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An Analytical Approach to Power Optimization of Concentrating Solar Power Plants with Thermal Storage

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Abstract: This paper deals with the problem of determining the optimal capacity of concentrated solar power (CSP) plants, especially in the context of hybrid solar power plants. This work presents an innovative analytical approach to optimizing the capacity of concentrated solar plants. The proposed method is based on the use of additional non-dimensional parameters, in particular, the design factor and the solar multiple factor. This paper presents a mathematical optimization model that focuses on the capacity of concentrated solar power plants where thermal storage plays a key role in the energy source. The analytical approach provides a more complete understanding of the design process for hybrid power plants. In addition, the use of additional factors and the combination of the proposed method with existing numerical methods allows for more refined optimization, which allows for the more accurate selection of the capacity for specific geographical conditions. Importantly, the proposed method significantly increases the speed of computation compared to that of traditional numerical methods. Finally, the authors present the results of the analysis of the proposed system of equations for calculating the levelized cost of electricity (LCOE) for hybrid solar power plants. The nonlinearity of the LCOE on the main calculation parameters is shown.

Keywords: concentrated solar power; thermal storage; hybrid solar power plants; design factor; solar multiple factor; optimization model; analytical approach

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1. Introduction

Current global developments once again demonstrate the need for reliable, readily available and predictable access to (electrical) energy. Solar energy has the potential to be a large quantitative source of long-term, reliable energy that is not dependent on any particular market player [1]. In order to provide electrical power according to the demand of the grid, the fluctuating availability of local solar power must be balanced. Concentrating Solar Power (CSP) provides relatively inexpensive medium-term energy storage in the form of heat that can be converted into electricity on demand. There are line-focusing and point-focusing CSP systems.

Point source CSP plants concentrate sunlight from a large area via mirrors (heliostats) onto a small receiver aperture at the top of a tower, which can easily reach temperatures above 1000 °C [2]. Due to the potential to reach high temperatures, solar tower plants (STPs) also offer good opportunities for chemical processing to produce substances that act as storage and/or fuel for other processes (ammonia, H2, etc.) [3]. Line-focusing CSP plants use parabolic mirrors to concentrate sunlight onto receiver tubes through which a heat transfer fluid flows. Parabolic trough plants (PTPs) typically operate in the 300–400 °C temperature range [4].

In solar towers and parabolic troughs, the heat generated can be stored in molten salt storage tanks and converted into electricity by a power unit. The power unit consists of a heat engine using a thermodynamic cycle and a generator. The design of a CSP plant is mainly determined by the size of the solar field and receiver, the storage capacity, and the gross electrical rated output of the power unit.

The operating costs of generating electricity and meeting demand generally increase with the size of the components. At the same time, the capital cost per unit of electricity decreases. In addition, the estimation of these values is highly dependent on the daily and monthly variations in solar energy as well as the energy demand schedule. The balance between demand and generation is achieved by energy storage. Therefore, finding the economically optimal design for a given site and demand profile becomes a non-trivial task that can be solved using optimization methods. In this article, a new analytical optimization approach is proposed to investigate the fraction of available solar energy that should be used by CSP at a given site, so that the rest can be covered by other systems e.g., photovoltaic (PV).

The method presented in this research can also be used to calculate the optimal ratio of heat production from CSP to electricity production from PV in solar fuel production systems, according to the scheme presented in [5].

The focus of this study is the projected concentrated solar power plant as a part of hybrid renewable power plants. The subject of this study is the functional dependence between the levelized cost of electricity (LCOE) and the projected CSP power. LCOE is an indicator used to compare the cost of generating electricity from different sources and is the main criterion for the economic viability of CSP construction [6]. It includes capital, operating, maintenance, fuel, financing and decommissioning costs over the life of the plant.

The purpose of the article is to build a target function to determine the optimal integrated CSP capacity to obtain the minimum levelized cost of electricity. Two dimensionless parameters were used for this purpose: the design factor (DF) and solar multiple (SM). The SM is a factor used in CSP installations to compare the actual thermal output of the solar field with the thermal output required for the power unit. It helps to optimize the size of the solar field, which allows for efficient energy storage and maximizes electricity production [7]. An SM greater than 1 indicates an excess capacity for storage or increased generation, while an SM equal to 1 means that the solar field produces exactly the same thermal power as the power unit [8]. The design factor is the coefficient equal to the ratio of the CSP capacity to the maximum required capacity of the power plant.

2. Materials and Methods

The issue of power optimization in CSP plants has been raised by different authors to determine the features of a hybrid CSP plant [9], to develop a strategy to mitigate the effects of high-power electricity shortages [10], to investigate the impact of weather forecast uncertainties [11] and to improve the efficiency of CSP cavity absorbers [12]. Optimizing the design of a mirror field is a compromise between the possible thermal power of the field and the cost [13]. One of the most effective procedures for determining the characteristics of the mirror field is to determine the radial shift [14]. In this paper, it is proposed to consider the optimization of the solar power plant capacity embedded in a hybrid system to determine the main parameters of influence on which to focus and to find new engineering solutions to improve CSP plants.

The main criteria for the implementation of solar power plants is the determination and comparison of the following values: the levelized cost of electricity (LCOE), net present value of the project (NPV), benefit-to-cost ratio (BCR), total capital cost, and annual load satisfaction factor (ALSF) [15]. According to the authors, the most influential of the above criteria that affects the use of CSP and the construction of new plants is the price per kWh of electricity produced: the LCOE. At a given power consumption and due to the nature of the change in solar radiation during the year (given by the schedule of solar irradiance for the duration of the year), it is necessary to determine the characteristic parameters of the CSP (solar receiver, tower height, field size and layout, power block size, thermal energy storage (TES) size) considering the minimization of the price per kWh of electricity produced.

The available solar power of the solar power plant N_{DNI}^{avail} and its geographically advantageous location are determined on the basis of GIS (geographical information system) assessment using the average annual amounts of direct normal irradiation (DNI) [16]. As a rule, this task is solved with the help of state-of-the-art tools to optimize the LCOE of CSP plants like SAM (NREL) or Greenius from DLR [17,18].

SAM is a techno-economic computer model designed to facilitate decision making for people involved in the renewable energy industry [19]. For example, a model of a SUPCON Delingha 50 MW MS ST plant was developed with SAM and a simulation took place in order to calculate the annual electrical output performance of the commercial power plant [20]. SAM is a very useful tool, making it possible for solar energy professionals to analyze photovoltaic systems and concentrate solar power parabolic trough systems in the same modeling platform using consistent financial assumptions. Such a PV-CSP power plant with a parabolic trough of 50 MW gross capacity has been simulated with SAM for two different locations in Southern Spain and South Africa [21]. It has also been used for a research study which investigated the concept of providing both heat and power from a PV and CSP hybrid plant to meet the energy demand of LNG export terminals [22].

Another approach is the use of a Hybrid Optimization and Performance Platform (HOPP), as mentioned in [23], in order to evaluate the technological and financial performance of a CSP-PV hybrid system without detailed modeling of annual operations. A HOPP is an open-source modeling tool that uses a Python-based scripting interface to access and combine underlying single-technology performance models in NREL's System Advisor Model (SAM) to evaluate the performance and financial viability of hybrid renewable energy systems [24].

Greenius [25] is a simulation tool for the annual yield assessment of solar energy systems. It can be used to calculate the operation of a solar power plant depending on irradiance data in hourly or sub-hourly fidelity using a set of technical parameters to define the plant design as well as a predefined operation strategy. It is usually used to evaluate a typical operational year (TOY) of a solar power plant with operational results describing the plant state in every time step of a typical meteorological year (TMY). With the results of the TOY and additional economic parameters, defining the costs and financing a detailed economic evaluation can be performed, calculating the cash flow and key performance indicators like the levelized cost of electricity (LCOE) and the capacity factor (CF). The modeling in Greenius is based on the energy flow between the components, assuming steady-state behavior. Some transient effects in the scope of the time step size are accounted for using simplified equations. Such effects occur for components with large thermal inertia, e.g., the heating up and cooling down process of the solar field or the power block. To optimize a plant layout for a certain site, Greenius can be used to evaluate different plant designs via grid search with varying technical parameters and compare the results using the key performance indicators.

In contrast to a numerical solution, here, the authors propose an analytical approach to optimization. The analytical approach is simple and fast to solve and allows for the minimization of the investment to obtain a profit close to the maximum. It also shows the capacity limit below which the construction of a CSP plant is not cost-effective. The analytical approach to the equation also allows the designer of a CSP plant to quickly perform a comprehensive analysis and find the conditions under which the LCOE at a given site will change its character. This will allow for the analysis of how changes in these conditions will change the optimum of the LCOE function. It is planned that the proposed analytical approach, in combination with existing LCOE calculation software, will allow for a comprehensive analysis of the optimization of several variables in the design process of CSP plants.

The proposed analytical approach is centered around the incorporation of the design factor and the solar multiple factor into a mathematical optimization model. This model specifically targets the power capacity of concentrated solar power plants with thermal storage as the primary energy source.

Hybrid CSP systems can combine the best of CSP and PV renewable energy. By seamlessly integrating solar thermal and electrical conversion methods, these systems ensure a consistent and efficient power supply. Such hybrid system solutions, including connection with a PV field, have been identified as a viable solution to reduce the LCOE of CSP plants while maintaining the flexibility and high capacity factors granted by the TES unit [26]. The PV unit is used to directly produce cheap power during daylight, while the CSP unit offers the storage capacity, e.g., of molten salt TES, as shown in [27], which guarantees the required flexibility and power production during evening and night, increasing the plant capacity factor. With the added benefit of energy storage integration, hybrid CSP systems promise uninterrupted power even during periods of low sunlight or high demand.

In optimization models, the input information is the load forecast data and the projected electricity demand. The amount of electricity to be generated is defined as

$$E_{year}^{need} = E_{year}^{CSP} + E_{year}^{PV}, \tag{1a}$$

$$E_{year}^{CSP} = \int_{0}^{\tau} P_{CSP} dt = P_{CSP}^{max}\, h_{CSP}^{FLH} \tag{1b}$$

where τ—the time period considered, usually $\tau = 1\ year$;

P_{CSP}^{max}—the necessary electric power to fulfill the demand schedule from CSP;

h_{CSP}^{FLH}—the number of hours of operation per year, according to which the amount of electricity produced will be equal to the yearly energy consumption. It is usually referred to as the full-load hours (FLH), or the annual full-load hours for a year.

Figure 1 shows the main considerations regarding the dependence of the required CSP power demand on the CSP operating time. The area of the graph (yellow) corresponds to the CSP power demand. If we represent the selected area (the same amount of electricity generated) as a rectangle with a height of P_{CSP}^{max}, we obtain the imaginary number of hours h max that the CSP should operate to obtain E_{year}^{need}. If a CSP is designed with less than the required capacity for a given area P_{CSP}^{design}, the lack of electricity can be compensated for by energy storage and PV. Thus, the red line shows the theoretical operation of a CSP plant with a capacity of $P_{CSP}^{design}$and possibly three periods of plant shutdown. P_{CSP}^{design}—the normalized design capacity of the CSP. $P_{hybrid} = P_{need}^{peak}$—the maximum required electric output power of the hybrid plant from demand schedule. For CSP without PV, $P_{CSP}^{max} = P_{need}^{peak}$.

The full-load hours are calculated as follows:

$$h_{CSP}^{FLH} = \frac{E_{year}^{CSP}}{P_{CSP}^{max}} \tag{2}$$

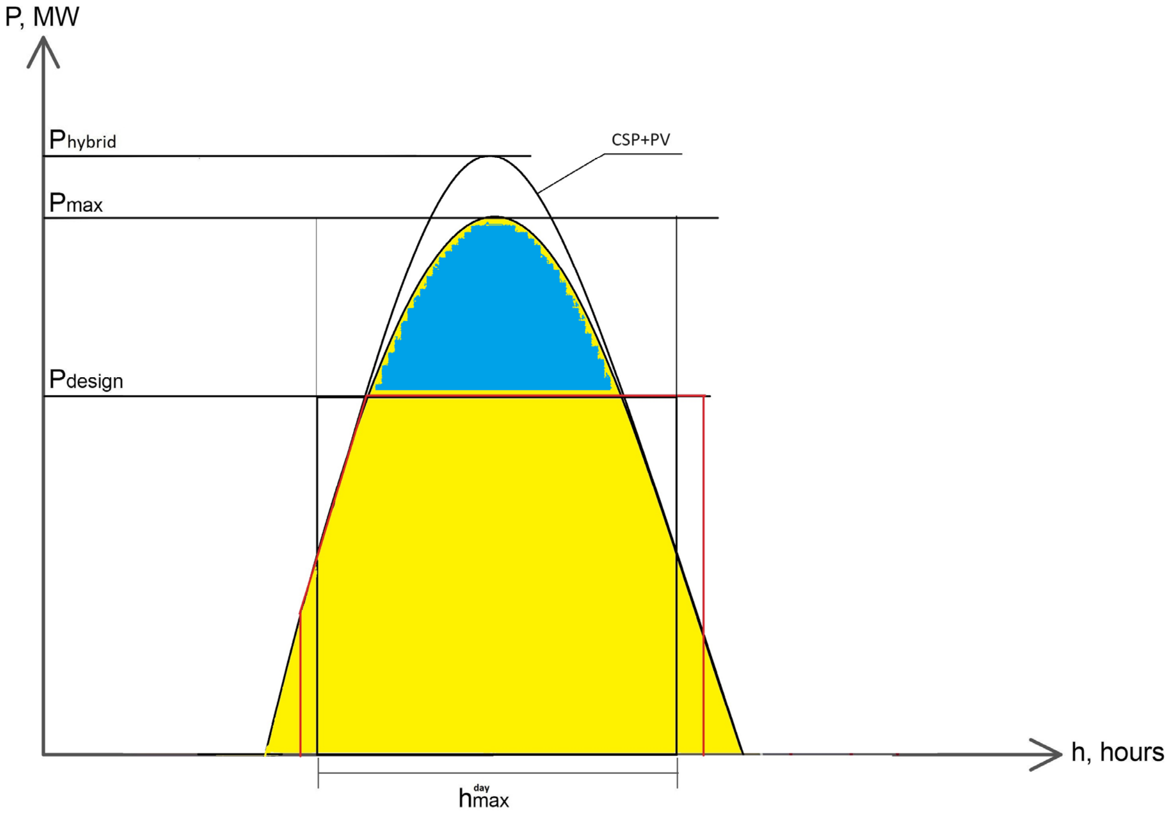

Figure 1. Schematic explanation of the calculation of h_{CSP}^{FLH} by different types of hybrid power plant elements: yellow is the planned electricity produced by CSP, blue is the energy produced for thermal storage. The red line is the planned mode of operation. No color area—CSP+PV.

The CSP electricity generation per year is calculated as follows:

$$E_{year}^{\text{design}} = P_{CSP}^{design}\, h_{CSP}^{FLH} \tag{3}$$

The target function of the complex optimization of energy supply is the sum of the specific costs of electricity, €/(MWh). For this approach, the concept of the levelized costs of electricity (LCOE) to define the economically viable specific costs of electricity production in €/MWh is used [28]:

$$LCOE = \frac{TLCC}{\sum_{y=1}^{Y} \frac{E_y}{(1+i)^y}} \tag{4}$$

where *TLCC*—total life cycle cost;

E_y—produced energy in year y;

Y—total number of years considered for the operation of the plant;

i—considered discount rate.

The results of annual simulations for PV CSP hybrid concepts are mainly compared, using the levelized electricity cost as the figure of merit for comparing the different configurations, as shown in [29].

Using the assumption of constant yearly operational costs defined as operational expenditures (OPEX) and the capital invested in the beginning defined as capital expenditures (CAPEX) as well as a constant yearly electricity production of E_{year}, the annuity factor to simplify the equation is introduced as

$$LCOE = \frac{CRF\ CAPEX + OPEX}{E_{year}} \quad (5)$$

The capital recovery factor is as follows:

$$CRF = \frac{(1+i)^Y\ i}{(1+i)^Y - 1} \quad (6)$$

A weighted average cost of capital method [29] for the discount rate is used to depict the costs of equity i_{equ} and debt i_{debt} less the income taxes:

$$WACC = (1 - f_{debt})\ i_{equ} + f_{debt}\left(1 - r_{tax,inc}\right)\ i_{debt}. \quad (7)$$

To account for further tax costs, the fixed charge rate FCR, according to [30], is introduced:

$$FCR = CRF\ \frac{1 - r_{tax,inc}\ PrV_{depr}}{1 - r_{tax,inc}}, \quad (8)$$

where PrV_{depr}—the present value of the depreciation cash flows.

The depreciable money benefits can be calculated depending on the present value of the depreciated cash flows assuming a linear depreciation schedule:

$$PrV_{depr} = \sum_{y=1}^{Y_{depr}} \frac{1}{Y_{depr}\ (1 + WACC)^y} \quad (9)$$

To represent the optimal yearly electricity production in consideration of the production costs and the demand–coverage ratio, the LCOE is extended by further specific cost components in €/MWh representing the specific reduced cost due to the damage caused by the network failure flow Z_{CSP}^{fail} and costs due to penalties $Z_{CSP}^{penalties}$:

$$LCOE = \frac{FCR\ CAPEX + OPEX}{E_{year}} + Z_{CSP}^{fail} + Z_{CSP}^{penalties} \rightarrow min \quad (10)$$

According to the life cycle assessment performed in reference [31], the operation phase decreases with increasing capital expenditures in CSP. So $OPEX = f\left(\alpha_{CSP} \cdot N_{DNI}^{avail}\right)$. But there is still no specific model for building an optimization function for changing the cost of electricity from the power of the plant.

3. The Proposed Function of Optimization

3.1. The Mathematical Model

For CSP with thermal storage, it is necessary to design a solar field larger than the required thermal load for the power unit. Therefore, the solar multiple factor (SM) [32,33] is introduced as the ratio of the available thermal power from the solar field to the input thermal power of the power unit:

$$SM = \frac{\dot{Q}_{SF}^{max}}{\dot{Q}_{PB}^{design}} \quad (11)$$

where $\dot{Q}_{SF}^{max}$—the thermal power output of the solar field at the reference DNI value;

$\dot{Q}_{PB}^{design}$—the design nominal electric output power CSP according to its efficiency.

For the averaged values,

$$SM = \frac{P_{CSP}^{max}}{P_{CSP}^{design}} \frac{\eta_{CSP}^{design}}{\eta_{CSP}^{max}} \quad (12)$$

where η_{CSP}^{max} and η_{CSP}^{design} —the effectiveness CSP for P_{CSP}^{max} and P_{CSP}^{design}.

η_{CSP}—efficiency CSP. In this study, it is assumed to be linearly dependent on the receiver efficiency. Then, according to [34], $\eta_{CSP} = a \cdot ln(f_j) + b$. Here, a, b—const $a > 0$, $b < 1$. Hence, η_{CSP} does not depend on the CSP capacity.

The amount of electricity to be produced by the CSP plant is given by

$$E_{year}^{CSP} = E_{year}^{\text{design}} + E_{year}^{\text{TES}} \tag{13a}$$

where E_{year}^{TES}—the energy from thermal storage. So

$$E_{year}^{CSP} = P_{CSP}^{design}\ h_{CSP}^{FLH} + E_{year}^{\text{TES}} \tag{13b}$$

To find the analytical optimization function, the concept of the design factor by analogy with a combined heat and power plant is introduced as in [35]. Here, DF is a coefficient equal to the ratio of the CSP capacity to the maximum required capacity of the power plant. $DF \in [0, 1]$ is defined as

$$DF = \frac{P_{CSP}^{max}}{P_{\text{need}}^{peak}} \tag{14}$$

where P_{CSP}^{max}—the design nominal electric output power of the CSP according to its efficiency.

P_{need}^{peak}—the maximum required electric output power of the hybrid plant from the demand schedule.

If $P_{\text{need}}^{max} = I\frac{P_{CSP}^{max}}{DF}$, the maximum electric output power of the CSP plant is required from the demand schedule (the design power of the entire power plant), so

$$E_{year}^{need} = P_{CSP}^{design}\ h_{CSP}^{FLH} + E_{day}^{\text{TES}}\, day + (1 - DF)\, P_{\text{need}}^{peak}\ h_{CSP}^{FLH} \tag{15}$$

where E_{day}^{TES}—the energy from storage, MWh/day;

day—the number of days per year of CSP working time.

The storage capacity relative to the nominal thermal input power of the power block in h/day is calculated using

$$CP_{TES} = \frac{Q_{day}^{\text{TES}}}{\dot{Q}_{PB}^{design}} = \frac{Q_{day}^{\text{TES}}\, \eta_{pow}}{P_{CSP}^{design}} \tag{16a}$$

where η_{pow}—the efficiency of the power block;

Q_{day}^{TES}—the thermal energy storage capacity in MWh/day.

$$Q_{day}^{\text{TES}} = E_{day}^{\text{TES}}/\eta_{TES} \tag{16b}$$

$$E_{year}^{\text{TES}} = E_{day}^{\text{TES}}\ \frac{h_{CSP}^{FLH}}{24} \tag{16c}$$

Therefore,

$$E_{year}^{need} = P_{CSP}^{design}\ h_{hybrid}^{FLH} + \frac{CP_{TES}}{\eta_{pow}}\ P_{CSP}^{design}\ \eta_{TES}\ \frac{h_{hybrid}^{FLH}}{24} + P_{CSP}^{max}\ \frac{1 - DF}{DF}\ h_{hybrid}^{FLH}; \tag{17a}$$

$$E_{year}^{need} = P_{CSP}^{design}\ h_{hybrid}^{FLH}\left[1 + \frac{\eta_{TES}}{\eta_{pow}}\ CP_{TES}\ \frac{1}{24} + SM\ \frac{\eta_{CSP}^{max}}{\eta_{CSP}^{design}}\frac{(1 - DF)}{DF}\right]; \tag{17b}$$

$$E_{year}^{CSP+TES} = P_{CSP}^{design}\ h_{CSP}^{FLH}\left[1 + \frac{\eta_{TES}}{\eta_{pow}}\ CP_{TES}\ \frac{1}{24}\right]; \tag{17c}$$

$$h_{CSP}^{FLH} = \begin{cases} h_{CSP}^{avaible}, \text{ if } h_{CSP}^{FLH} > h_{CSP}^{avaible} \\ \dfrac{E_{year}^{need}}{P_{CSP}^{design}\left[1 + \dfrac{\eta_{TES}}{\eta_{pow}} CP_{TES}\, \dfrac{1}{24}\right]}, \text{ if } h_{CSP}^{FLH} < h_{CSP}^{avaable} \end{cases} \quad (17d)$$

This equation shows the relationship between the required energy and the designed capacity of the CSP output unit through the parameters CP_{TES}, SM, α_{CSP} and the efficiency of the plant. Assume that the dependence of the CSP efficiency on the receiver efficiency is known. Then, P_{CSP}^{design} is dependent on three parameters, CP_{TES}, SM and DF.

To reduce the number of input parameters, we can define the location where the CSP is designed. The electrical power of the CSP depends on the efficiency, the DNI value, and the mirror area.

The area of the solar field for range P_{CSP}^{max} is

$$A_{CSP}^{max} = SM \cdot A_{CSP}^{design} = \frac{E_{year}^{CSP}}{\int_0^n DNI^n dh\, \eta_{CSP}^{design}} \quad (18)$$

where dh —the hours of DNI data resolution.

Assuming a constant efficiency for the normalized available operating hours, the following equation results:

$$h_{CSP}^{FLH} = \frac{\int_0^n DNI^n\, dh\, SM\, A_{CSP}^{design}}{P_{CSP}^{max}\, \eta_{CSP}^{design}} \quad (19)$$

where A_{CSP}^{design}—the area of the solar field for reaching $P_{CSP}^{designe}$.

To consider the minimum and maximum capacity of the power generation system during deviations from the selected average value,

$$DNI^n = \begin{cases} 0 \text{ for } DNI^n \leq\ 10\% \cdot DNI^{design} \\ DNI^n \text{ for } 10\%\, DNI^{design} \leq P_{CSP}^n \leq 120\%\, DNI^{design} \\ 120\%\, DNI^{design} \text{ for } DNI^n \geq\ 120\%\, DNI^{design} \end{cases} \quad (20)$$

Assuming that excess power is generated due to deviations between the maximum power generation and design and is fed into the energy storage, the following equation results:

$$CP_{TES} = \frac{\left(E_{year}^{CSP} - E_{year}^{\text{design}}\right)\eta_{pow}}{P_{CSP}^{design}\ \eta_{TES}} \frac{24}{h_{CSP}^{FLH}} \quad (21a)$$

And Equation (18) is used:

$$CP_{TES} = \frac{\left(SM\, A_{CSP}^{design} \int_0^n DNI^n\, dh\, \eta_{CSP}^{design} - P_{CSP}^{design}\ \ h_{CSP}^{FLH}\right)\eta_{pow}}{P_{CSP}^{design}\ \eta_{TES}} \frac{24}{h_{CSP}^{FLH}} \quad (21b)$$

Or suppose that the energy for the energy storage is extracted by increasing the area of the mirror field; then, the following equation can be used:

$$CP_{TES} = \frac{\left(P_{CSP}^{max}\eta_{CSP}^{design} h_{CSP}^{FLH} - P_{CSP}^{design}\ \ h_{CSP}^{FLH}\right)\eta_{pow}}{P_{CSP}^{design}\ \eta_{TES}} \frac{24}{h_{CSP}^{FLH}} \quad (22a)$$

$$CP_{TES} = 24 \frac{\left(P_{CSP}^{max}\eta_{CSP}^{design} - \dfrac{P_{CSP}^{max}}{SM}\dfrac{\eta_{CSP}^{design}}{\eta_{CSP}^{max}}\right)\eta_{pow}}{\dfrac{P_{CSP}^{max}}{SM}\dfrac{\eta_{CSP}^{design}}{\eta_{CSP}^{max}}\ \eta_{TES}} \quad (22b)$$

$$CP_{TES} = 24\frac{(SM-1)\,\eta_{pow}}{\eta_{TES}} \tag{23}$$

Given that the dependence A_{CSP}^{design} is determined by the type and internal characteristics of the designed CSP, it is assumed that $\left(\frac{A_{CSP}^{design}}{P_{CSP}^{design}}\right)_{ref}$ is known.

In reality, not all of the solar energy can be used because the storage has a maximum capacity and the components need to warm up and cool down. Depending on the storage size, the irradiance distribution, the sunshine hours, and the solar multiplier, the real normalized operating hours can be defined as

$$h_{CSP}^{available} = h_{CSP}^{FLH} - f\left(f_j, h_{sd}, DNI^{ref}\right) \tag{24}$$

where DNI^{ref}—the reference DNI for the normalized value for operating hours;

h_{sd}—the sunshine duration, h/year;

f_j—the relative load corresponding to the average arrival of solar radiation [36].

$$f_{\mathrm{j}} = \frac{\exp\left(-\beta\,\frac{D_j - D_{min}}{D_{max} - D_{min}}\right)}{\sum_{j=1}^{J}\exp\left(-\beta\,\frac{D_j - D_{min}}{D_{max} - D_{min}}\right)} \tag{25}$$

where D_{max} *and* D_{min} denote the maximum and minimum distance among historical days to the current forecasting day, respectively.

β is a free parameter controlling the effective number of profiles which are averaged.

Dj is the distance between the current day and the historical day.

The accuracy of load forecasting for CSP is directly affected by input uncertainties such as the weather forecast. These are specified by black box models, or white box models, to provide a probabilistic load forecast [37]. Using Gaussian kernel density estimation, the procedure converts the point load forecast into a probabilistic load forecast based on historical data provided by the internal and external monitoring system.

3.2. The Function of Optimization

The target function is the following:

$$LCOE = \frac{FCR\ CAPEX + OPEX}{P_{CSP}^{design}\ h_{CSP}^{FLH}\left[1 + \frac{\eta_{TES}}{\eta_{pow}}\ CP_{TES}\ \frac{1}{24} + SM\ \frac{\eta_{CSP}^{max}}{\eta_{CSP}^{design}}\ \frac{1-DF}{\mathrm{DF}}\right]} + Z_{CSP}^{fail} + Z_{CSP}^{penalties} \to min \tag{26}$$

where Z_{CSP}^{fail} —mathematical expectation of the specific impaired value due to losses caused by the flow of failures in the network;

$Z_{CSP}^{penalties}$—the cost and the penalty function.

The *CAPEX* can be divided into overnight capital costs *OCC* and costs for network connections $C_{transit}$ as well as costs for financing the construction C_{fin}.

$$CAPEX = OCC + C_{transit} + C_{fin} \tag{27a}$$

The EPC costs are divided into component costs, land costs including preparation, and service costs and are extended by a contingency factor f_{cont}. The *OCC* cost components all depend on the size of the plant and therefore on DF. The scaling can be performed using an exponential economy of scale relationship, as described in [38].

$$OCC = OCC_{CSP} + OCC_{PV}; \tag{27b}$$

$$OCC_{CSP} = (C_{comp}^{max}\ (DF)^{s_{comp}} + C_{service}^{max}\ (DF)^{s_{service}} + C_{land}^{max}\ DF) \cdot f_{cont}; \tag{27c}$$

$$OCC_{PV} = (C_{comp}^{max}\,(1-DF) + C_{service}^{max}\,(1-DF) + \ C_{land}^{max}\ (1-DF))\,f_{cont}; \quad (27d)$$

where C_{comp}—capital investment for all components and equipment [€];

$C_{service}$—capital investment for all engineering, procurement and construction services [€];

C_{land}—capital investment to purchase and prepare the land [€];

DF—design factor (Equation (14));

f_{cont}—contingencies relative to the investment costs [%];

s_{comp}—exponential scaling factor for component costs, s_{comp} = [0.7, 0.9] [38];

$s_{service}$—exponential scaling factor for service costs, $s_{service}$ = [0.3, 0.5] [38].

$$C_{service}^{max} = \ C_{comp}^{max}\,f_{service} \quad (27e)$$

where $f_{service}$—factor of service costs to component costs, which are usually around 5% [38].

The transit costs are mainly associated with the construction of transit networks from the CSP to the distribution point:

$$C_{transit} = \ K_{max}^{tr}\,n\,\eta_{tr}\,L_{\text{B}} + Z_{min}^{tr}\ \ E_{year}^{need} \quad (27f)$$

where K_{max}^{tr}—capital investments in electricity transit networks, €/m;

n—the number of parallel strands of wire 1 or 2;

η_{tr}—the network performance indicator;

L_{B}—the transit network length, m;

Z_{min}^{tr}—the minimum cost of the necessary equipment, €/MWh.

The construction finance costs depend on the capital investment and therefore can be introduced relative to the *OCC* and transit costs. They include costs for up-front and commitment fees r_{fees}, for the interest during construction i_{constr}, assumed to be accountable for half of the construction period N_{constr}, and additional money loaned for reserve accounts r_{res}:

$$C_{fin} = f_{debt}\,(OCC + C_{transit})\,(r_{fees} + i_{constr}\,\frac{N_{constr}}{2} + r_{res} \quad (27g)$$

The annual operational expenditures *OPEX* are divided into fixed and variable costs C_{fix} and C_{var}, both in €, and are introduced as [39]

$$OPEX = C_{fix} + C_{var} \quad (28a)$$

Fixed operating costs are the costs of land lease, insurance, personnel, and the operation and maintenance of components. They can be represented by a functional relationship to the electrical capacity of the plant P_{CSP}^{design}:

$$C_{fix} = \ c_{fix}\ P_{CSP}^{design} \quad (28b)$$

where c_{fix}—the relative fixed OPEX costs per year in €/*kW-yr.*

Variable operational costs are costs in € depending on the yearly electricity produced, e.g., for auxiliary electric consumption or water use. This leads to

$$C_{var} = \ c_{var}\,E_{year} \quad (28c)$$

where c_{var}—the relative variable OPEX costs per year in €/*MWh-yr.*

The mathematical expectation of the specific reduced cost due to the damage caused by the internal network failure flow is given by the following equation:

$$Z_{CSP}^{fail} = C_{\text{SCP}}n_{mirror}\frac{1}{h_{CSP}^{max}}\left\{1-\exp\left[-\frac{(\omega_{mirror}n_{mirror})h_{CSP}^{FLH}}{h_{year}}\right]\right\} + C_{PV}n_{PV}\frac{1}{h_{PV}^{max}} \times\left\{1-\exp\left[-\frac{(\omega_{PV}n_{PV})h_{PV}^{max}}{h_{year}}\right]\right\} \quad (29a)$$

where C_{CSP} , C_{PV}—the cost of repairing a mirror unit or PV panel €/(pcs);

n_{mirror}, n_{PV}, —the number of mirrors or PV panels;

ω_m—the mirror failure rate, 1/(year);
h_{PV}^{max}—the number of hours of PV operation per year;
A_{mirror}—the single mirror area.
Or

$$Z_{CSP}^{fail} = SM\, C_{\text{т}} \frac{A_{CSP}^{design}}{A_{mirror}} \frac{1}{h_{CSP}^{FLH}} \left\{1 - \exp\left[-\frac{(\omega_{mirror} n_{mirror}) h_{CSP}^{FLH}}{h_{year}}\right]\right\} + C_{PV} \frac{(1-DF)E_{year}^{need}}{P_{PV}^{pcs}} \frac{1}{h_{PV}^{max}} \times \left\{1 - \exp\left[-\frac{(\omega_{PV} n_{PV}) h_{PV}^{max}}{h_{year}}\right]\right\} \quad (29b)$$

where P_{PV}^{pcs}—the power of one panel, €/MWt.

Using this equation, it should be noted that α_{CSP} represents the ratio of the used plant size to the maximum plant size not only for the solar field but for all components and corresponding processes, influencing the costs as well as the yearly energy produced.

The function of costs and penalties is proposed and investigated by the authors in [40] for a 50 MW CSP plant with molten-salt-based $C_{CSP}^{penalties} = 7.69$ €/MWh, given the theoretical support from the government for the introduction of a green tariff at which $Z_{CSP}^{penalties} < 0$, so C_Z can be negative.

The target function has been calculated as

$$LCOE = \frac{FCR\ CAPEX + OPEX}{E_{year}} + SM\, C_{\text{т}} \frac{A_{CSP}^{design}}{A_{mirror}} \frac{1}{h_{CSP}^{FLH}} \left\{1 - \exp\left[-\frac{(\omega_{mirror} n_{mirror})\, h_{CSP}^{FLH}}{h_{year}}\right]\right\} + C_{\text{PV}} \frac{(1-DF)E_{year}^{need}}{P_{PV}^{pcs}} \frac{1}{h_{PV}^{max}} \left\{1 - \exp\left[-\frac{(\omega_{PV} n_{PV})\, h_{PV}^{max}}{h_{year}}\right]\right\} \to min \quad (30a)$$

$$E_{year}^{produce} = P_{CSP}^{design}\ h_{CSP}^{FLH} \left[1 + \frac{\eta_{TES}}{\eta_{pow}} CP_{TES} \frac{1}{24} + SM \frac{\eta_{CSP}^{max}}{\eta_{CSP}^{design}} \frac{1-DF}{DF}\right]; \quad (30b)$$

$$h_{CSP}^{FLH} = \begin{cases} h_{CSP}^{aviable}, if\ h_{CSP}^{FLH} > h_{CSP}^{aviable} \\ \dfrac{E_{year}^{need}}{P_{CSP}^{design}\left[1 + \frac{\eta_{TES}}{\eta_{pow}} CP_{TES} \frac{1}{24}\right]}, if\, h_{CSP}^{FLH} < h_{CSP}^{aviable}; \end{cases} \quad (30c)$$

$$CP_{TES} = \begin{cases} \dfrac{\left(SM\ A_{CSP}^{design} \int_0^n DNI^n dh\, \eta_{CSP}^{design} - P_{CSP}^{design}\ h_{CSP}^{FLH}\right)\eta_{pow}}{P_{CSP}^{design}\ \eta_{TES}} \dfrac{24}{h_{CSP}^{FLH}}\ for\ SM = const \\ 24 \dfrac{\left(1 - \frac{1}{SM}\frac{1}{\eta_{CSP}^{max}}\right)\eta_{pow}}{\frac{1}{SM}\frac{1}{\eta_{CSP}^{max}}\ \eta_{TES}}\ for\ \dot{Q}_{PB}^{design} = const \end{cases} \quad (30d)$$

$$P_{CSP}^{max} = DF\ P_{\text{need}}^{max}; \quad (30e)$$

$$P_{CSP}^{design} = \frac{DF\ P_{need}^{max}}{SM} \frac{\eta_{CSP}^{design}}{\eta_{CSP}^{max}}; \quad (30f)$$

$$CAPEX = OCC_{CSP} + OCC_{PV} + C_{transit} + C_{fin}; \quad (30g)$$

$$OCC_{CSP} = (C_{comp}^{max}\ (DF)^{0.8} + C_{service}^{max}\ 0.05\ (DF)^{0.4} + C_{land}^{max}\ DF)\ f_{cont}; \quad (30h)$$

$$OCC_{PV} = (C_{comp}^{max}\ (1 - DF)^{0.8} + C_{service}^{max}\ 0.05\ (1 - DF)^{0.4} + C_{land}^{max}\ (1 - DF))\ f_{cont}; \quad (30i)$$

$$OPEX = C_{fix} + c_{var\_CSP}\ DF\ E_{year}^{need} + c_{var_{PV}}\ (1 - DF)\ E_{year}^{need}. \quad (30j)$$

This function has three variables, SM, P_{CSP}^{design} and DF.

4. Results and Discussion

The following results are calculated according to the proposed mathematical dependencies with different technical and economic indicators of the plant. A techno-economic analysis has been developed for 15–150 MW CSP which used the function of optimization in this research. The storage capacity was from 0 to 10 h.

The type of CSP is that from a solar tower. The solar multiple is 1.5. The grid connection costs and costs of transit are not included. The location is Almeria, Spain. The efficiency of the CSP is a function of the power capacity and the efficiency ratio of the TES is set at 0.9. The prices of the equipment and service were chosen as those for 2022. Figure 2 shows the validation of the analytical model with the above parameters and the numerical model calculated by Greenius.

As can be seen from Figure 2, for the selected parameters, the data convergence is very high, which allows us to recommend the selected analytical approach for building an optimization model of hybrid power plants.

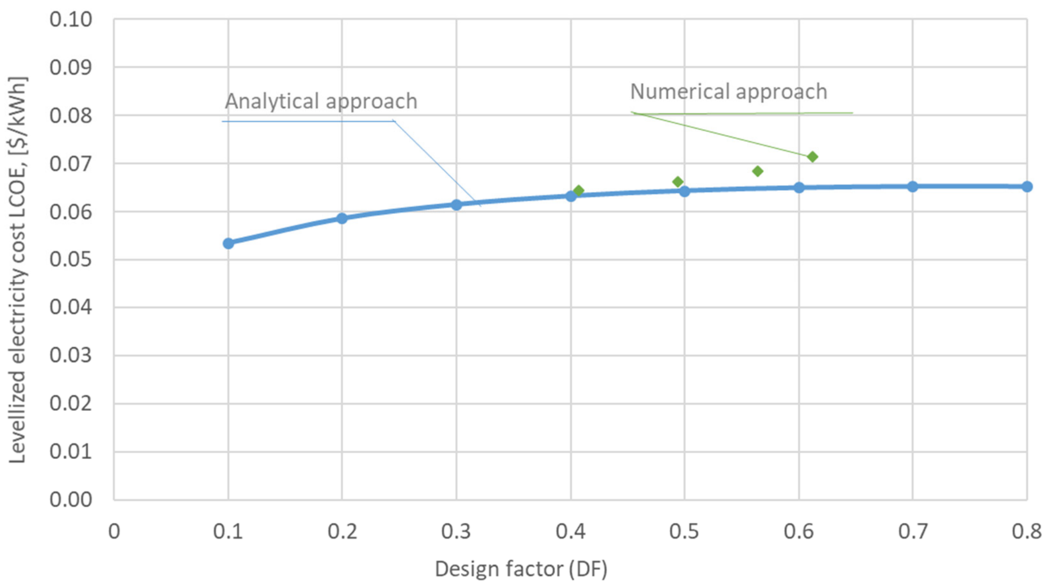

Figure 2. Comparison of analytical and numerical approach. The numerical approach overestimates the LCOE by about 6% but reflects the cost increase for higher design factors.

The same SPP parameters as before (without TES) and the same extremes of the function are obtained when the price of Battery Energy Storage Systems (BESSs) for PV storage is added (Figure 3). From the analysis of Figures 2 and 3, it can be seen that with the selected economic indicators, the optimization function has a minimum at the point $\alpha_{CSP} =$

0. So, with lower PV prices, and the higher the share of PV in the plant, the better. Therefore, the methods for finding the roots of the optimization function are not presented in this article. But this is true only for selected technical and economic indicators and may vary depending on the economic and political conditions of the area.

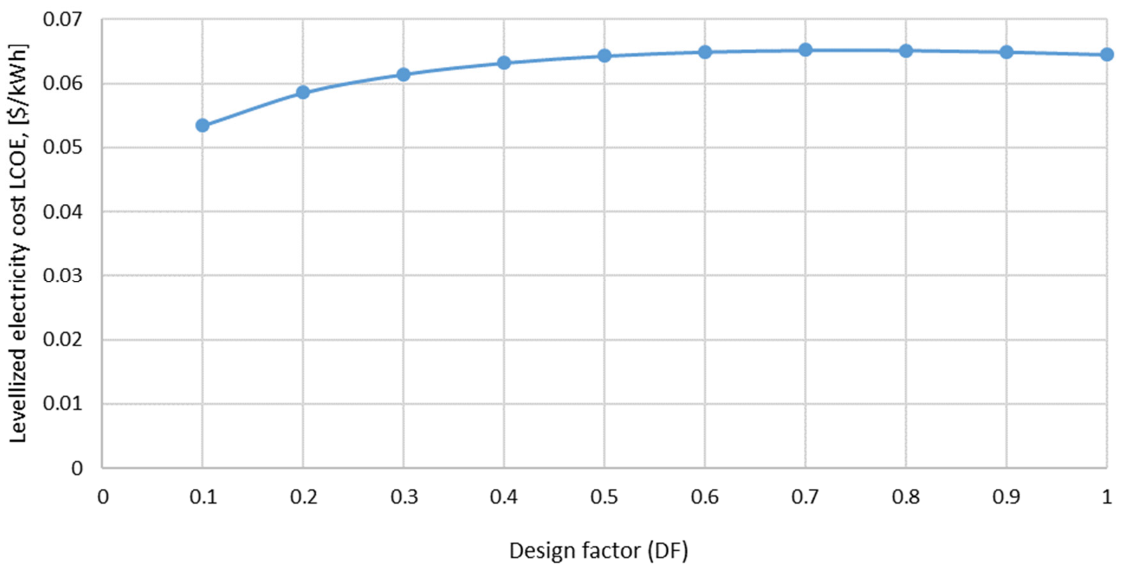

Figure 3. Levelized cost of electricity as a function of design factor with BESSs for PV shows higher LCOE for all DF values.

Figure 4 shows the percentage of electricity generated by different components of the hybrid power plant, calculated using the analytical model. In this case, it is assumed that all the excess energy from the SM goes to the energy storage, including additional energy losses. This figure shows that due to the TES, the generation of electricity from the PV and CSP is not linear.

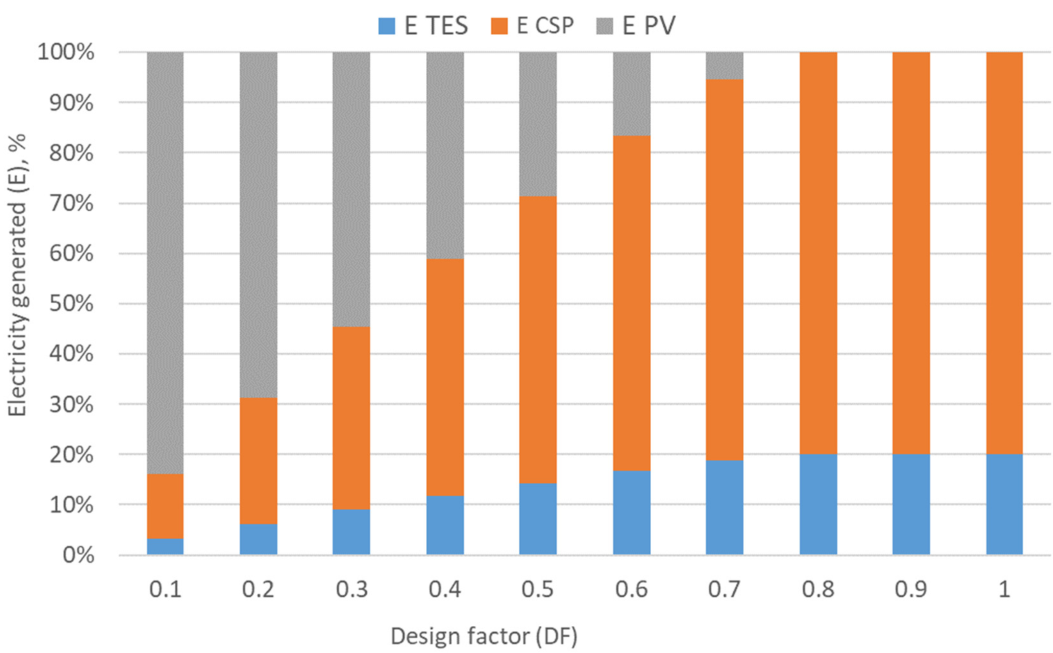

Figure 4. Share of electricity generated. Solar multiple (SM) = 1.3 with BESS for PV.

Since, in the proposed analytical method, the storage size function is set through the solar multiple factor, Figure 5 shows the change in the LCOE with the design factor DF. As the power of the concentrated station and the size of the mirror field increase, the size of the drive also increases, but the LCOE does not increase linearly. The nonlinearity is caused by the difference in the cost of the CP TES and the mirror field.

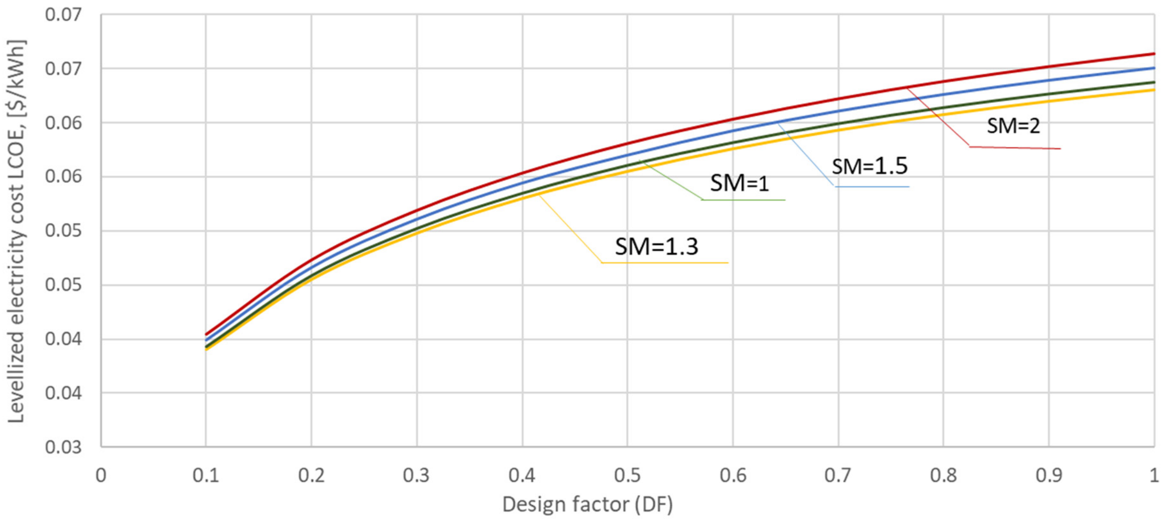

Figure 5. Dependence of levelized cost of electricity (LCOE) on design factor for different values of solar multiple (SM). The minimum LCOE is achieved at SM =1.3.

Despite the fact that the developed optimization model under the current economic conditions has an optimum at DF→ 0, the very method of building this model allows us to analyse various indicators of the designed hybrid power plant. Figure 6 also shows the existence of an SM optimum, which shows the importance of calculating the optimal capacity of a hybrid solar station for a specific geopolitical location in order to obtain the minimum LCOE.

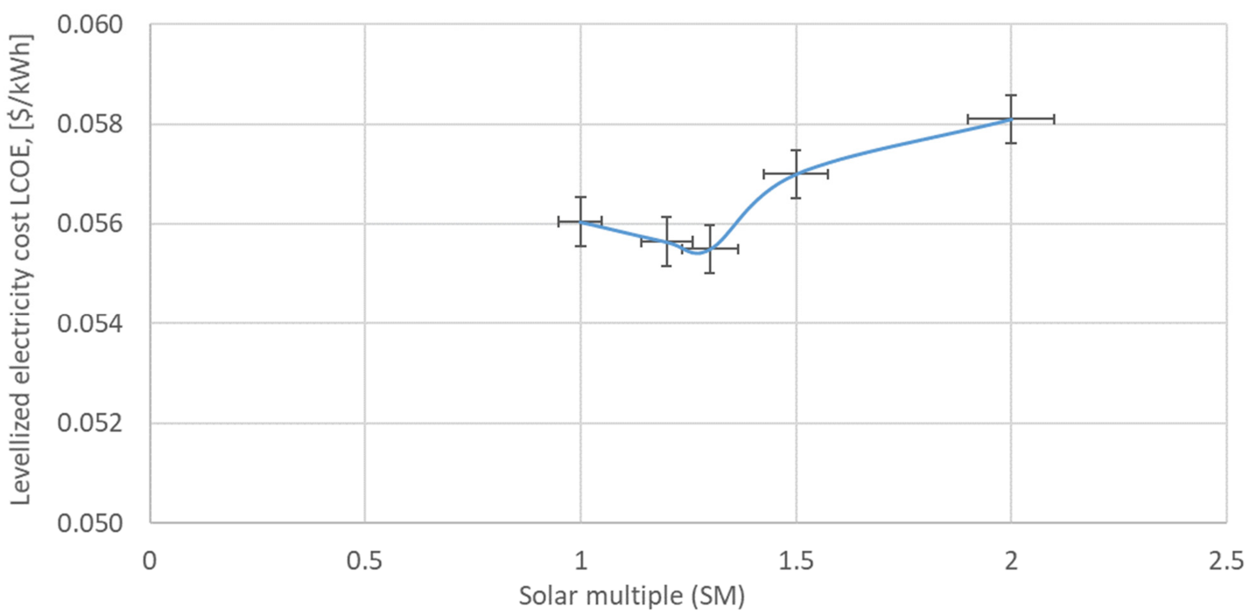

Figure 6. Dependence of the levelized cost of electricity from the solar multiple (SM) with design factors (DF) = 0.5. A clear extreme of the function is expressed.

5. Conclusions

This paper presents a novel analytical approach for optimizing the capacity of concentrated solar power plants in hybrid configurations. By incorporating the design factor and the solar multiple factor into a mathematical optimization model, the method provides a more detailed analysis of the design possibilities while offering faster computational speeds. This advancement contributes to ongoing efforts to improve the efficiency and feasibility of concentrated solar power plants, particularly in hybrid systems.

The developed analytical approach to the performance optimization of CSP plants has shown that it is possible to use analytical functions to obtain the same results as those usually obtained by numerical methods.

The cost of electricity in a hybrid power plant has been analyzed. Hybrid power plants show a relative LCOE with increasing storage capacity, but the cost of the PV-BESS system increases significantly due to higher storage costs. The costs of heat production from CSP without storage and PV systems with an electric heater are comparable.

As the design factor increases, the capital expenditures increase, but the operating costs decrease. Further research in the field of analytical calculations of the levelized costs of electricity for hybrid power plants could involve the calculation of the threshold level of economic indicators for which the use of CSP will be economically more feasible and the function LCOE = f(DF), DF∈(0;1) will be extreme.

The dependence LCOE = f (SM) is not linear and has a clear optimum (for the selected economic indicators at SM = 1.3; see Figure 5).

From the above, there are two different ways to determine the optimal storage capacity. The first way is to take the optimal SM value as a constant of the ratio of the mirror field area to the CSP capacity according to the CSP efficiency change graph, and direct the energy that is higher than this to the storage during peak hours. The second way is to take as constant the value of the $\dot{Q}_{PB}^{design}$ of the nominal electrical output power of the CSP according to its efficiency and to increase the SM to obtain energy for the energy storage. According to the authors, the best way to commence this research is to optimize these two functions using the regulator simplex method.

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