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Towards cost-competitive solar towers – Energy cost reductions based on Decoupled Solar Combined Cycles (DSCC).

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Abstract

A preliminary analysis of the potential for cost reduction of the innovative decoupled combined cycle concept for Solar Towers was presented in SolarPACES 2012 [1]. This work has been continued with a more detailed analysis of the cost-competitiveness of the decoupled solar combined cycle (DSCC) concept and is presented in this paper.

Solar towers that use a combined Brayton – Rankine cycle, in which the Brayton cycle is decoupled from the Rankine cycle by means of the thermal storage system, have shown up as a cost-effective alternative due to their increased flexibility in the design and operation leading to better efficiencies and reduced costs. This paper is focused in the Levelized Cost of Energy (LCOE) reduction that can be achieved by a mid-scale DSCC Solar Tower plant based mainly on already existing components and concepts, alongside simple and short term technological developments.

Since today's costs of medium size gas turbines are very competitive, while the specific cost of steam turbines still decreases significantly with size, this paper presents the analysis of a multi-tower system using several small Brayton cycles feeding a single oil-based storage system that, in turn, is used to drive a superheated Rankine cycle in a decoupled way (Fig. 1).

This paper presents a stochastic analysis of the cost and performance of the proposed DSCC plant by providing probabilistic cost and efficiency distributions to the most sensitive figures. The results obtained show that the DSCC concept has the potential to achieve cost reductions in the LCOE in the order of 25 % with a probability greater than 90 %, based upon short term technological developments and adaptations.

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Keywords: CSP; Decoupled Solar Combined Cycles; DSCC; Brayton; Rankine; storage system; multi-tower.

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1. Introduction

In [1] we presented the use of a decoupled Brayton and Rankine combined cycle as main innovative concept for achieving a substantial cost reduction in the solar electricity production. As stated in that work, the DSCC concept relies not only on the decoupled operation of the topping and bottoming power cycles, but also on the wide range of possibilities for the design of each plant subsystem and for the combination of different technologies that allows creating flexible, reliable, and more cost-effective systems.

Similarly, several characteristics are considered for the Solar Tower concepts presented in this paper in order to reach a substantial cost reduction in the final energy yield. These characteristics go from the innovative decoupled combined cycles by means of a large capacity storage system, to the multi-tower concept with small and thus efficient heliostat fields, as well as the use of small single facet heliostats with a significant cost reduction potential.

Before carrying out the analysis of the proposed concept a wide literature review of the literature regarding the main concepts considered has been accomplished. Some remarkable references are cited here: regarding solar combined cycles, [2]-[4], solarized turbines [5]-[7], solar field design [8]-[9] and high temperature receivers [10]-[11]. From all the information gathered and the wide range of possibilities available, one DSCC concept has been identified. This concept is based in the most plausible technologies and the most pragmatic approaches for a short term development project.

For the analysis carried out, probabilistic distributions have been used for the most representative and uncertain parameters, in order to analyze the potential for cost reduction of the proposed DSCC concept in a more reliable way. The specific technologies and the details of the analyzed concept are explained in the next section.

2. Description of the DSCC proposed plant

The DSCC plant concept analyzed in the present work can be mainly described as a multi-tower system using several small regenerative Brayton cycles feeding a single medium-temperature oil thermal storage system that, in turn, is used to drive a mid-temperature superheated Rankine cycle. A simple scheme of this plant is shown in Fig. 1, stating the most important characteristics and components of the proposed plant.

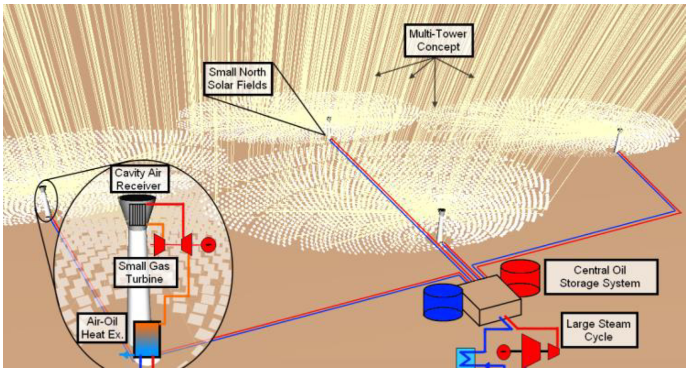


Fig. 1. Scheme of the proposed DSCC Concept

This concept takes advantage of today’s very competitive costs of medium size gas turbines alongside the specific cost reduction of steam turbines with size. Besides, the DSCC operates in a decoupled way, so that the Rankine cycle is running at full nominal power or not running at all, thus substantially increasing its operating efficiency.

Furthermore, the optical efficiency of the heliostat fields decreases significantly with size due to atmospheric attenuation and cosine effect losses, thus multi-tower power plants, using several Brayton cycles feeding a single Rankine cycle allow us to have the best of all. In this plant design, the emphasis is placed on cost-effective medium to large size plants with limited technological risk and based upon short term development requirements. This objective can be achieved by using a medium-to-high temperature air receiver on top of the towers operating at about 800 ºC and used for running a regenerative gas turbine in combination with a low temperature oil-based storage system, with smaller complexity and investment costs, operating at about 300 ºC and used to run a slightly superheated steam turbine (280 ºC, 40bar) as bottoming cycle.

In the next sub-sections, the specific technologies proposed for this plant and their most important performance and cost figures are shown. The design concept shown in the following is the result of a previous analysis carried out in order to select the most convenient and realistic technologies for the analyzed concept and for estimating plausible figures of the most important efficiencies and costs. As stated before, the most uncertain figures will be varied with probabilistic distributions in order to perform a stochastic analysis.

2.1. Solar field design

The solar field proposed for the analyzed plant has, basically two innovative approaches: the use of small, single-facet heliostats with a large potential for investment cost reduction, and the use of a biomimetic heliostat layout configuration, which leads to larger optical efficiencies in the solar field.

Since the current cost of the solar field represents about 30-40 % of the total investment cost in Solar Towers, large efforts are being made to reduce the costs of the heliostats nowadays [12]-[13]. Although there are many trends for achieving substantial heliostat cost reductions, one of the most promising one is the use of small heliostats with cheaper tracking system and more relaxed support structure and foundations. In this work, a small and single facet heliostat (1-8 m^2) with a cost reduction of 25 % with respect to the reference large-sized heliostat is considered [14].

Besides, large solar field efficiencies have been considered in this analysis. This increased efficiency is due, not only to the relatively small size of each module's solar field in the proposed multi-tower arrange, but also due to an improved layout of the heliostats based in biomimetic concepts. In these concepts, the heliostats are arranged in the same way as the spirals on a sunflower, maximizing the packing of the heliostats in the field and minimizing blocking and shadowing effects.

A hexagonally shaped solar field has been considered in order to have a good packing of the different modules composing the DSCC plant. The governing parameters of the spirals have been preliminary optimized by ray-tracing with the program Tonatiuh, obtaining a design point optical efficiency of 65.7 % and mean annual efficiency of 58.6 %, for a 60 m height solar tower, quite above the existing solar field efficiencies.

2.2. Pressurized air receiver

To reach high efficiencies, the operation temperatures to drive a Brayton cycle with a solarized gas turbine should be the higher as possible, at least between 800 ºC and 1200 ºC. Since this is the most critical and uncertain point of the present analysis, a temperature of 800 ºC has been selected to meet this DSCC concept criteria, i.e. keeping a limited technological risk and be based upon short term developments. This reduced operating temperature means an important penalty in the Brayton cycle efficiency (and also in the Rankine), but makes the considered receiver technology and efficiency more plausible in the short term scope.

In the present paper, a pressurized air receiver based on advanced cavity configurations has been considered. Although many recent studies have shown the viability of air receivers at high temperatures [10]-[11], these studies show quite low efficiencies that are not reasonable for a real plant. This is why, for the proposed DSCC plant, a reduced operating temperature of 800 ºC has been used. This reduced temperature makes it realistic to consider high receiver efficiencies, of around 80 % at nominal conditions, based on short term developments. An empirical model regarding operation temperatures and state-of-the-art material properties has been used to correct the nominal receiver efficiency depending on the thermal load. Certainly this is one of the most uncertain parameters, so a probabilistic distribution will be assigned to the receiver's nominal efficiency in the simulations; however, the efficiency correction curve will be kept constant for simplicity.

2.3. Brayton cycle

Coming from the previous consideration, the Brayton cycle will operate with a gas turbine inlet temperature of 800 ºC. In the cycle used in this analysis, the exhaust gasses exit the turbine at about 360 ºC and then are conducted to a heat recuperator to increase the cycle efficiency, and the final outlet temperature of the gases is at 303 ºC. The

Brayton cycle analyzed within this study has been simulated with state-of-the-art specialized software (GateCycle) for getting appropriate on-design and off-design balances, what has allowed characterizing the operation of the air compressor and the gas turbine by means of an efficiency curve depending on the thermal load.

In the Fig. 2, a descriptive scheme and balance of the Brayton cycle used for the present analysis is presented. As shown in the figure, the Gas Turbine used for the present analysis has a nominal gross power of 3.34 MW and its thermal to net electric efficiency in nominal operation is 39.7 %.

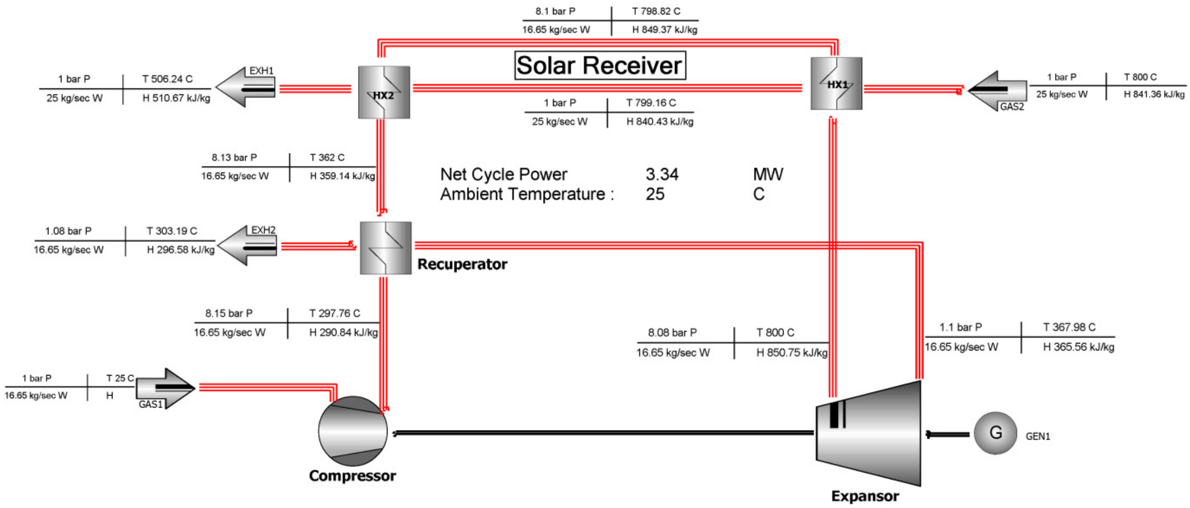


Fig. 2. Scheme and balance of the Brayton cycle used in the present analysis.

In Fig. 3, the curve used for correcting the efficiency in terms of the thermal load of the Gas Turbine is presented. Although not presented here, the Brayton cycle's efficiency dependence with the ambient temperature has also be considered in the analysis by means of an efficiency correction curve.

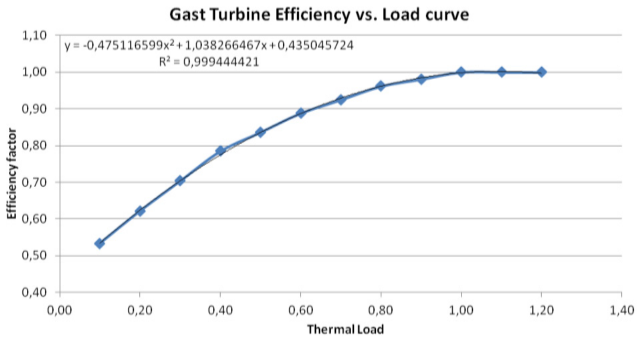


Fig. 3. Efficiency correction factor depending on the thermal load in the Brayton cycle

2.4. Storage system

The storage system analyzed within the present study has been selected in order to minimize the technological risk and ensuring a cost-effective system. Since the maximum operating temperature of the storage system depends on the exhaust gasses of the selected Brayton system, i.e. 303 ºC and the lower temperature has to be as low as possible in order to maximize the combined cycle efficiency, the storage media has to be selected accordingly.

The reference state-of-the-art storage system is the two tank molten salts storage system [15], however, this media makes not so much sense in the present analysis, since the lower temperature allowed for the salts is very high for our purposes (250 ºC) and the advantage of reaching high storage temperatures (565 ºC) is not used in this case. Although several media could exist and could fit even better the requirements of this design, the selected media has been the mineral oil. This storage media can be used between 300 ºC and <100 ºC, and presents a very low cost together with a very low technological risk. In the same way as for the storage media, the thermal storage configuration for this analysis has been selected in order to minimize the technological risk, and thus it consists in a two tank configuration [15]. Although more advanced configurations could fit better the proposed plant, for instance a single tank, thermocline based system [15]; the uncertainty in the performance and costs of these potential systems have made us to select a better known system for which accurate costs and performance values are known.

2.5. Rankine cycle

The Rankine cycle used for simulating the proposed DSCC plant is presented in Fig. 4, which shows both the scheme and the balance of the power block at the design point. This power block is a superheated Rankine cycle operating at 40 bars and 274 ºC, including three pressure levels in the steam generator and the corresponding three steam turbines with a reheater in the middle-pressure one.

The nominal net power of the Rankine cycle is 10.8 MW and has an efficiency of 19.6 %. Since this Rankine cycle is driven from the storage system in a decoupled way from the Brayton operation, it will be either running at full nominal power or not running at all; thus maximizing the efficiency of the system. Consequently, an efficiency curve depending on the cycle's operating load is not needed in this case.

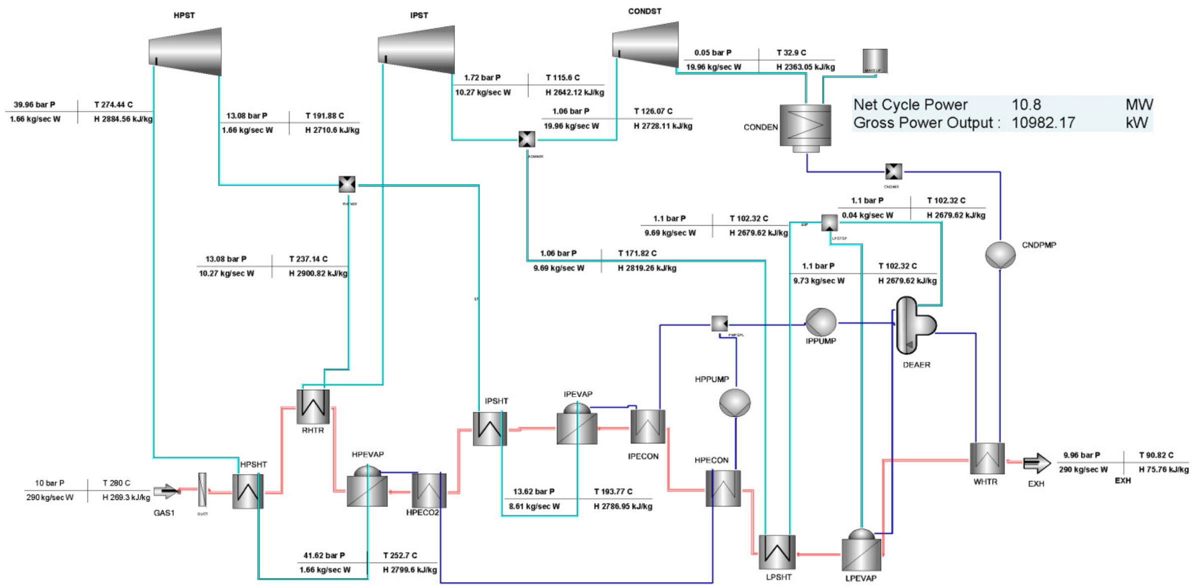


Fig. 4. Scheme and balance of the Rankine cycle used in the present analysis.

2.6. Proposed plant technical summary

The following table (Table 1) shows a comprehensive description of the proposed plant main characteristics, summarizing the already mentioned design values and efficiency figures, and also showing some of the most decisive technical assumptions considered in the present analysis.

Table 1. Proposed DSCC plant summary and technical assumptions.

System	Property	Proposed DSCC Plant
Solar Field	Aperture Area	~35000 m^2
	Tower Height	60 m
	Heliostats mean reflectivity	90 %
	Design optical efficiency	65.7 %
	Mean yearly optical efficiency	58.2 %
Receiver	Working fluid	Air
	Design thermal Power	8.4 MWt
	Outlet temperature	800 ºC
	Nominal Efficiency	80 %
Brayton Cycle	Heat recovery	YES
	Design electric power	3.34 MWe
	Design point efficiency	39.7 %
	Inlet temperature	800 ºC
	Exhaust temperature	303 ºC
Thermal storage	Media and configuration	Mineral Oil – Two Tanks
	Hot temperature	300 ºC
	Cold Temperature	90 ºC
Rankine Cycle	Technology	Superheated Steam – 40 bar, 274 ºC
	Design net electric power	10.8 MWe
	Design point efficiency	19.6 %
	HTF Inlet temperature	280 ºC
	HTF Outlet Temperature	90 ºC

2.7. Proposed plant costs

After having defined the proposed plant, the base costs of the plant and of its different sub-systems and components can be assessed. Specific costs estimated for the different components and systems have been based on previous work and CENER’s know-how and can be checked with data available in the specific literature.

Some costs strongly dependent on the location of the power plant (as a consequence mainly of regulations or policies), like electricity grid connection or land renting, have not been included in the study. And some of the costs estimated require a little rationalization:

- Heliostats costs have been estimated in 120 €/m^2, considering 160€/m^2 as reference and a 25 % achievable reduction at near term cost.
- Receiver cost has been calculated from an exergetic specific cost analysis, regarding data gathered.
- Brayton and Rankine cycle costs (including turbine and the rest of the components needed) have been estimated as a combination of obtained literature and information provided by specific manufacturers.
- The storage medium costs have been largely treated in available literature, for instance in [15] and [16]. However, as there are important discrepancies in the values found in different works, CENER’s previous works and consultations to manufacturers have been used to select the most realistic values and uncertainty margins.
- Besides the investment cost, the cost of energy depends on the O&M costs that allow for the operation of the plant. These costs account for personnel costs, water and electricity consumptions, maintenance of the different systems, etc. and have been estimated based on CENER’s previous knowhow and consultations.
- Costs for EPC contractor have been estimated to be a 5 % of the investment costs of the project.

Since the specific cost analysis and breakdown is out of the scope of the present work, only the most relevant costs for the plant analysis are presented in this paper: the specific heliostat cost, a specific receiver cost of 200 €/kWt, a storage media cost of 0.82 €/kg, and operation and maintenance cost of 0.028 €/kWh.

3. Simulation of the proposed DSCC plant

3.1. Simulation methodology

The potential for cost reduction of the proposed DSCC concept has been analyzed by simulating the plant energetic behavior and using the results to calculate the expected Levelized Cost of Electricity (LCOE) [17]. This LCOE has been compared with the LCOE calculated for a reference state-of-the-art power plant similar to Gemasolar, based on molten salts technology.

On the other side, a specific steady-state computer program has been developed for simulating the energetic performance of the plant. This model, although being quite simple, allows estimating with up to the required level of detail, the expected electricity production of the proposed concept. The model relies on theoretical and empirical state-of-the-art efficiencies of the different subsystems that compose the solar tower power plant [1].

A solar field efficiency matrix comprising the heliostats field performance is used to calculate the concentrated solar energy reaching the receiver from the meteorological data, i.e. the DNI, and the sun position algorithm. This solar field efficiency matrix is one of the most critical models in the simulation and a detailed ray-tracing optical analysis has been performed in order to get enough accurate results. This optical analysis has been performed using the open-source Tonatiuh ray-tracer, developed by CENER and validated against real measured data [18]-[19]. After calculating the concentrated solar energy reaching the receiver, a receiver efficiency curve depending on the thermal load is used to estimating the thermal energy provided to the gas turbine. Then, another load depending efficiency curve is used for modeling the Brayton cycle, resulting in the generated electricity production of each solar tower.

The power provided to the storage system is calculated then from the exhaust gasses mass flow and temperature together with the air properties, considering the lower temperature of the thermal storage. A single storage efficiency value is considered for modeling the heat losses, which are supposed to be independent of the state of charge of the system. Accordingly to the multi-tower concept, the amount of stored energy is multiplied by the number of Brayton cycles feeding the single storage/Rankine system, as it is the electricity generated by the Brayton cycle. As stated before, the Rankine cycle is supposed to work always at full load, thus maximizing the efficiency of the system. This way, all the energy stored at the thermal storage system is converted to electric energy at full load Rankine efficiency. Other operation strategies could be implemented in the real plants if desired, but this simple approach seems enough for the LCOE comparison undertaken in this work. Note that no fuel usage is considered in this analysis, of course, due to the large flexibility of the proposed concept, many options would appear if considering certain amount of energy coming from fossil fuels, both regarding the configuration of the plants and the operation strategies, but this is out of the scope of the present work.

For the simulations performed, a typical meteorological year with a direct normal irradiation (DNI) of 2015 kW/m$^2\cdot$year for a location near Seville has been selected as reference.

3.2. Reference plant data

The solar power plant used as reference for assessing the potential for cost reduction, is similar to Gemasolar, located near Seville. This reference plant, based on molten salts technology and large storage capacity, is well described in the public literature. For this reference plant a total investment cost of 163.4 M€ and O&M costs of 0.035 €/kWh have been considered. Simulating the performance of the plant for the typical meteorological year stated above, the annual energy yield results in 91.4 GWh, what leads to a LCOE of 15.1 c€/kWh that will be used as reference for calculating the cost reduction of the proposed DSCC plant.

3.3. Preliminary optimization of the proposed DSCC plant

One of the most important advantages that the DSCC concept has is the great flexibility in the design and configuration of the solar plant. However, a complete optimization of the proposed DSCC concept would need a multivariable optimization comprising an unaffordable number of parameters. For this reason, many parameters that could be optimized in a much deeper analysis, like the solar field configuration, the operating temperatures, the Brayton and Rankine cycle's sizes, etc. are kept constant in this study.

As shown in the description of the proposed plant, much of this flexibility has been limited by establishing the main technical characteristics of the power cycles, for instance their size and operating temperatures, as well as by setting the storage operating temperatures and media. However, although much flexibility has been limited, there are still some design parameters that have to be optimized before analyzing a specific plant. The optimization variables of the present analysis have been: the number of solar towers for a single Rankine cycle, the storage capacity, and the solar multiple (for each Brayton cycle).

For this preliminary optimization, a deterministic approach using the base cost and efficiency figures stated above (Table 1) has been used. The results from this preliminary optimization show that, near the optimum, both the number of towers and the storage capacity can be selected over quite a large range with small influence in the energy cost, while the LCOE is strongly coupled to the solar multiple. Specifically, the optimization showed an optimum value for the solar multiple of 2.10, while the number of towers could be between 30 and 40 and the storage capacity between 8 and 14 hours with small (<5 %) repercussion in the LCOE.

The selected configuration consisted in 32 Brayton cycles with a solar multiple of 2.1, feeding a storage system with a capacity of 9 Rankine cycle full load equivalent hours. With this configuration a deterministic LCOE of 11.27 c€/kWh was obtained. This LCOE value shows a potential for cost reduction of the proposed DSCC concept of 25 % with limited technological risk and based upon short term development requirements. This DSCC plant configuration will be used in the subsequent stochastic analysis.

3.4. Probabilistic distributions

Once the proposed plant has been completely defined, a more detailed analysis of the LCOE taking into account probabilistic distributions for the most uncertain and relevant costs and efficiencies has been performed. In Table 2 the stochastic variables considered for the present analysis, together with the information of the probabilistic distribution used for the analysis, are listed. The table shows, for each variable, the base value, already stated above in this document as well as a minimum and a maximum value. These three values will be used to define the most likely value, the minimum value and the maximum value of triangular probability distributions for each variable. The list includes costs and efficiencies of the systems and components that are most uncertain and have strong influence in the results, i.e. the cost of the heliostats and the efficiency of the solar field, both the cost and efficiency of the receiver, the thermal storage media cost. Also, the cost related to the operation and maintenance will be treated stochastically.

Table 2. List of stochastic variables for the cost reduction potential of the proposed DSCC plant.

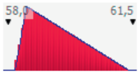
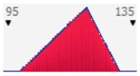
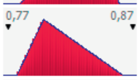
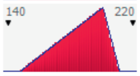
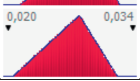
System	Property	Base value -most likely	Min.	Max.
Solar Field	Mean yearly optical efficiency	58.6 %	58.3 %	61.63 %
	Specific Heliostats Cost	120 €/m^2	100 €/m^2	130 €/m^2
Receiver	Nominal Efficiency	80 %	78 %	86 %
	Specific Receiver Cost	200 €/kWt	150 €/kWt	210 €/kWt
Thermal Storage	Storage Media Cost	0.81 €/kg	0.4 €/kg	1.0 €/kg
O&M	Operation and Maintenance	0.028 €/kWh	0.021 €/kWh	0.032 €/kWh

Note that in most of the listed variables, larger ranges have been selected in the lower costs and higher efficiencies directions. This has been done since the base values (most likely) have been estimated with quite conservative criteria, so it is more probable to reach better figures as the technology is developed, while worse figures will be relatively improbable.

4. Simulation results

The stochastic simulation performed in this analysis consisted of 10000 simulation runs. The information of the sampling performed for the probabilistic inputs is presented in Table 3.

Table 3. Sampling information of the probabilistic input variables.

Variable	Graph	Min	Mean	Max	5%	95%
Mean yearly optical efficiency (%)		58.31	59.48	61.51	58.52	60.84
Specific Heliostats Cost (€/m^2)		100.10	116.60	129.87	105.47	126.13
Receiver nominal Efficiency (%)		78.02	81.33	85.95	78.89	84.45
Specific Receiver Cost (€/kWt)		150.30	186.67	209.98	162.25	204.52
Storage Media Cost (€/kg)		0.4018	0.7400	0.9981	0.5122	0.9265
Operation and Maintenance (€/kWh)		0.0210	0.0270	0.0320	0.0230	0.0305

Since probabilistic distributions have been used for cost and efficiency inputs, both the investment cost and the annual electricity yield of the plant resulted in probabilistic distributions. These distributions are presented in Fig. 5.

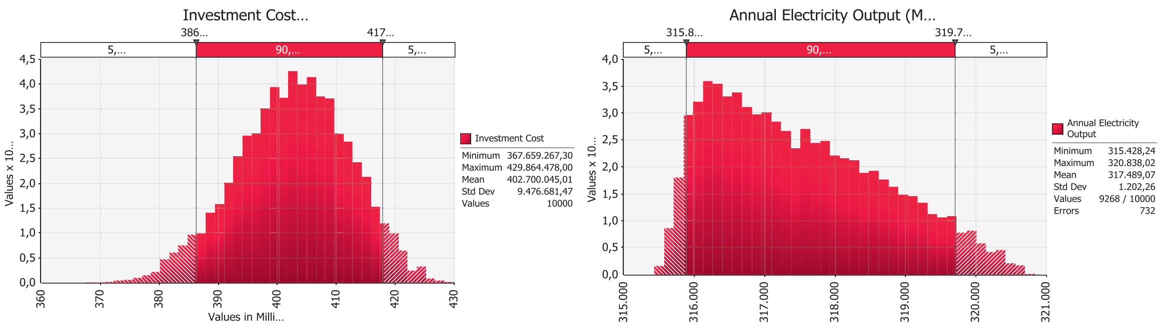


Fig. 5. Investment cost distribution (left) and annual electricity output distribution (right) resulting from the stochastic simulation.

These investment cost and energy output distributions, together with the probabilistic distribution of the O&M costs resulted in a LCOE distribution presented in Fig. 6.

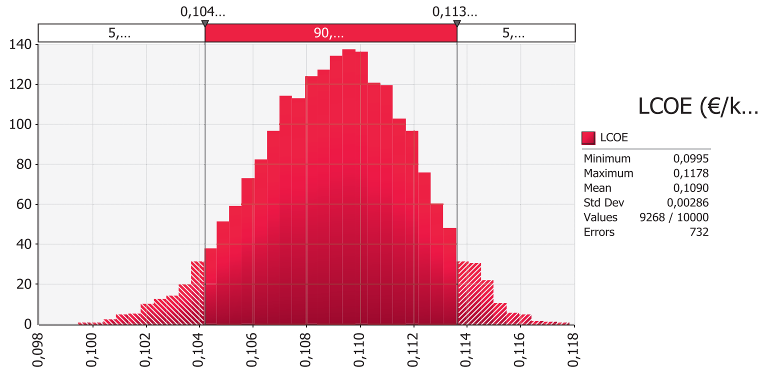


Fig. 6. Levelized Cost of Energy distribution resulting from the stochastic simulation.

The results of the stochastic analysis performed within this work show that there is a 90 % probability of achieving LCOE values between 10.42 c€/kWh and 11.36 c€/kWh with a mean value of 10.9 c€/kWh, according to the probability distributions assigned to the most uncertain figures. These values represent that a cost reduction higher than 24.75 % would be achieved with a 95 % probability.

5. Conclusions and outlook

The results obtained show the high potential for cost reduction that decoupled combined cycles schemes have for solar towers. For the configuration analyzed in this study cost reductions between 24.75 % (90 % probability) and 31 % (5 % probability) in the LCOE can be achieved, based upon technological developments and technological adaptations which can be carried out in no more than three years. These results demonstrate that the DSCC concept shows a great potential for achieving significant cost reduction in solar towers.

In addition to the study herein performed, many additional benefits associated to the decoupled concept could be also mentioned. One important benefit is the large flexibility of the design and the high expected efficiency of the combined system; however other advantages of the system rely on its main characteristic: modularity. This advantage is taken from the beginning, as it is not needed to wait until all the modules of the power plant are erected to begin operation as each unit can operate individually. This is also an advantage for reducing maintenance costs and gaining simplicity. Every source of energy on the field can be repaired independently from the rest, making it possible to continue with the normal operation of the rest of the power plant.

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References

[1]. M. Blanco, M. Sánchez, J. García-Barberena, A. Monreal, "The Potential for Cost Reduction of Solar Towers with Decoupled Combined Cycles", Proceedings SolarPACES 2012, Marrakech, Morocco.

[2]. Koketsu, M., & Ota, H. Heating Medium Supply system, integrated solar combined cycle electric power generation system and method for controlling these systems. US20090320828A1. 2009.

[3]. Carroni, R., Pedretti, C., Dalla Piaza, T., & Drouvot, P. P. A. Method for operation of an integrated solar combined-cycle power station, and a solar combined-cycle power station for carrying out this method. US20110232295A1. 2011.

[4]. Heide, S., Gampe, U., & Freimark, M. Solar Hybrid Combined Cycle Gas and Steam Power Plant. US20110185742A1. 2011.

[5]. Pye, J., Lovegrove, K., & Burgess, G. Combined-cycle solarised gas turbine with steam, organic and CO 2 bottoming cycles. Proceedings SolarPACES 2010. Perpignan, France.
[6]. Heller, P., Pfänder, M., Denk, T., Tellez, F., Valverde, A., Fernandez, J., & Ring, A. Test and evaluation of a solar powered gas turbine system. Solar Energy, 80(10), 1225-1230. 2006.
[7]. Kribus, A., Zaibel, R., Carey, D., Segal, A., & Karni, J. A solar-driven combined cycle power plant. Solar Energy, 62(2), 121-129. 1998.
[8]. Wei, X., Lu, Z., Wang, Z., Yu, W., Zhang, H., & Yao, Z. A new method for the design of the heliostat field layout for solar tower power plant. Renewable Energy, 35(9), 1970-1975. 2010. Elsevier. Ltd.
[9]. Noone, C. J., Torrilhon, M., & Mitsos, A. (2012). Heliostat field optimization: A new computationally efficient model and biomimetic layout. Solar Energy, 86(2), 792-803. 2012. Elsevier Ltd.
[10]. SOLGATE. Solar hybrid gas turbine electric power system. Final Publishable Report for the EUROPEAN COMMISSION. 5th RTD Framework programme. Contract ENK5-CT-2000-00333
[11]. J. Karni, A. Kribus et Al. "The "porcupine": a novel high-flux absorber for volumetric solar receivers. J. Sol. Energy Eng. 120(2), 85-95 (May 01, 1998).
[12]. G. J. Kolb, and all. “Power Tower Technology Roadmap and Cost Reduction Plan” SAND2011-2419 – April 2011
[13]. G. J. Kolb, S. A. Jones, M. W. Donnelly, and all. “Heliostat Cost Reduction Study” SAND2007-3293 – June 2007
[14]. M. Sanchez, C. Villasante. EASY: hEliostats for eAsy and Smart deployment. SolarPACES Annual Report 2012.
[15]. Pilkington Solar International GmbH. Survey of Thermal Storage for Parabolic Trough Power Plants; Period of Performance: September 13, 1999 - June 12, 2000. NREL/SR-550-27925. September 2000.
[16]. A. Sharma, V.V. Tyagi et Al. Review on thermal energy storage with phase change materials and applications. Renewable and Sustainable energy reviews 13 (2009) p. 318–345.
[17]. W. Short et al. “A Manual for the EconomicEvaluation of Energy Efficiency and Renewable Energy Technologies”. NREL/TP-462-5173. March 1995
[18]. M. Blanco, A. Mutuberria, D. Martinez. “Experimental Validation of Tonatiuh using the Plataforma Solar de Almería Secondary Concentrator Test Campaign Data”. Proceedings SolarPACES 2010. Perpignan, France.
[19]. M. Blanco, A. Mutuberria, A. Monreal, R. Albert. “Results of the empirical validation of Tonatiuh at Mini-Pegase CNRS-PROMES facility”. Proceedings SolarPACES 2011. Granada, Spain.