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Analysis of an electrical energy production system from solar energy using a microscale CSP and ORC

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Abstract:

Topics such as climate change and global warming that the world has been experiencing are increasingly a cause for alarm and concern which means that several goals must be achieved to avoid irreversible damages to the environment that interfere with its stability. For that aim, it is crucial to reduce emissions by discontinuing the use of fossil fuels, as an energy source to produce electricity, and replacing it with renewable energies. For a 100% renewable energy transition it is necessary to ensure dispatchability, flexibility, safety, and reliability of the electrical distribution grid. The main goal of this study is to evaluate the potential of a small-scale system using solar energy captured by Concentrated Solar Power (CSP) technology to produce electricity through an Organic Rankine Cycle (ORC). The System Advisor Model (SAM), one of the main tools for evaluating renewable energy projects, was used for system analysis. The CSP system implemented has gross installed power of 50kW$_e$ with 6 hours of Thermal Energy Storage (TES), whose main results are: production of 145529 kWh in the first year of operation, \$559416.06 total investment cost and a Levelized Cost of Electricity (LCOE) of \$0.3009/kWh. From the analysis of the results obtained, it can be seen the effect of economies of scale reflected in the LCOE value, which an expected consequence of scale reduction.

Keywords:

Concentrated Solar Power; Dispatchability; Organic Rankine Cycle; Renewables; Small-scale.

1. Introduction

The development of the humanity and society has brought, inherently, an energy dependence that is so naturally present in our daily life, almost like something previously acquired, that if for some reason there is a failure in the electricity distribution grid, there is no redundant system until that same failure is solved. This dependence coupled with the progressive increase in energy needs due, in part, to population growth and improvement in living standards, has led to an increase in the implementation of conventional electricity generation systems based on fossil fuels, resulting in increased greenhouse gas (GHG) emissions.

Topics such as climate change and global warming have emerged more frequently, more prominent and alarming, as they can result in irreversible damage to the environment. The use of renewable energy cannot be seen as a mere investment, but rather as a civil obligation, which implies a change of mindset to achieve carbon neutrality, a zero balance between GHG emissions and carbon retention. Knowing that this is a global problem with increasing emphasis among various organizations, several targets have been imposed and sanctions are applied to those who do not comply with them. For that aim, the member states of the European Union (EU) have stipulated and agreed to carry out, through the Paris Agreement (2015), three main goals [1] : limit the global average temperature rise below 2ºC compared to pre-industrial levels and pursuing efforts to keep it below 1.5ºC; increase the capacity to adapt to the impacts of climate change and foster climate resilience; make financial flows consistent with a pathway towards climate resilient and low-carbon development. Among the goals presented, the first is the most important since it could prevent irreversible damage to the environment that could put the population at risk.

In 2016, Portugal committed to ensuring carbon neutrality by the end of 2050 and developed the Roadmap for Carbon Neutrality (RNC2050) [1], which presents the main vectors of decarbonization and the path to follow for emission reduction, in conjunction with National Energy-Climate Plan (PNEC) [2], the main energy and climate policy instrument for the decade 2021-2030.

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As can be seen from Figure 1, Portugal showed a growth in GHG emissions from 1990 until 2005, when it reached a peak, with a significant decrease from then on, in line with the targets for carbon neutrality. In 2017, there was a sharp increase in emissions related to the forest fires that occurred that year. An analysis of the evolution without considering emissions from Land Use, Land-Use Change and Forestry (LULUCF) shows a global trend of reducing GHG emissions.

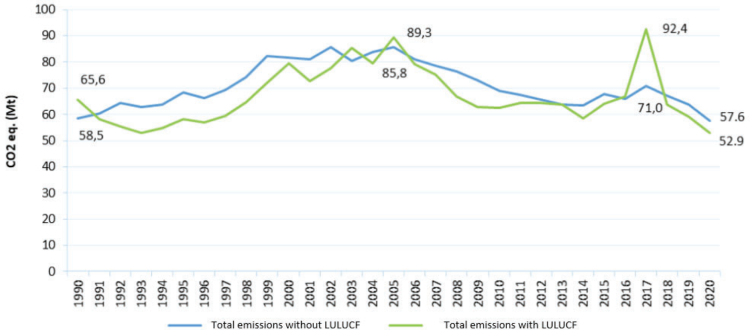

Figure. 1. Evolution of Portugal’s GHG emissions [3].

The electricity production sector, which will be target of analysis in this study, is one of the most potential for reducing emissions. The goal that Portugal has in this sector is clear, total decarbonization by 2050. The main drivers for decarbonisation in this sector are the transition from conventional electricity generation systems based on the use of fossil fuels to renewable energy systems, the discontinuation of use of coal by 2030 (already achieved) and natural gas by 2040, the development of new technologies that enable energy storage and ensure greater intelligence and flexibility of electrical distribution grid [1].

Investing in carbon neutrality will result in savings importing fossil fuels with a reduction in dependence on foreign countries. This result is of extreme importance for Portugal economy, as the acquisition of these fuels from other countries represents one of the main expenses. On the other hand, it would somehow attenuate fluctuations in the price of energy as it would be produced nationally, reducing the dependence on the availability of fossil fuels and external requirements or impositions.

In 2020, Portugal was the 11th country in the EU with the most energy dependence, with a value of 65.8%, while the European average was at 58%. The 8.4% decrease between 2020 and 2019 has three main causes: breakdown in energy consumption due to the COVID-19 pandemic; cessation of imports of coal for electricity production; increased production of energy from renewable sources at residential level [4]. The breakdown in consumption due to the pandemic leads the value of energy dependence in 2020 is not taken as a benchmark, since it is “artificially” low. The Figure 2 show the energy dependence in Portugal from 2000 until 2020, the latest data available.

Figure. 2. Evolution of Portugal’s energy dependence [4].

In recent years there have been large investments in photovoltaic (PV) and wind technology, but since their production is highly variable and depends on the availability of the resource, problems arise in terms of the dispatchability and stability of the electricity distribution network. As the goal is to ensure that 100% of the energy produced by 2050 comes from renewable resources, there will be a need to invest in other technologies that allow for some gap between the availability of the renewables and the production of electricity.

Following the development and investment in non-dispatchable electricity production technologies such as photovoltaic and wind, arises the need to create means of storage that allow a gap between renewable resource availability and electricity production. CSP technology emerges as one of the potential solutions to

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ensure this gap. Its main advantage is the possibility of incorporating a TES system whose associated costs, as well as storage efficiency and environmental impact, make the technology favourable when compared to battery storage systems. Large-scale systems are well-known and mature but requires a very significant geographical area and a transport costs and losses due to a central electric production. Micro and mini-scale CSP – ORC systems integrated with TES can overcome the geographical limitation in a decentralized production.

1.1. Solar energy as a renewable resource

Solar energy is one of the most abundant renewable resources. Only 47% of the available solar energy reaches the Earth's surface (31% directly and the remaining 16% diffuse, through dust, water vapor and other molecules), with the remainder 53% of energy being divided into: 15% absorbed in the troposphere, 23% reflected by clouds, 7% reflected by the soil, 2% absorbed by the stratosphere and 6% of radiation diffused by the atmosphere, which does not reach the surface [5].

In Portugal, the implementation of renewable resources as a way of producing electricity has verified 3 main waves, each of which is represented by the development, growth and deployment of a given technology. The 80s and 90s were represented by the exploitation of water energy as a strong bet on electricity production, however, from the 2000s there is an increase in the use of wind energy and more recently the solar resource with a great potential for exploration and development [6].

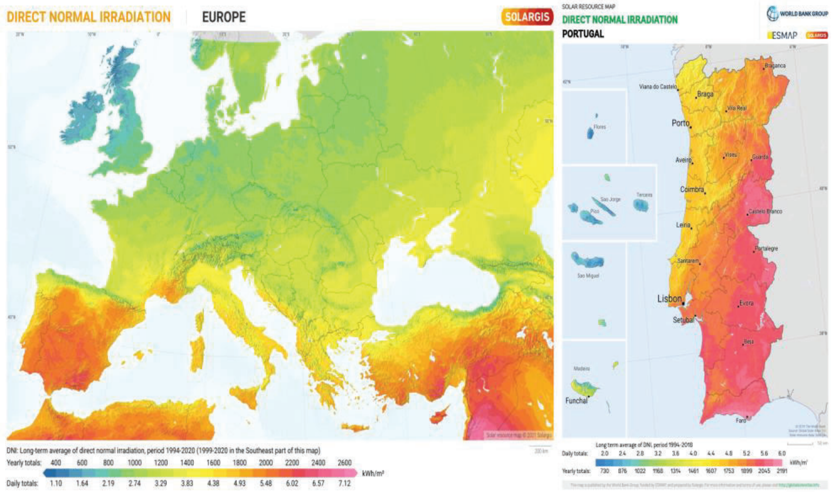
The electricity consumption in Portugal has, in the last 10 years, an average value of 50 TWh/year, but only 2% of the total electricity production is made from solar energy [7], which reveals a fairly reduced value in relation to the potentiality it presents, however this technology is relatively recent when compared to the production systems from water and wind energy, which have a higher degree of maturity [8].

In assessing the potential of a zone for solar energy exploitation, radiation is the most important factor, being divided as: Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance (DHI) and Global Horizontal Irradiance (GHI).

Among several parameters, the one that has the greatest influence on the decision on the potential of a region to implement a Concentrated Solar Power (CSP) system is the DNI, which are considered more interesting and economically more viable when the value of the average DNI is equal to or greater than 2000 kWh/m^2.year [8,9]. Besides that, it is necessary to consider factors such as the level of nebulosity and dust since it decreases the fraction of available DNI.

Portugal is one of the countries in Europe with the highest availability of solar radiation, which, despite having a large variability in the distribution of the DNI, presents an annual average value across the national territory of 1800 kWh/m^2 [8], reaching 2200 kWh/m^2 in certain regions, with a number of annual hours of sun from 2200 to 3100 hours, which is much higher than the values of 1200 to 1700 hours presented by Germany [11], or 1750 hours of European average [12]. This makes Portugal one of the European countries with the greatest potential for exploiting this resource for national energy production. According to the study conducted in [9], CSP technology presents, in Portugal, the greatest potential among all renewable energies, namely: hydraulic, geothermal, biomass, wind, photovoltaic and waves / tide.

The DNI distribution in Europe and Portugal is presented in Figure 3.



(a) (b)

Figure. 3. DNI distribution in Europe (a) and Portugal (b) [11].

2. Concentrated Solar Power - CSP

The principle of operation of the CSP technology, presented in Figure 4, is based on the generation of electricity through a heat machine involving the concentration of solar radiation. Unlike PV technology that makes use of GHI, CSP technology only takes advantage of the DNI fraction of the radiation that, through solar concentrators, causes it to focus on a receiver, heating a Heat Transfer Fluid (HTF), thereby transforming solar radiation into thermal energy. The concentration of radiation makes it possible for the HTF to reach quite high temperatures, and this thermal energy can be used to produce electricity through a heat machine, usually with a turbine associated with a generator. on the other hand, to be stored to create a gap between solar radiation and electricity production, the concept of dispatchability.

The existence of Thermal Energy Storage (TES) allows thermal energy to be stored, creating a gap between solar radiation and electricity production, the concept of dispatchability. This makes it possible to create a more stable power distribution network, since most of the power generation systems are non-dispatchable, they produce and introduce electricity into the grid only when the primary resource is available. This inherent feature of CSP systems is one of its main advantages.

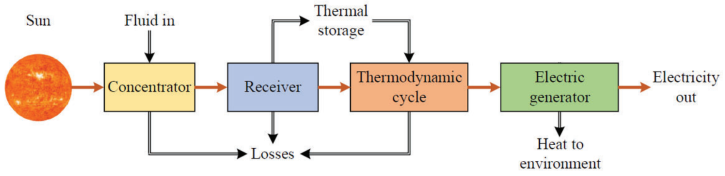


Figure. 4. Principle scheme of a CSP system [8].

2.1. CSP technologies

The aim of the solar field is to concentrate solar radiation in a receiver, converting it into thermal energy. The concentration of radiation causes the absorbed radiative density to be higher than that on the Earth's surface, so that, high temperatures are reached to operate a heat machine. The CSP technologies can be classified according to Figure 5. Despite having the same goal, they have forms and characteristics that distinguish them and that cause their application to be differentiated.

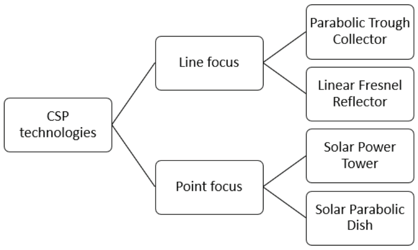
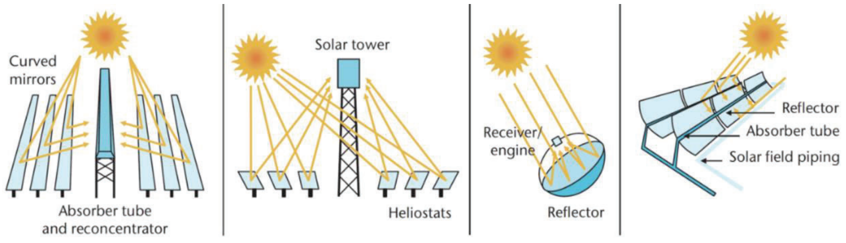


Figure. 5. Classification of CSP technologies

The aforementioned technologies are illustrated in Figure 6. A tracking system is implemented with the aim of making greater use of solar radiation, so that it constantly focuses the radiation on the receiver as the sun moves. Linear focus systems use single-axis tracking systems, while point focus systems are implemented with two-axis tracing systems. The orientation of the collectors is usually made in the longitudinal north-south direction with tracking east-west, as they ensure a greater amount of energy absorbed.



(a) (b) (c) (d)

Figure. 6. Configuration of CSP different technologies: Linear Fresnel Reflector (LFR) (a); Solar Power Tower (SPT) (b); Solar Parabolic Dish (SPD) (c); Parabolic Trough Collector (PTC) (d) [12].

3. Thermal Energy Storage - TES

The production of electricity from renewable energies is not deterministic due to the variation of the natural resources' availability, as well as variation in electricity consumption demand. Given the intermittent availability, variability and limitation of certain natural resources, the existence of storage means becomes crucial to compete with the dispatchability that fossil-based electricity production systems offer, which has led to the development of different forms of energy storage, making them efficient and sustainable [13]. In general, the TES allows, not only the temporary storage of thermal energy for subsequent use of that same energy, compensating the intermittency of the solar resource or ensuring the dispatchability of the system, but also gives it thermal inertia, ensuring a greater stability of operation. Some of the advantages of its use are: increase the capacity factor (CF), ratio between actual energy produced during a certain period and maximum theoretical production in the same period, by 20-25%, without TES, up to 60-85% with TES; reduce the operation of the power cycle at partial load; and adjust production for peak hours [14].

3.1. Application of TES to CSP systems

The TES system can be classified, according to Figure 7, in Sensible Heat Storage, Latent Heat Storage and Chemical Energy Storage. The TES system can be characterized according to the following characteristics: capacity, charge and discharge power, efficiency, storage time, charge and discharge time and cost [13].

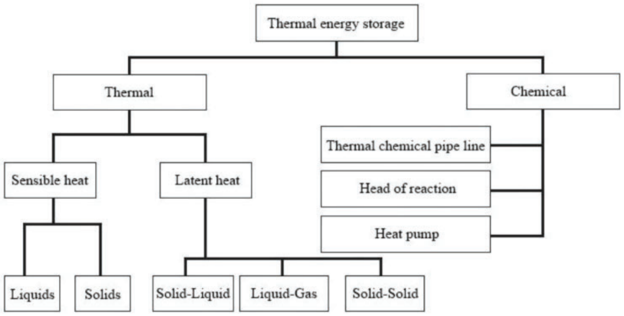
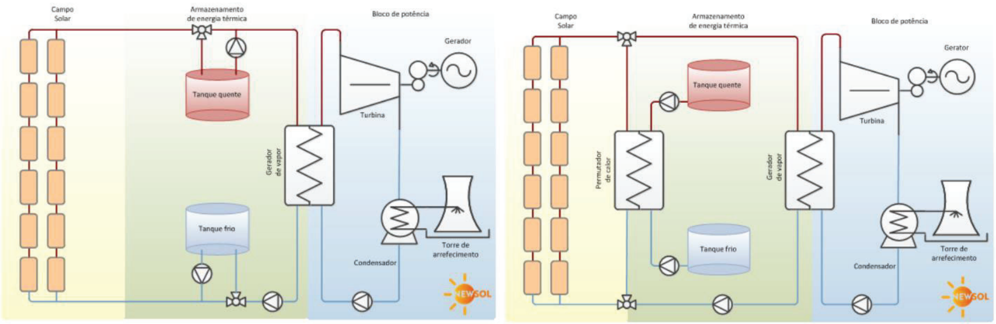


Figure. 7. Types of TES [13].

The development and choice of the TES system to be implemented requires knowledge of the heat flows between HTF and TES during the charge process and between TES and the heat machine in the discharge process [13]. Most CSP systems feature two types of TES configurations: two tanks and a single tank.

In the two-tank system the HTF is stored in two tanks with different temperatures, one of high temperature and another of low temperature, referred to as hot tank and cold tank, respectively. This type of TES can also be divided in direct, where the solar field HTF itself is used as a storage fluid, and indirect systems, where the HTF is different from the storage fluid, which requires the use of a heat exchanger that promotes energy exchange between the two fluids, as illustrated in Figure 8.



(a) (b)

Figure. 8. Configuration of a two-tank direct (a) and two-tank indirect (b) storage system [15].

In single tank storage systems is typically used thermocline technology, presented in Figure 9. The storage medium can be the HTF itself or be a solid medium, such as rock or silica. In the first case, the hot HTF remains at the top of the tank while the cold is at the bottom, with a dividing line called the thermocline gradient. The distribution of temperatures is guaranteed by the difference in material density at different temperatures. In the second case, in the charging process, the hot solar field HTF enters the upper zone of the tank and goes out in the lower zone of low temperature, adding thermal energy to the solid medium, and the opposite happens in the discharge process [13]. This type of storage is suitable for small-scale applications as it allows a cost reduction compared to a two-tank system [16].

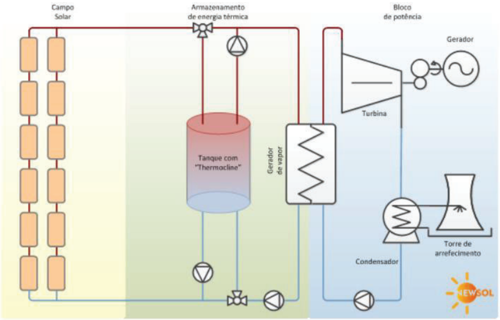


Figure. 9. Single-tank storage system [15].

4. Heat Transfer Fluid - HTF

The HTF is one of the key components of a CSP system with direct influence on its performance and efficiency [17]. According to Benoit et al. [18], the HTF should be compatible with the materials used and the storage medium and be able to operate in the required temperature range, receive and transfer heat easily and circulate well in confined spaces. Given the high amounts of HTF required in the system, since it can be used as a receiver and storage medium, it is necessary to minimize its cost while increasing performance [17]. In addition to having direct influence on overall system efficiency, the choice of the HTF determines the type of TES and the power cycle to be implemented, as well as the performance it can achieve [19]. Table 1 lists the main properties to be considered when choosing the HTF and its influence on the system.

Table 1. Influence of the HTF properties on the CSP system, adapted from [14]

Property	Related to
Solidification temperature	Minimum operation temperature Thermal protection needs
Thermal stability limit	Maximum operation temperature
Heat capacity	TES capacity
Viscosity	HTF pumping
Density	TES volume
Thermal conductivity	Heat transfer Heat exchanger

Improvement in the thermal properties of HTF is one of the most effective ways to improve the efficiency of CSP systems, as improvements in physical system have little potential since thermal losses are reduced [20]. The range of operating temperatures set by the HTF, and its thermal stability are the limiting factors in the overall system performance. The most used HTFs are water, gases, thermal oils, and molten salts.

5. Analysis of a small scale CSP system through the System Advisor Model (SAM)

CSP systems modelling is quite complex due to existing time fluctuations, resulting in transient effects on the system, unlike conventional power generation systems that operate much of the time at nominal conditions under a predominantly stationary regime [21].

The System Advisor Model (SAM) is a program developed by the National Renewable Energy Laboratory (NREL) from funding from the U.S. Department of Energy and is presented as: “free techno-economic software model that facilitates decision-making for people in the renewable energy industry”, namely, solar, water, wind, geothermal and biomass energy [22]. SAM is based on several series of the Transient System Simulation Program (TRNSYS) model that uses the program interface inputs as data to make the annual simulation with hourly system resolution.

SAM is currently one of the most widely used software for the techno-economic analysis of CSP systems worldwide. One of the main benefits of using SAM, in addition to the high reliability of results, is the possibility of making probabilistic, stochastic, and parametric analyses, with special emphasis on the latter, since it allows to make the optimization of the systems based on the change of certain parameters.

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5.1. Implementation of the system in SAM

For the simulation of a model in SAM it is necessary, firstly, to choose the systems model and then the economic model that is intended to be used to carry out the analysis.

Due to the power cycle type being implemented and since it is the most mature technology and one of the most developed models in SAM, it was chosen the PTC system. Within the PTC option, the SAM have two distinct models: physical and empirical. The empirical model is based on correlations derived from data analysis obtained in systems already implemented, mainly from the Solar Energy Generating Systems (SEGS) in the United States of America, which makes the analysis of systems with distinct conditions more controversial and uncertain. On the other hand, the physical system uses concepts of heat transfer, thermodynamics, and fluid mechanics to characterize the system [23], so that, it was the model considered.

The economic model chosen was the Levelized Cost of Electricity (LCOE) Calculator, suitable for preliminary analysis of project feasibility, that is calculated using the Fixed Charge Rate method.

After base simulation, an optimization of the CSP system can be done. It involves choosing several parameters that result in a minimum LCOE value. If, on the one hand, the increase in the solar field area increases the electricity production, reducing the LCOE, on the other hand, in periods when the power cycle operates at maximum capacity and the TES is at maximum, the waste of energy increases, as well as the costs of installation, operation and maintenance. There is a turning point where the benefits of electricity production are overtaken by the remaining costs.

The system's layout to be implemented in SAM is presented in Figure 10.

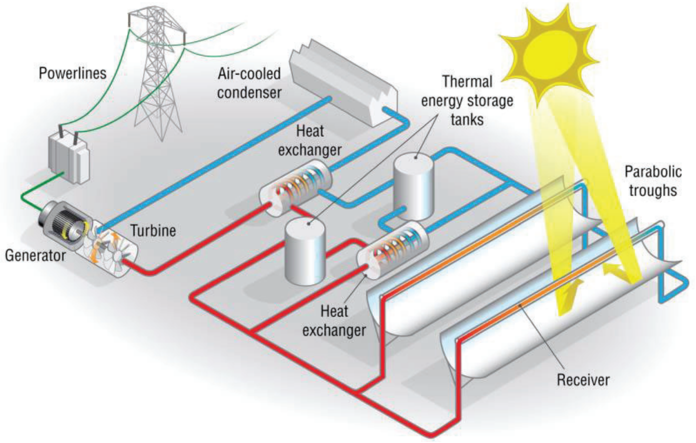

Figure. 10. Configuration of a CSP with PTC technology and a two-tank indirect TES [24].

5.1.1. Location and Resource

The SAM uses weather data from the National Solar Resource Data Base (NSRDB) developed by NREL.

Based on the levels of radiation that are potentially most viable for the implementation of a CSP system presented earlier, average values of DNI above 2000 kWh/m^2/year or 5.5 kWh/m^2/day, the region of Faro was chosen for the analysis of the system, since it is in the south of Portugal that is the region with the highest potential to implement CSP systems, exceeding the values presented above. The main values taken from the database with applicability in CSP systems are: DNI, average temperature and average wind speed and the values referring to Faro are 5.56 kWh/m^2/day, 18.5 ºC and 4.0 m/s, respectively.

5.1.2. System Design

The main system design parameters that determine the nominal capacity of the system are related with solar field, power cycle and TES, as presented in Table 2. Regarding the solar field, two crucial factor needs to be set: Solar Multiple (SM), design DNI.

The SM consists of the multiple of the area of the solar field required to operate the power cycle at its nominal capacity, in other words, a SM=1 represents the opening area of collectors that, when exposed to the design DNI, generates the exact thermal energy needed to operate the power cycle at nominal capacity.

The design DNI value is used to calculate the opening area of the solar collectors, which allows the power cycle to operate at the nominal capacity. Since the DNI varies over the course of the day and year, it is necessary to set a fixed value for the size of the solar field, knowing that its value depends on the geographical location and its value should be close, but lower, to the maximum value of annual DNI.

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Table 2. Main system design parameters for SAM simulation [24].

Solar field	
Solar Multiple	2
Design point DNI	800 W/m^2
HTF	Pressurized water
Solar field inlet/outlet HTF temperature	100-150ºC
Power Cycle	
Design turbine gross output	50 $\mathrm{kW_e}$
Estimated gross to net conversion factor	0.9
Cycle thermal efficiency	0.15
Thermal Energy Storage	
Hours of storage at design point	6 hours

5.1.3. Power cycle

The CSP system that comes implemented in SAM by default is the conventional Rankine cycle. SAM allows to use a custom power cycle, called User-Defined Power Cycle (UDPC), that uses data from a certain range of operating conditions to make a regression model. The performance of an ORC was modelled using actual operating data. The UDPC requires, as independent variables, the HTF temperature, HTF mass flow, and ambient temperature and, as dependent variables, gross electrical power generated and the thermal power entering the cycle.

5.1.4. Thermal Storage

The TES sizing is made based on the number of hours of storage of thermal energy that allow the power cycle to operate at the defined nominal power. In small-scale systems, the use of the thermocline tank has great potential, as it reduces costs and has high performance. According to Rodriguez et al. [16], the use of thermocline can represent a 33% reduction in TES costs when compared with a two-tank system with the same thermal storage capacity. SAM only allows to set two tanks direct and indirect storage system configurations, so that it was not possible to use thermocline in the simulation. The main parameters for TES are summarized in Table 3.

Table 3. Main parameters for TES system implementation [24].

Parameter	Value
TES type	Two-tank indirect storage system
TES fluid	Therminol VP-1
Hours of storage at design point	6h
TES thermal capacity	2 $\mathrm{MWh_t}$
TES volume	109.04 m^3

5.1.5. Financial Parameters

The choice of the economic model, LCOE Calculator, leads to the need to introduce the relative installation costs as well as the fixed and variable operating costs. The relative installation costs were calculated through Power Purchase Agreement (PPA) economic model given that it allows to detail each of the system costs. The values used for installation costs are the values that SAM presents by default since they are an estimate of the NREL that best represents the typical costs of a CSP system. All standard values were kept except the cost of the power cycle which was adjusted to $\$1000/\mathrm{kW_e}$ to best represent the ORC under study. In Figure 11 the cost to install the CSP system is presented, where it is possible to verify that the solar field and TES system are the main costs, with shares of 31,5% and 22,2%, respectively.

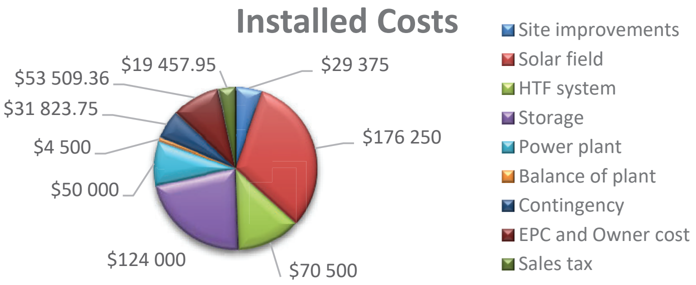

Figure. 11. CSP system installation costs [24].

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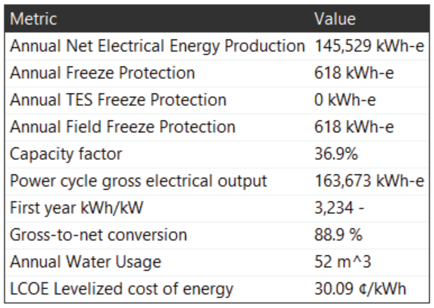
5.2. Results

SAM offers several options that allow the analysis of the obtained data. The main results of the simulation are summarized in the Table 4 and a heat map is presented in the Figure 12. The implemented model has an annual electricity output of 145529 kWh for the gross installed power of 50 kW$_e$, which reveals a relative output of 3234 kWh/kW. The capacity factor of 36.9% is representative of the dispatchability that the system offers. The economic indicator obtained is the LCOE with a value of \$0.3009/kWh which, when compared to the benchmark costs in the literature, \$0.10-\$0.20/kWh for large scale systems [8], is evident the effect of economies of scale of CSP systems.

Table 4. Main results of SAM simulation [24].



Metric	Value
Annual Net Electrical Energy Production	145,529 kWh-e
Annual Freeze Protection	618 kWh-e
Annual TES Freeze Protection	0 kWh-e
Annual Field Freeze Protection	618 kWh-e
Capacity factor	36.9%
Power cycle gross electrical output	163,673 kWh-e
First year kWh/kW	3,234 -
Gross-to-net conversion	88.9 %
Annual Water Usage	52 m^3
LCOE Levelized cost of energy	30.09 ¢/kWh

The heat map shows the system's electricity output over the first year of operation, which allows to identify the TES influence on the overall system performance. The period where the largest continuity of production occurs is between the 70th and 260th days of the year, between March and September, as expected. It is possible to verify the non-linear form as the system begins to operate in the early hours of the morning, which is in accordance with the relative movement of the sun during the year. Similarly, although the TES does not allow to see it, the system would also present a rounded shape in the afternoon. There are periods when the system presents negative power values, which is explained by the power required for the system to operate exceeds the power produced, such as the consumption of circulation pumps or tracking system.

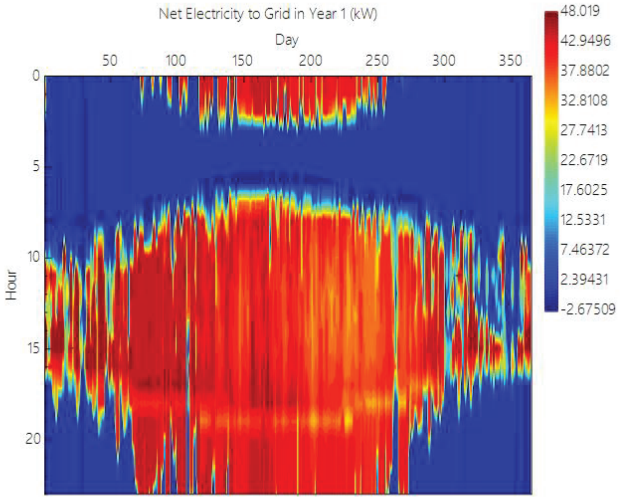


Figure. 12. Heat map of the system's electricity production in the first year of operation [24].

A comparison between the typical operation of the system on a winter day compared to a summer day is presented in Figure 13 and Figure 14, respectively. It is possible to verify that on winter days the system rarely operates at the design point as the available DNI is quite small and heavily affected by weather. All the energy that is captured in the solar field is used for power generation, there is no TES charging. On the other hand, in a typical summer day, a large amount of DNI is available which leads the system to a more stable operation at nominal capacity with great use of TES. The profile of the DNI on June 21 is perfect, which indicates that during that day the radiation does not face any obstacles to its passage, such as clouds.

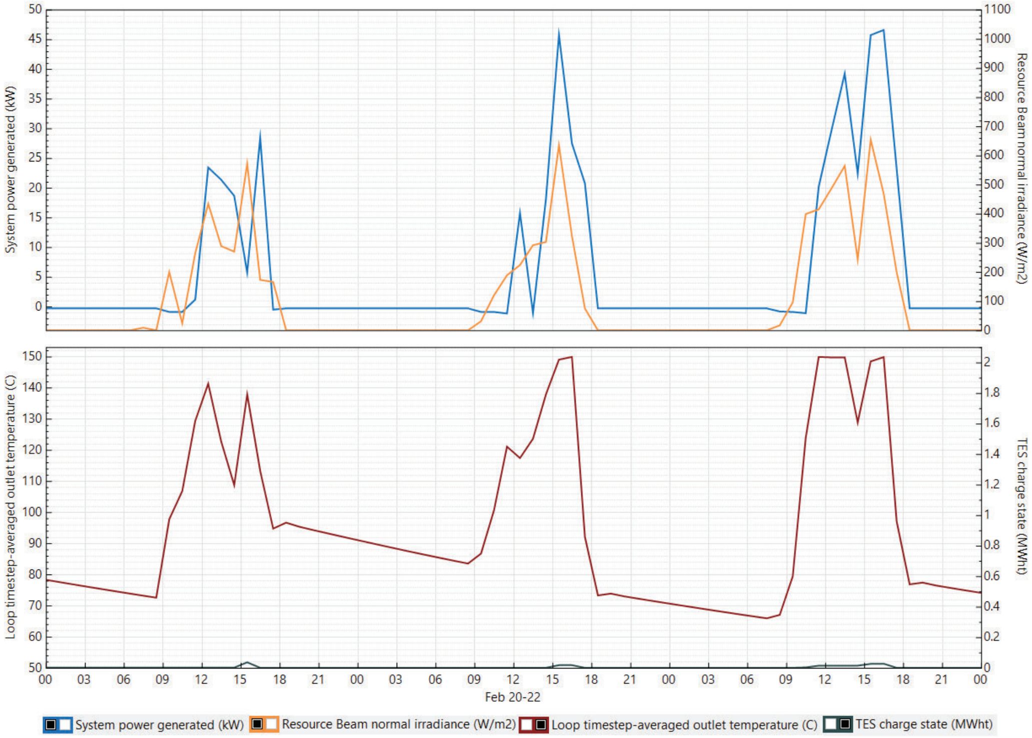


Figure. 13. System operation on a typical winter day [24].

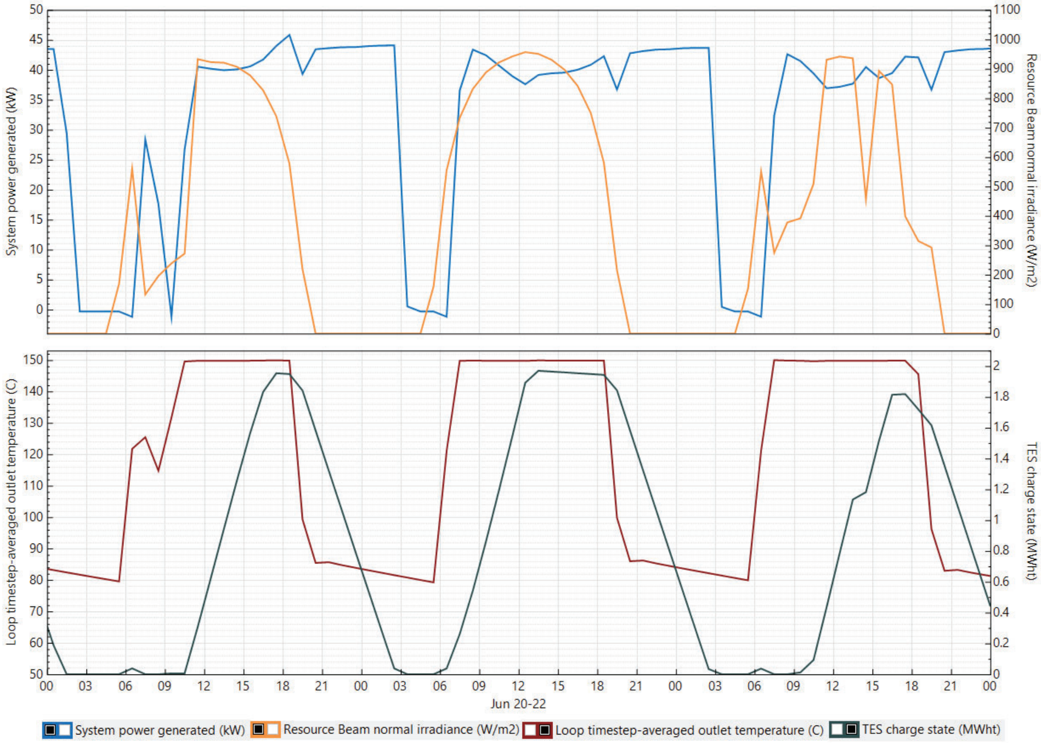


Figure. 14. System operation on a typical summer day [24].

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Figure 15 presents the monthly production of energy throughout the year, where it is possible to prove that most of the production takes place between March and September. That profile results from the climate discrepancy between the seasons of the year in Portugal.

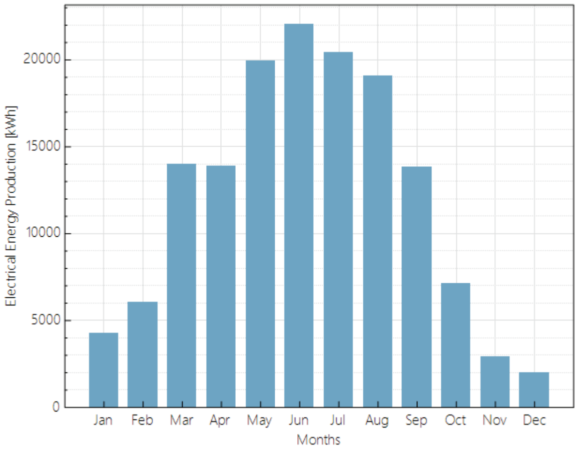

Figure. 15. Monthly electricity production in the first year of operation [24].

6. Conclusion

The shift in energy paradigm to reduce GHG emissions brings with it the need to replace the use of fossil fuels with renewable energies. In the power generation system, the transition to 100% renewable has some challenges to ensure the safety, reliability and dispatchability of the power grid. Following the development and investment in non-dispatchable electricity production technologies such as hydropower, wind, and PV, arises the need to create means of storage that allow a gap between renewable resource availability and electricity production.

CSP technology emerges as one of the potential solutions to ensure this gap. Its main advantage is the possibility of incorporating a TES system whose associated costs, as well as storage efficiency and environmental impact, make the technology favourable when compared to battery storage systems.

SAM is one of the leading tools for the techno-economic analysis of renewable energy systems, but its use for small-scale CSP systems analysis has proved challenging. Despite this, it was possible to implement a small-scale CSP case study that enabled the integration of an ORC actual data. The main results are: annual electricity production (145529 kWh), system cost ($559416.06), capacity factor (36.9%) and LCOE ($0.3009/kWh).

Even though SAM has several options that allow to create models with different characteristics and functions, it was found that it is not fully adapted for systems with such a small scale.

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