World Academy of Science, Engineering and Technology
International Journal of Energy and Power Engineering
Vol:17, No:10, 2023

A Comparative Study of the Techno-Economic Performance of the Linear Fresnel Reflector Using Direct and Indirect Steam Generation: A Case Study under High Direct Normal Irradiance

Ahmed Aljudaya, Derek Ingham, Lin Ma, Kevin Hughes, Mohammed Pourkashanian

***Abstract*—**Researchers, power companies, and state politicians have given concentrated solar power (CSP) much attention due to its capacity to generate large amounts of electricity whereas overcoming the intermittent nature of solar resources. The Linear Fresnel Reflector (LFR) is a well-known CSP technology type for being inexpensive, having a low land use factor, and suffering from low optical efficiency. The LFR was considered a cost-effective alternative option to the Parabolic Trough Collector (PTC) because of its simplistic design, and this often outweighs its lower efficiency. The LFR power plants commercially generate steam directly and indirectly in order to produce electricity with high technical efficiency and lower its costs. The purpose of this important analysis is to compare the annual performance of the Direct Steam Generation (DSG) and Indirect Steam Generation (ISG) of LFR power plants using molten salt and other different Heat Transfer Fluids (HTF) to investigate their technical and economic effects. A 50 MWe solar-only system is examined as a case study for both steam production methods in extreme weather conditions. In addition, a parametric analysis is carried out to determine the optimal solar field size that provides the lowest Levelized Cost of Electricity (LCOE) while achieving the highest technical performance. As a result of optimizing the optimum solar field size, the solar multiple (SM) is found to be between 1.2 – 1.5 in order to achieve as low as 9 Cent/KWh for the DSG of the LFR. In addition, the power plant is capable of producing around 141 GWh annually and up to 36% of the capacity factor, whereas the ISG produces less energy at a higher cost. The optimization results show that the DSG's performance overcomes the ISG in producing around 3% more annual energy, 2% lower LCOE, and 28% less capital cost.

***Keywords*—**Concentrated Solar Power, Levelized cost of electricity, Linear Fresnel reflectors, Steam generation.

ACRONYMS

AEG	Annual Energy Generated
CAPEX	Capital Expenditures
CSP	Concentrated Solar Power
DNI	Direct Normal Irradiance
DSG	Direct Steam Generation
HTF	Heat Transfer Fluid
ISG	Indirect Steam Generation
LFR	Linear Fresnel Reflector
MENA	Middle Eastern and Northern Africa
NREL	National Renewable Energy Laboratory
OPEX	Operating Expenses
PDC	Parabolic Dish Collector
PTC	Parabolic Trough Collector
SAM	System Advisor Model
SF	Solar Field
SM	Solar Multiple
SPT	Solar Power Tower
TMY	Typical Metrological Year

I. INTRODUCTION

THE increase in the global energy demand and the dependency on conventional energy sources have caused an escalation of greenhouse gas emissions. In order to reduce the emissions, more renewable energy installations are required, and their cost are becoming more competitive with fossil fuels. In addition, reducing the LCOE has been recently the main interests of researchers for most of the clean energies. For example, the price of electricity generated by solar energy technology has been reducing over the previous decade and is expected to decline much further in the future [1]. Regarding the CSP technologies, further research is needed since it indicates promising cost-cutting potential [2]. The most common CSP types commercially are PTC, LFR (line focusing technique), Solar Power Tower (SPT), and Parabolic Dish Concentrator (PDC) (point focusing technique). The PTC is the most mature type of all CSP; nevertheless, the LFR is a promising technology for cost reduction [3]. Also, although the LFR is a cost effective alternative with much lower costs due to its design simplicity, it has lower optical efficiency [3]. It has been known for a DSG by using water as the HTF since it is an option to decrease the capital expenditure (CAPEX) and the operating and maintenance expenses (OPEX) [4]. Compared to the PTC, the LFR costs are about only 2/3 of the overall costs [5].

With the DSG power plant, the heat exchanger can be eliminated since the use of pressurized water can achieve very

A.A. is a member of Energy 2050, Department of Mechanical Engineering, Faculty of Engineering, The University of Sheffield, Sheffield S3 7RD, United Kingdom and also a member of the Department of Mechanical Engineering, Faculty of Engineering, Najran University, Najran P.O Box 1988, King Abdul-Aziz Road, Saudi Arabia (corresponding author, phone: 07444110594; e-mail: armaljudaya1@sheffield.ac.uk).

D. I., K. H., and L. M., and M. P. are members of Energy 2050, Department of Mechanical Engineering, Faculty of Engineering, The University of Sheffield, Sheffield S3 7RD, United Kingdom (e-mail: d.ingham@sheffield.ac.uk, k.j.hughes@sheffield.ac.uk, lin.ma@sheffield.ac.uk, m.pourkashanian@sheffield.ac.uk).

high temperatures without the need for a heat exchanger and steam can directly operate the turbine without the need for a further HTF. Furthermore, the antifreeze protection system is not required since the water does not freeze at high temperatures and this is in contrast to other HTFs.

Recently, multiple HTFs have demonstrated feasible thermodynamic and heat transfer performances since it could reach a temperature up to 550-600 °C of the solar field (SF) output temperature [6]. Higher temperatures of the steam input may result in an improved technical performance, but this is at a higher cost. The ISG approach is more expensive when compared to the DSG method since it requires an appropriate heat exchanger, and the HTF is likewise more costly.

Where the cost reduction is critical, enhancing the technical performance is also essential. Thus, this techno-economic analysis is to investigate the direct and indirect steam generation by utilizing different HTFs that can improve the thermodynamic capabilities.

II. System Description

LFR operating method involves reflecting the Direct Normal Irradiance (DNI) into a single evacuated tube receiver that is positioned above the collectors and this is achieved by using single-axes tracking mirrors (flat or slightly curved). The key and important benefits of the design are the light supporting structure, the reduced leakage of the ball joints due to the fixed receiver (unlike the PTC), and the minimized wind impacts, all of which will, importantly, result in cost reductions [4]. Furthermore, the reflected sunlight increases the temperature and pressure of the HTF, and converts it to steam, which powers the turbine to generate electricity.

The main advantages of the DSG are that it reduces the costs even further by using water as the HTF and this eliminates the requirement for a heat exchanger. In contrast, the ISG requires the use of a heat exchanger, which increases the capital cost, but the used HTFs may reach higher field output temperatures, resulting in an improved thermal performance.

As shown in Fig. *1*, the main components of the LFR power plant are the SF, the heat exchanger, and the power block. The major subsystem of all the CSP is the SF, which is mainly composed of parallel, rectangular, and flat mirrors which are known as collectors. Generally, the collector is flat in order to reduce the cost of the SF; nevertheless, slightly curved mirrors may improve the performance of the collectors, so companies are examining its effectiveness. Novatec Solar, Areva, and Solar Euromed are three reputable companies that are making investments to produce and design LFR technology collectors [4]. The SF consists of multiple modules, and each module typically has 16 mirrors, eight on each side of the mounted receiver. In addition, a secondary collector is placed on top of the receiver to reduce the heat losses [7]. The small diameter receiver is coated in a glass envelope to improve the heat conduction and heat the steam. The heated fluid circulates through the SF and then powers the turbine, which produces electricity through the generator. Then this flows into the condenser, which lowers the temperature of the steam and is pumped again to the SF.

The operating technique for the ISG method is similar, except the HTFs heat the steam indirectly via the heat exchanger. Several HTFs with varying specifications, such as nitrate (molten) salt, synthetic oil, and mineral hydrocarbon could achieve higher heat transfer capabilities compared to water.

III. Materials and Methods

A. Metrological Data and the Site of the Study

The metrological characteristics of the CSP power plant are critical, such as the temperature, humidity, and wind speed; nevertheless, the DNI is the most important crucial parameter. The Middle Eastern and Northern Africa (MENA) region has the highest DNI on the Earth since it is located in the Sunbelt region, which could be an ideal location for the CSP installation.

The selected location is the Duba city, which is located in Saudi Arabia, and it has a 50 MW PTC power plant (ISCC Duba-1 power plant) [8]. The Typical Metrological Year (TMY) weather file is adapted from METEONORM that offers ground and metrological data for more than 20 years, which leads to further improved simulation accuracy. In addition, both the DSG and ISG proposed models are simulated in a very high DNI location (> 2700 kWh/m^2 and Fig. 2 shows the location of the study with the different ranges of the DNI.

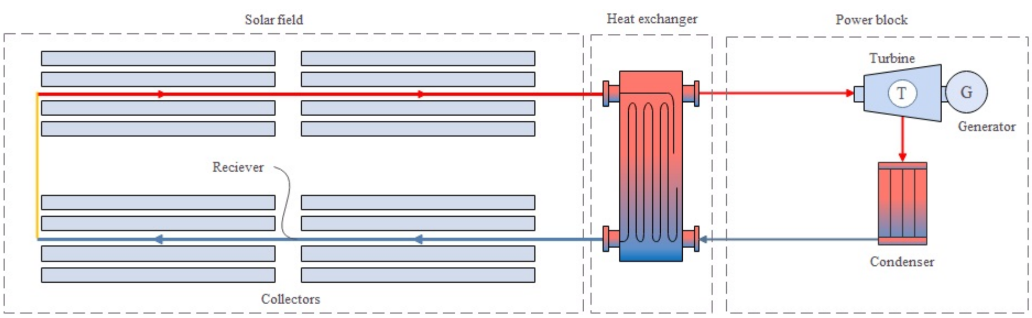

Fig. 1 A simple schematic diagram of the subsystem for the LFR power plant

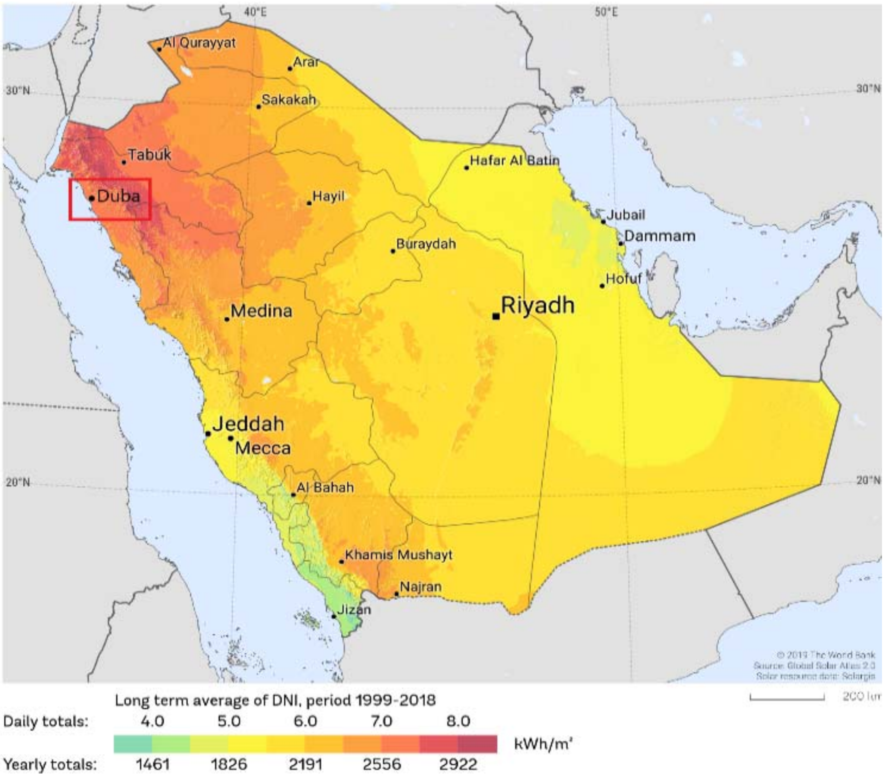

Fig. 2. The site location in Saudi Arabia adopted from SolarGIS and edited [accessed 17/03/2023] [8]

TABLE I
DESIGN SPECIFICATIONS AND PARAMETERS OF THE LFR POWER PLANT

	Parameter	Value
SF		
	SM	1-4 (step of 0.1)
	Irradiation at design	650 W/m^2
Collector		
	Reflective aperture area	513 m^2
	Length of collector model	44.8 m
	Mirror reflectivity	0.935
	Mirror soiling	0.95
Receiver		Schott PTR 70
	Absorber tube inner diameter	0.065 m
	Absorber tube outer diameter	0.07 m
	Glass envelope inner diameter	0.109 m
	Glass envelope outer diameter	0.115 m
Power cycle		
	Design turbine gross output	(50) MW
	Design thermal input power	120.7 MW_{th}
	High pressure turbine inlet pressure	112 bar

B. Off-design Parameters

The System Advisor Model (SAM), which is developed by the National Renewable Energy Laboratory (NREL), has been selected to be the simulation tool since it has good capabilities in the technical and economic performance simulation. Firstly, the LFR model has been simulated with 50 MW of the turbine capacity in order to validate both steam production methods. In the parametric analysis, the SF size is varied from one to four with the step size of 0.1 with the main objective of lowering the LCOE. TABLE I shows the important parameters of the simulated power plant.

C. Economic Model

The most important parameter in the evaluation of the CSP is the LCOE, which is calculated as:

$$LCOE = \frac{-C_0 - \frac{\sum_{n=1}^{N} C_n}{(1+d_{nominal})^n}}{\frac{\sum_{n=1}^{N} Q_n}{(1+d_{real})^n}} \quad (1)$$

where, Q_n (kWh): Electricity delivered by the system to the grid (and/or load if applicable) in year n; N: Analysis period in years (30 years); C_0: The project's equity investment amount; C_n: The annual project costs in Year n; d_{real}: The real discount rate is the discount rate without inflation; $d_{nominal}$: The nominal discount rate is the discount rate with inflation.

Also, CAPEX and OPEX are crucial in evaluating the feasibility of the LFR installation, which are modified through a parametric analysis, primarily with relation to the SF size.

D. HTF Characteristics

The used HTF in the DSG method is water, but for the ISG, nine different HTFs are used with different thermal specifications and this is summarized in TABLE II.

E. Parametric and Techno-Economic Analysis

The parametric analysis is carried out between the SF size or SM and the rated turbine capacity. The SM is that the field aperture area is expressed as a multiple of the aperture area required for operating the power cycle at its design capacity. The SM is varied from 1-4 with a step size of 0.1 and the turbine capacity ranges from 10 MW to 150 MW. The primary objective of the parametric analysis is to find the optimum sizes of the SF and the turbine capacity that result in the lowest LCOE.

TABLE II
SPECIFICATIONS OF ALL HTFS

Name	Type	Minimum optimal operating temperature	Maximum optimal operating temperature
Hitec Solar Salt	Nitrate Salt	238	593
Hitec	Nitrate Salt	142	538
Hitec XL	Nitrate Salt	120	500
Caloria HT 43	Mineral Hydrocarbon	-12	315
Therminol VP-1	Mixture of Biphenyl and Diphenyl Oxide	12	400
Therminol 59	Synthetic HTF	-45	315
Therminol 66	Synthetic HTF	0	345
Dowtherm Q	Synthetic Oil	-35	330
Dowtherm RP	Synthetic Oil	-	330

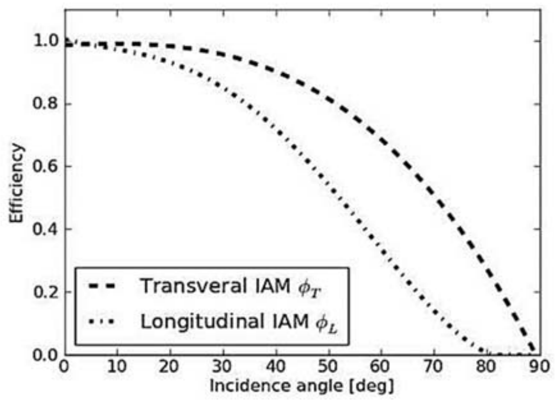

Fig. 3 The incident angle modifier curve for both the longitudinal and transversal planes [9]

The SAM defines the CF as the ratio of the simulated annually energy output for the first examined year to the system's rated capacity if it were to operate continuously. following expression can be used to compute the capacity factor:

$$\text{Capacity factor} = \frac{\text{Net Annual Energy } (\frac{\text{kWh}}{\text{year}})}{\text{System capcity (kW)}/8760\ (\frac{\text{h}}{\text{year}})} \quad (2)$$

The simulation performance method is the Incident Angel Modifier (IAM), which calculates the solar optical efficiency as a function of the longitudinal and transversal incidence angles using up to the fourth order polynomial. The following polynomials ((3) and (4)) are applicable to calculate the reduction of the optical efficiency driven by a deviation in the irradiation incidence angle in the longitudinal and transversal plane.

$$IAM_T = 0.9896 + 0.044 \times \phi_T - 0.0721\phi_T^2 - 0.2327\phi_T^3 \quad (3)$$

$$IAM_L = 1.0031 - 0.2259 \times \phi_L + 0.5368 \times \phi_L^2 - 1.6434\phi_L^3 + 0.7222 \times \phi_L^4 \quad (4)$$

The IAM behaviour is significantly influenced by the optical characteristics of the collector and the receiver geometry, however Fig. *3* illustrates the general trend using a sample system based on the Novatec Solar design [9].

IV. RESULTS AND DISCUSSION

A. Validation of the Models

The suggested DSG model has been validated using data from the 50 MW LFR power plant in Seville, Spain [10]. The result of the validation is shown in TABLE III.

TABLE III
EVALUATION OF THE PRESENT MODEL AGAINST REPORTED DATA

Parameter	Spain model	Present model
Number of loops	50	50
Total SF area (m^2)	757,000	739,603
Actual SF Aperture area (m^2)	411,000	410,880
Solar thermal power (MW_{th})	218	207
SM	1.72	1.72
Annual energy production (GWh)	102	102
Capacity factor (-)	23.4%	23.7%
Annual water usage m^3	-	288,207
LCOE (Cent/kWh)	13.61	13.22
Net capital cost (million $)	-	167.4

The validation for the second model (ISG) performed against an actual power plant, which is the first worldwide utility scale LFR that is using molten salt (Dacheng Dunhuang 50 MW – China) is illustrated in TABLE IV [11].

TABLE IV
THE PROPOSED MODEL EVALUATION AGAINST THE ACTUAL POWER PLANT

Parameter	Dacheng Dunhuang model	Present model
Field HTF outlet temperature $°C$	550	551
Actual SF Aperture area (km^2)	1.27	1.27
LCOE ($\$/kWh$)	0.14	0.154
SM	-	5.7
Annual energy production (GWh)	214	215

Both models show a good agreement with the reported data and the actual power plant. The highest deviation of the DSG model is 3% and of the ISG is 9%.

B. Model Performance

The chosen location has been used to simulate both direct and ISG using the proposed models with a fixed SM. The most significant techno-economic parameters of the 50 MW LFR power plants' performance are listed in TABLE V.

TABLE V
THE ANNUAL PERFORMANCE OF THE DSG AND ISG LFR

Parameter	DSG	ISG
Annual energy production (GWh)	143	154
SM	1.72	1.72
Annual water usage m^3	394,285	458,849
LCOE (Cent/kWh)	10.71	10.79
Net capital cost (million $)	170	265

It can be noted from Table V that the DSG has a lower capital cost than the ISG and this is due to the elimination of the heat exchange and the expenses of the HTF. On the other hand, it generates less annual energy, yet the electricity price remains slightly cheaper. The direct and indirect steam generation of the LFR shows a good performance. However, further analysis is required since the ISG exhibits higher thermal performance but the DSG offers a cheaper electricity price. Thus, a sensitivity analysis of the important parameters for both steam generation methods, such as the SF size, turbine capacity, and the HTFs specifications, is vital to achieve the lowest possible electricity price.

C. The SM and Turbine Capacity Optimization

The process is conducted within the SM, which ranges from one to four, and the turbine capacity, which varies from 10 MW to 150 MW, with the primary goal of minimizing the LCOE.

For the DSG method, it has been found that increasing the rated turbine capacity lowers the price of the electricity. The lowest overall electricity rates are obtained when the SM is between 1.6 and 1.8 and the turbine size is around 130 MW and 150 MW. Fig. *4* shows the lowest LCOE with the capacity of 150 MW.

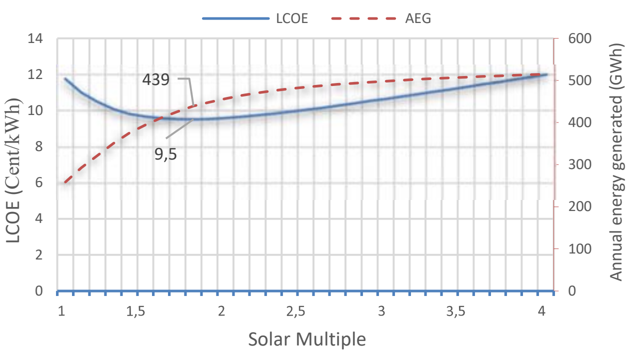

Fig. 4 The lowest LCOE of the 150 MW DSG against the SM and the annual energy generated

It is important to note that the lowest LCOE occurs at SM 1.8 since the AEG steadily increases as the size of the SF increases. However, when the SM is large enough to generate enough steam to operate the turbine at its rated capacity, the growth in energy output begins to flatten out. After the optimum size is achieved, the SF cost overcomes the increase of the energy production and this leads to a higher LCOE.

For the ISG, a similar parametric analysis is performed by examining nine different HTFs. Generally, the optimum solar SM sizes for all the HTFs are between 1.2 and 1.6, whereas the rated turbine capacity ranges between 20-60 MW. For the sake of simplicity, the lowest LCOE occurs when the rated turbine capacity is 20 MW for the majority of the HTFs and this is shown in TABLE VI.

Fig. 5 summarizes the effect of the SF sizes of the ISG LFR on the LCOE for all examined HFTs.

TABLE VI
THE LOWEST LCOE FOR ALL HTFS WITH THE OPTIMUM SIZES OF THE SF AND THE TURBINE CAPACITY

HTF TYPE	SM (-)	Turbine capacity (MW)	LCOE (Cents/kWh)
Caloria	1.2	20	10.52
Downtherm Q	1.3	50	10.43
Downtherm RP	1.3	40	10.42
Hitec	1.2	20	10.25
Hitec SS	1.2	20	10.24
Hitec XL	1.2	20	10.25
Therminol 59	1.5	60	15.37
Therminol VP	1.3	20	10.40
Therminol 66	1.5	60	10.73

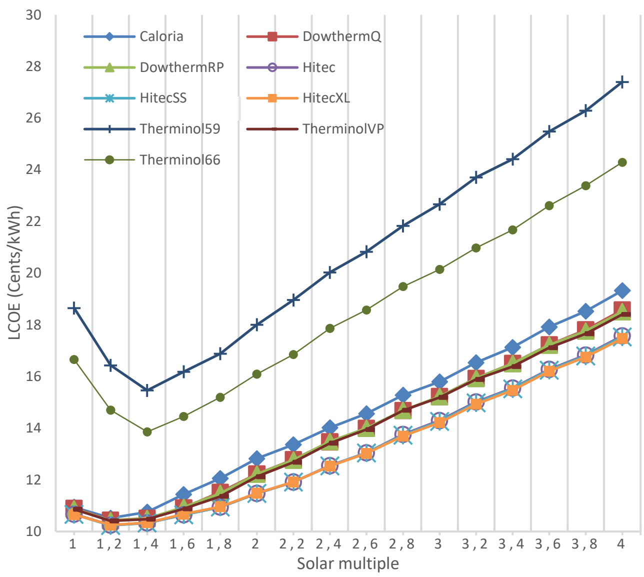

Fig. 5 The effect of the SM on the LCOE for different HTFs

It is clear that the molten salt types (Hitec solar salt, Hitec XL, and Hitec) prove their capability of producing steam at the lowest cost. Therminol VP performs similarly to other synthetic oils, such as Caloria and both Downtherm oils, in producing comparably low energy prices because of its lower cost and reduced heat losses. Finally, Therminol59 and Therminol66 produce energy at the highest cost due to their lowest outlet steam temperatures, which needs larger SF sizes that increase the overall cost of the LFR power plant.

D. Discussion

The major purpose of the optimization is to attain the lowest possible electricity price for both direct and indirect steam generation. The analysis reveals that the DSG has a lower LCOE when the turbine capacity exceeds 120 MW, but the ISG has a lower LCOE when the turbine capacity is between 20 MW and 60 MW. In addition, the ISG records 10.24 Cents/kWh when the Hitec Solar Salt (Hitec SS) is used as the HTF, whilst the DSG model reaches only 9.5 Cents/kWh.

In comparison with other types of HTFs, the molten salt types have the highest heat transfer performance and then the lowest economic cost. Despite the ISG's very high SF output temperatures, the DSG approach has a lower LCOE and this is due to the absence of the heat exchanger and reduced water costs. However, there are other crucial factors to take into account, such as the amount of cooling water used, the yearly energy production, and the net capital cost. As a result, it is crucial for decision-makers to thoroughly evaluate these factors, and for the purpose of comparison, the validated models are used to evaluate each of these important parameters in the accompanying Fig. 6.

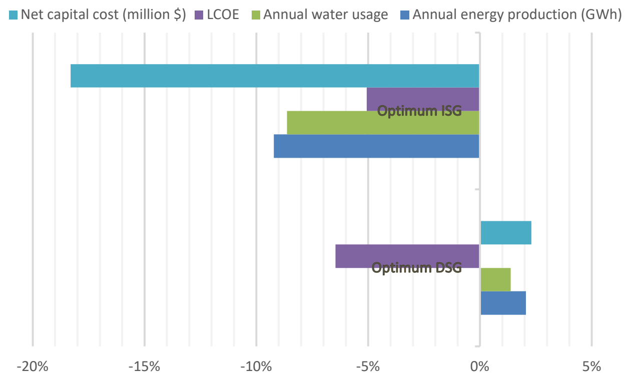

Fig. 6 Evaluation of the important techno-economic factors of the optimum ISG and DSG models against the reference models

Fig. 6 illustrates the differences in the optimum models of the ISG and DSG with a reference to the validated models (50 MW of LFR in Spain and China). Although the optimized ISG model reduces the annual energy production by approximately 9% (from 154 to 141 GWh), it also reduces the capital cost, LCOE, and annual water usage by 18%, 5%, and 9%, respectively. The DSG optimum model offers an increase in the yearly electricity generated by 2% with a slight increase in the net CAPEX and the water use by 2% and 1% respectively; however, it shows a considerable reduction in the electricity price by more than 6%.

It is important to note that even though the DSG optimum design has a larger SF, which is responsible for the highest costs of the LFR power plant, the benefit of eliminating the heat exchanger overcomes the high SF costs. In addition, the examination of the major techno-economic criteria greatly assists decision makers in determining which model design to install based not only on the amount of electricity produced, but also on the economically feasibility parameters.

V. Conclusion

This study has analysed the important direct and indirect steam generation of the solar-only LFR in a very high DNI location, i.e., Duba, Saudi Arabia. The DSG optimization findings demonstrate that the larger the rated turbine capacity, the lower is the value of the LCOE. When the rated turbine capacity is 50 MW, a maximum reduction of 6.5% in electricity price and a 2% improvement in the annual energy production have been observed, and the LCOE can reach as low as 9.5 Cents/kWh when the turbine size is 150 MW.

The ISG optimization findings for nine alternative HTFs demonstrate that molten salt (Hitec Solar Salt) has the lowest electricity cost of 10.24 Cents/kWh. The parametric analysis offers reductions of 18% in the capital cost, 9% of yearly water usage, and 5% of the LCOE, whereas also reducing the annual electricity produced by 9% when the turbine size is 50MW.

The main and important conclusions are that the DSG produces considerably greater energy by 3.4%, whereas having a lower LCOE by approximately 2% and this is mainly due to the absence of the heat exchanger and the lower cost of water compared to the molten salt. This study will very much assist investors to access the reliable up to date results in the prices and the performance of the LFR technology.

VI. Future Work

The LFR shows a very promising solution for lowering the LCOE and integrating a thermal energy storage may lower the cost even more as well as increasing the annual electricity production. In addition, optimizing the size of the SF and the thermal energy storage is essential. We intend to optimize the collector's geometry to improve the optical efficiency of the LFR power plant. Finally, a multi-objective optimization is required to accurately evaluate all the techno-economic parameters with different weights based on their importance.

Acknowledgment

We gratefully acknowledge Najran University for its valuable financial support.

References

[1] D. Gielen, F. Boshell, D. Saygin, M. D. Bazilian, N. Wagner, and R. Gorini, "The role of renewable energy in the global energy transformation," *Energy Strateg. Rev.*, vol. 24, no. January, pp. 38–50, 2019.

[2] P. Viebahn, Y. Lechon, and F. Trieb, "The potential role of concentrated solar power (CSP) in Africa and Europe-A dynamic assessment of technology development, cost development and life cycle inventories until 2050," *Energy Policy*, vol. 39, no. 8, pp. 4420–4430, 2011.

[3] N. B. Desai and S. Bandyopadhyay, "Line-focusing concentrating solar collector-based power plants: a review," *Clean Technol. Environ. Policy*, vol. 19, no. 1, pp. 9–35, 2017.

[4] L. Coco Enriquez, J. Muñoz Antón, and J. M. Martínez-Val Peñalosa, "SolarPaces 2013: Innovations on direct steam generation in linear fresnel collectors," *SolarPACES 2013 | SolarPACES 2013 | 17/09/201 - 20/09/2013 | Las Vegas, EE.UU*, 2013.

[5] H. H. Sait, J. M. Martinez-Val, R. Abbas, and J. Munoz-Anton, "Fresnel-based modular solar fields for performance/cost optimization in solar thermal power plants: A comparison with parabolic trough collectors," *Appl. Energy*, vol. 141, pp. 175–189, 2015.

[6] E. Bellos, C. Tzivanidis, and A. Papadopoulos, "Optical and thermal analysis of a linear Fresnel reflector operating with thermal oil, molten salt and liquid sodium," *Appl. Therm. Eng.*, vol. 133, no. March, pp. 70–80, 2018.

[7] A. Roostaee and M. Ameri, "Effect of Linear Fresnel Concentrators field key parameters on reflectors configuration, Trapezoidal Cavity Receiver dimension, and heat loss," *Renew. Energy*, vol. 134, pp. 1447–1464, 2019.

[8] A. Kassem, K. Al-Haddad, and D. Komljenovic, "Concentrated solar thermal power in Saudi Arabia: Definition and simulation of alternative scenarios," *Renew. Sustain. Energy Rev.*, vol. 80, no. May, pp. 75–91, 2017.

[9] M. J. Wagner, "WREF 2012: Results and comparison from the SAM linear fresnel technology performance model," *World Renew. Energy Forum, WREF 2012, Incl. World Renew. Energy Congr. XII Color. Renew. Energy Soc. Annu. Conf.*, vol. 4, no. April, pp. 2666–2673, 2012.

[10] C. Marugán-Cruz, D. Serrano, J. Gómez-Hernández, and S. Sánchez-Delgado, "Solar multiple optimization of a DSG linear Fresnel power plant," *Energy Convers. Manag.*, svol. 184, no. February, pp. 571–580, 2019.

[11] Y. Xu, J. Pei, J. Yuan, and G. Zhao, "Concentrated solar power: technology, economy analysis, and policy implications in China," *Environ. Sci. Pollut. Res.*, vol. 29, no. 1, pp. 1324–1337, 2022.