.

TABLE 2. Solar salt thermal properties [8].

Parameter	Value	Units
Melting point	220	ºC
Boiling point	565	ºC
Thermal conductivity	0.53	W/(m·K)
Density	1804	Kg/m^3
Specific heat capacity	1.52	kJ/(kg·K)

The solar thermal group is a central tower power plant, composed of a heliostat field and a central receiver at the top of a tower. The biomass group consists of a biomass boiler and other auxiliary systems to treat exhaust gas fuel and for purification. The hybrid plant also has a thermal storage system based on molten salt technology. This storage allows the excess energy produced by the solar thermal power plant to be stored. Finally, all thermal energy is transformed into electrical energy through a supercritical CO_2 Brayton power cycle. Figure 1 shows a schematic diagram of the power plant.

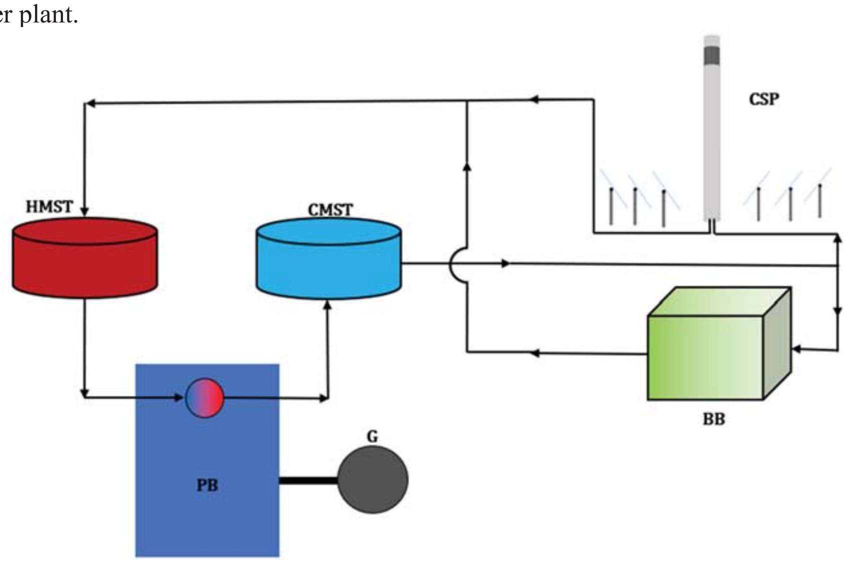


FIGURE 1. Schematic diagram of the studied power plant. G, generator; PB, power block; HMST, hot molten salts tank; CMST, cold molten salts tank; BB, biomass boiler; CSP, concentrated solar plant.

To select the plant's location, we conducted an iterative process of selecting different places with high solar radiation from radiation maps. Then, to validate the location, we used the BIORAISE program to analyze the availability of sufficient biomass resources in the plant's vicinity [9]. The final location selected was in Écija, Spain, which coincides with a real solar thermal plant's current location.

Supercritical CO_2 Power Cycle Design

The four following configurations of the power cycle are analyzed (Fig. 2): recuperation, recuperation with reheating, recompression, recompression with reheating.

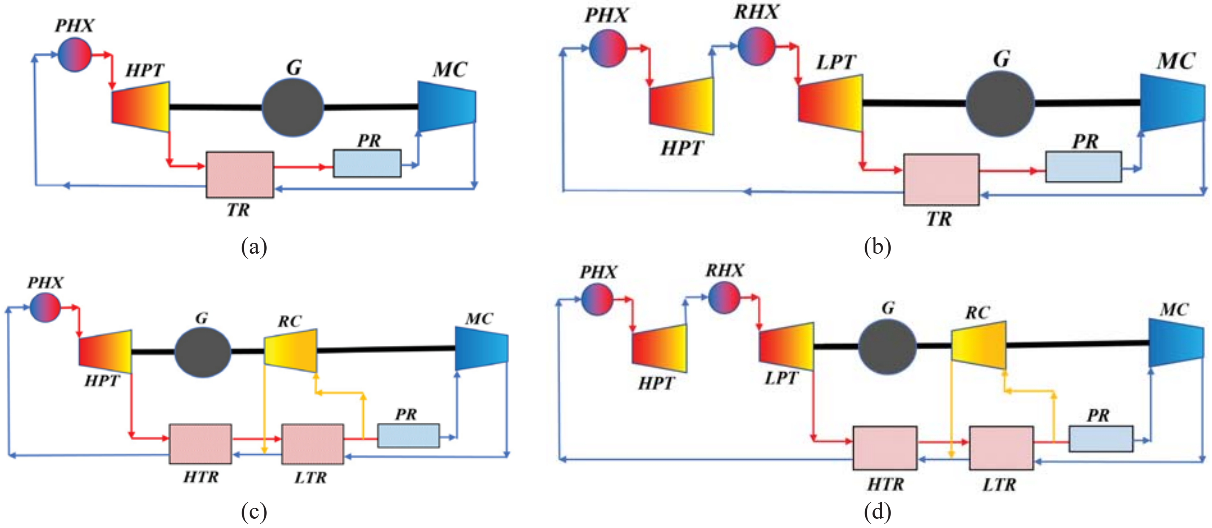


FIGURE 2. sCO_2 power cycles. (a) Recuperation cycle. (b) Recuperation with reheating cycle. (c) Recompression cycle. (d) Recompression with reheating cycle. PHX, primary heat exchanger; RHX, reheating heat exchanger; HPT, high-pressure turbine; LPT, low-pressure turbine; HTR, hot temperature recuperator; LTR, low-temperature recuperator; TR, temperature recuperator; PR, precooler; G, generator; RC, recompression compressor; MC, main compressor.

The first two recuperation configurations showed worse performance than the recompression ones. However, they are interesting from an economic point of view, as requiring less equipment will reduce initial investment in the power cycle. On the other hand, their worst performance will require higher thermal groups' investments as less cycle efficiency. For the same electric power output (50 MWe), it will require more thermal power from them. Therefore, the capital cost will increase.

Next, these four configurations are used to perform optimization, employing the SCPS program [5], which allows optimization of various parameters of the cycle depending on the size of the heat recuperators (measured as UA [W/K]). A higher value implies a higher cycle performance because it allows a more significant amount of heat to be recovered while reducing the heat requirement for the cycle. Nevertheless, a higher UA also implies a lower pinch point, and a minimum pinch between 5ºC and 10ºC must be reached. Moreover, higher UAs make installation more expensive, so finding an economic optimum is crucial.

The main parameters for the cycle optimization are presented in Table 3.

TABLE 3. Input parameters for the optimization process of the power cycle.

Parameter	Nomenclature	Value	Units
Electrical power	Pn	50	MW
Compressor inlet temperature	CIT	Optimized	K
Compressor inlet pressure	CIP	Optimized	MPa
Turbine inlet temperature	TIT	823.15	K
Turbine inlet high pressure	TIHP	25	MPa
Turbine inlet low pressure	TILP	Optimized	MPa
Compressor isentropic efficiency [5]	ηc	0,89	–
Turbine isentropic efficiency [5]	ηt	0,93	–
Low temperature recuperator conductance (LTR) [10] [11]	UA_{LTR}	2.5→15.0	MW/K
Hot temperature recuperator conductance (HTR) [10] [11]	UA_{HTR}	2.5→15.0	MW/K
Recompression fraction	γ	Optimized	%

The process of optimization is carried out by applying the mathematical algorithms SUBPLEX [12], BOBYQA [13], and NEWUOA [14].

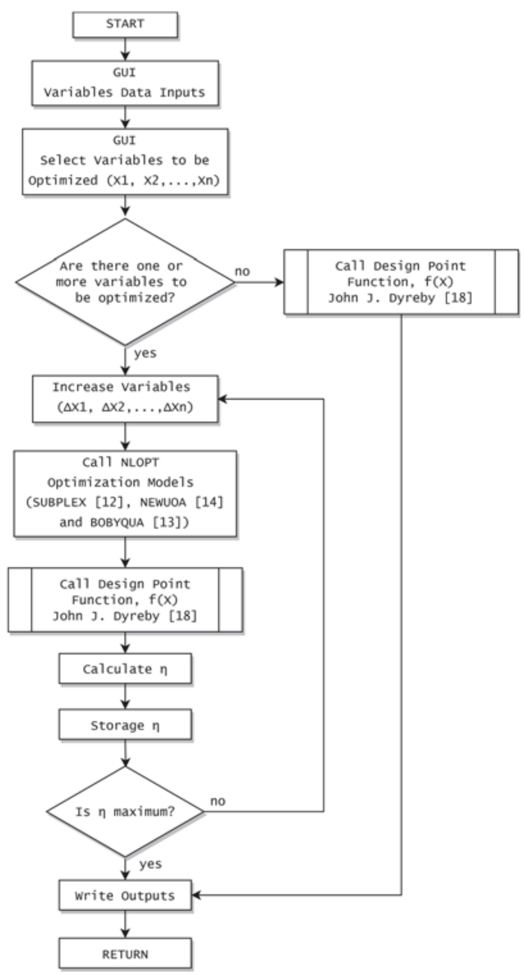


FIGURE 3. Power cycle optimization process.

These result in 24 optimized power cycles, whose efficiencies and required thermal power are presented in Fig. 4 (a) and (b), respectively, as a function of recuperator UA.

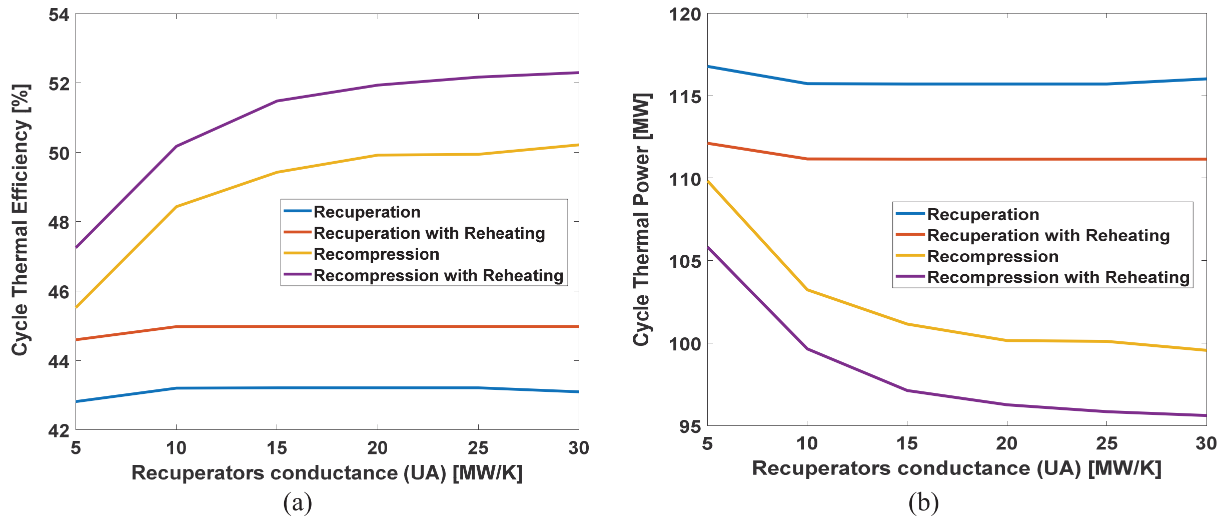


FIGURE 4. Power cycle optimization results for different UA sizes and configurations. (a) Cycle thermal efficiency vs. recuperator conductance (UA). (b) Cycle thermal power vs. recuperator conductance (UA).

Once the thermal power is calculated, it is possible to design the biomass and solar thermal groups.

Biomass Group Design

The biomass group's design is influenced by the plant's location and the biomass resource available in its surroundings. From the BIORAISE [9] data, olive grove clippings are chosen as the reference fuel for the plant, because there is a great abundance of this resource in the area.

At this point, a fundamental problem arises. Biomass fuels, coming from vegetable matter, contain chlorine as a result of metabolic processes in plants. This chlorine reacts with the boiler's materials, generating corrosion and fouling, which hinders the transfer of heat and reduces the useful life of the boiler. These processes generally occur at high temperatures above 500ºC. Given that our cycle has been optimized to work at 550ºC, it is necessary to determine, from the optimized cycle, what would be the performance and thermal power required by the power cycle working at 500ºC.

The sizing of biomass power plants requires the definition of the boiler and fuel dryers' power because biomass tends to have high water content, which is usually limited to 5% for the correct operation of the boiler. However, according to the PHYLLIS 2 [15] database, olive tree clippings have a humidity of 4.8%, so it is not necessary to implement a fuel dryer. Hence, it only remains necessary to define the boiler.

With the thermal power calculated under the conditions specified above, the boiler power can be determined with Equation (1), based on a boiler efficiency of 90%.

$$P_b = \frac{P_{th}}{\eta_b} \tag{1}$$

where P_b is boiler thermal power (W), P_{th} is thermal power required by the cycle (W), and η_b is boiler efficiency.

Solar Thermal Group and Thermal Storage Design

The thermal storage capacity determines the maximum amount of thermal energy coming from the solar receiver that can be stored. This capacity is defined as the number of hours that the power cycle production can be maintained at a nominal speed. The power cycle requires a specific thermal power to be able to produce the nominal 50 MWe. The thermal storage system can be dimensioned according to Equation (2).

$$SC = h \cdot P_{th} \tag{2}$$

where SC is storage capacity (MWh), P_{th} is thermal power required by the cycle at 550ºC (MW), and h is storage hours (h).

The storage hours considered in the present study were between 0 and 24 h.

The design of the solar thermal group is also highly influenced by the location. A location with higher radiation levels will reduce the necessary size of the plant and consequently the cost. The hourly DNI values for a typical year can be extracted from the PVGIS [16] website for the selected location.

The main systems to be dimensioned are the solar receiver, the height of the tower, the mirror area, and the storage system's size. The latter is designed according to the desired storage hours, defined as the number of hours that plant produces electrical energy from thermal energy storage.

The calculation of the receiver's size and the central tower is carried out using functions dependent on the solar field area developed from parametric studies carried out in the SAM software [6], whose main input parameters are presented in Table 4. Therefore, defining the area of the solar field is a critical parameter for sizing the plant.

TABLE 4. Input parameters in SAM software for parametric studies.

Parameter	Value	Units
Location	Écija, Spain	-
Design point DNI	950	W/m2
Solar multiple	1 → 4.5	-
Full load hours of storage	0 → 24	h
Design turbine gross output	50	MW
Estimated gross to the net conversion factor	90	%
Cycle thermal efficiency	42	%

The area is calculated as the quotient of the energy required by the power cycle and the solar field's energy generated per square meter.

$$A_{SF} = \frac{P_{th} \cdot (h + mh)}{\eta_{SF} \cdot \eta_{rc} \cdot mh \cdot DNI_{ave}} \tag{3}$$

where A_{SF} is solar field area (m^2), P_{th} is thermal power required by the cycle (W), h is hours of storage (h), mh is mean hours of solar radiation per day (h), η_{SF} is solar field efficiency, η_{rc} is solar receiver efficiency, and DNI_{ave} is average DNI (W/m^2).

Technical Combination of the Systems

From the TMY data, the DNI is extracted for each hour of the year at the location. With this DNI value, hourly production is determined for each group. The algorithm for select the technology and the thermal storage loading and unloading process has been developed in MATLAB [7].

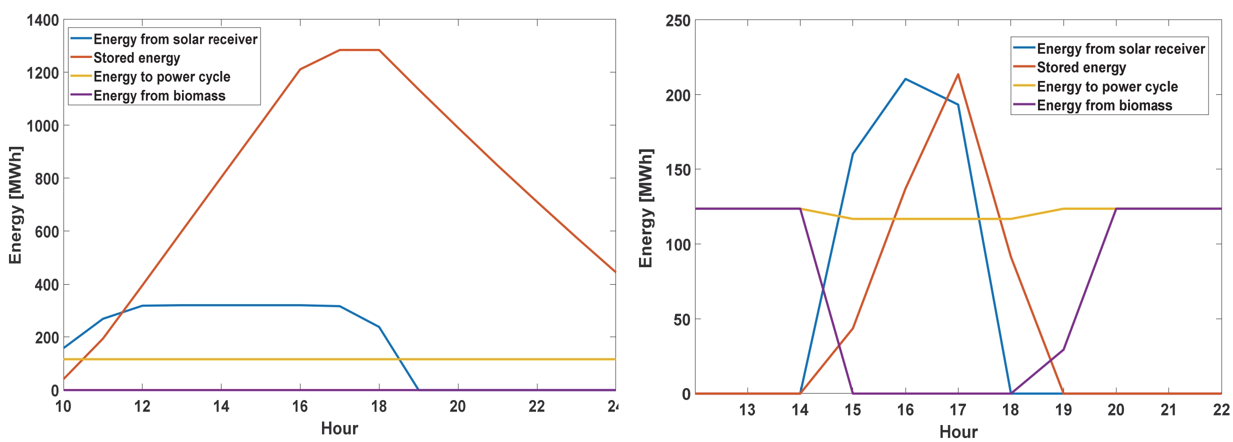
This algorithm considers the following simplifications:

- 100% capacity factor when maintenance problems and breakdowns arise in real operation.
- The starting times of the groups are immediate.
- The auxiliary consumptions of the plant are not calculated in detail.

Three measures are applied to compensate for the simplifications: increase the average DNI at the start of operation and increase the consumption of biomass fuel, take into account start-up and shutdown, and consider standby processes of each group. On the other hand, the 90% of the plant is applied for auxiliary consumption and electrical efficiency.

The generation strategies designed are listed below:

- When there is sufficient solar radiation, as in Fig. 5 (a), more thermal energy is produced (blue line) than demanded by the power cycle (yellow line), and the remainder is sent to thermal storage. When producing energy with solar thermal or thermal storage, the biomass group's energy is zero. On the other hand, when the desired storage hours are reached, the storage stops filling up.
- Finally, if there is not enough solar radiation or thermal storage, as in Fig. 5 (b), biomass comes into operation to make up for this lack of energy. It can be seen how the power cycle using biomass has worse performance when it works with a lower temperature and therefore requires a higher thermal power. This is because when biomass works, the energy demanded by the cycle increases slightly.



(a) (b)

FIGURE 5. Energy dispatch scenarios for different operational modes. (a) Excess thermal energy from the solar receiver, thermal storage, and no generation from biomass. (b) Insufficient energy from the solar receiver, thermal storage, and required biomass energy generation.

PLANT OPTIMIZATION

To optimize the hybrid plant, 600 cases were analyzed. For each of the 24 power cycles, 25 biomass and solar thermal groups were designed, corresponding to storage hours from 0 to 24. Each of the cases was calculated separately using a proprietary algorithm developed in MATLAB [7] (Fig. 6), in which the cost functions of the various elements are introduced.

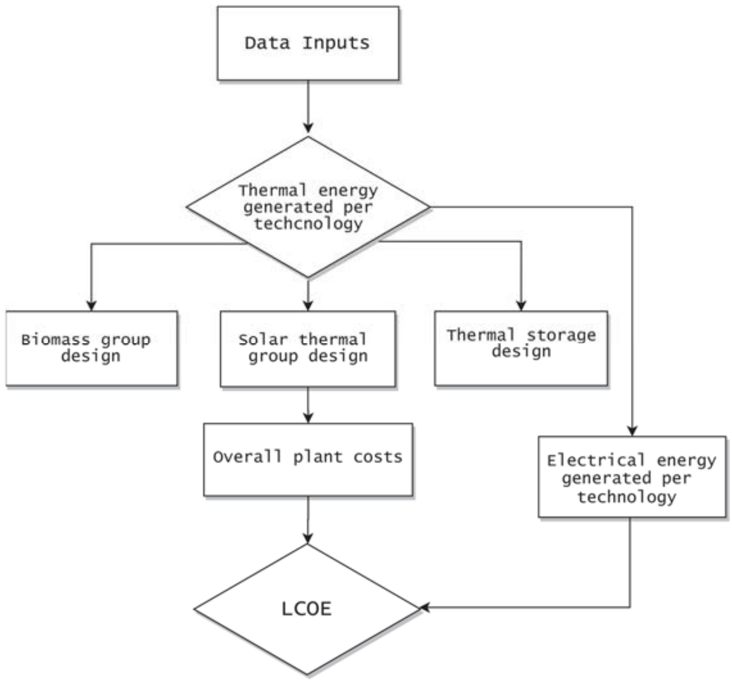


FIGURE 6. Hybrid power plant optimization process.

Optimization was carried out based on the LCOE. For the LCOE, only cost functions are applied, not incomes. The costs are those associated with thermal groups, fuel expenses, O&M, EPC, land, and contingencies, according to data from SAM [6,17].

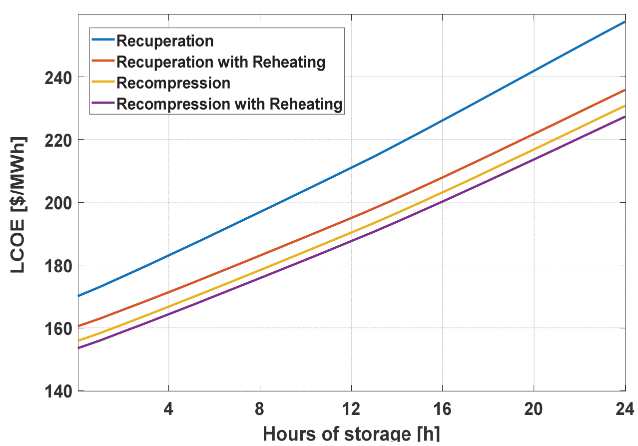


FIGURE 7. Hybrid power plant optimization results for different power cycle configurations and hours of storage.

Figure 7 shows the evolution of LCOE for different hours of storage and power cycle configurations. From the 600 cases analyzed, the case with the minimum LCOE was selected as the optimized plant. Its main parameters are shown in Table 5.

TABLE 5. Optimized parameters of the power plant for optimum LCOE.

Parameter	Nomenclature	Value	Units
Nominal power	P_N	50	MW
Net nominal power	P_e	45	MW
Cycle thermal power	P_{th}	97.13	MW_{th}
Thermal efficiency	η_{th}	51.48	%
Recuperator conductance	UA	15	MW/K
Hours of thermal storage	h	0	hours
Solar field area	A_{SF}	269624	m^2
Solar multiple	SM	1.24	-
Receiver maximum power	P_{rc}	119.97	MWth
Tower height	H_{tower}	81.67	m
Receiver area	A_{rc}	663.59	m^2
Biomass boiler power	P_b	113.64	MWth
Levelized cost of electricity	LCOE	153	$/MWh

ANALYSIS OF RESULTS AND CONCLUSIONS

One of our main objectives was to determine the need to implement thermal storage in a hybrid plant of the characteristics described herein. As shown in Table 5 and Fig. 7, the results show that a minimum LCOE of 153 $/MWh is obtained for 0 h of thermal storage. Therefore, no thermal storage is required, as providing heat using biomass fuel is more economical than having a more significant solar field and thermal storage system.

The optimum cycle configuration is a recompression cycle with one reheating and a UA of 15 MW/K, lower than the maximum studied of 30 MW/K. This means that higher UAs are not economically justified despite the higher efficiencies.

Finally, if there is no thermal storage, it is not necessary to use molten salts, so it is of interest to study a system with direct heating of supercritical CO_2. On the other hand, the maximum temperature achievable using biomass limits the performance of the plant. If the biomass is gasified, the temperature limit increases considerably; in which case its use in combined cycles can be considered.

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