Conference Paper

Comparative Assessment of an Innovative Dry-Cooled CSP System

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A comparative optimization assessment is carried out in order to identify the competitiveness of an innovative modular air-cooled condenser (MACC) system in relation to conventional water- or air-cooled condensers. Specifically, the technoeconomic performance of the combined cycle gas turbine (CCGT) technology, the parabolic trough concentrated solar power (CSP) technology, and the solar tower CSP technology are compared when all are integrated (a) with a MACC condenser of an optimum tube geometry and size, (b) with a conventional water-cooled condenser, and (c) with a conventional dry-cooled condenser. The comparison is performed across three different solar potential levels. The simulations are carried out using an optimization model based on the IPP v2.1 algorithm for the calculation of the electricity unit cost and other financial indicators of each technology under investigation. The results demonstrate that, under certain parameters, the investigated MACC condenser system can become a cost-competitive alternative to water- or dry-cooled condensers in various solar potential environments.

1. Introduction

Current concentrated solar power (CSP) systems utilize water- or air-cooled condensers in a conventional Rankine cycle for electricity generation. The condenser performance is a key factor affecting the overall generation efficiency since it determines steam output temperature and pressure and thus the total amount of work done by the steam turbine. The utilization of water-cooled condensers, although effective, is constrained by the need for water availability in the immediate plant location. On the other hand, conventional air-cooled condensers, which do not necessitate the presence of a water source, are not as effective because they cannot maintain optimum condenser pressure and temperature and are unresponsive to daily variations in ambient temperature. This may translate to increased fan power consumption and lower CSP system efficiency [1–6].

In order to overcome the technical limitations of conventional air-cooled condensers, the MACCSol research project

[7], partly funded by the European Commission, provides an innovative industry solution through a new dry-cooling approach for multi-MWe-sized CSP systems. The consortium of project partners consists of three universities and four industrial partners. The universities are the University of Limerick in Ireland, the University of Erlangen in Germany, and the Università Degli Studi di Perugia in Italy. The industrial partners involved are R&R Mechanical Ltd. in Ireland, Torresol Energy Investments Ltd. in Spain, AuBren Ltd. in Ireland, and the Electricity Authority of Cyprus.

The primary objective of the MACCSol project is the development and verification of an innovative modular air-cooled condenser (MACC) system. If successful, this innovative technology will remove a significant barrier to the deployment of CSP systems in desert and arid areas and thus assist the EU in achieving its 2020 renewable energy contribution targets [8–10]. It will also ultimately enable CSP systems to increase net power output and reduce costs compared to existing dry-cooled systems. The completed

FIGURE 1: Typical MACC module arrangement (a) and tube bundle (b).

MACC system will incorporate sensors which will detect changes in temperature, ambient wind, and fan flow rate and control algorithms, which will communicate with these sensors to continuously vary fan speed. It will therefore maintain optimum condenser pressure and temperature irrespective of ambient conditions. As a result, steam turbine outlet conditions will always be optimized, thus maximizing power output and reducing operating costs. Also, because the MACC system will be a modular design, installation and maintenance costs will be significantly reduced.

Prior to its commercialization, the MACC system performance first needs to be monitored and optimized at both module and system levels. The optimization process involves numerical simulations, analytical modeling, physical scale modeling, and measurements on full-scale prototypes. The effects of all design options are to be assessed using thermodynamic models, while technoeconomic modeling will assess the lifetime cost implications of various design options of MACC systems. Finally, to prove the merits of the optimized MACC design, full-scale testing in an operational steam power plant will be performed.

A typical MACC module, with a length and width of 2 m by 2 m, is shown in Figure 1. The module is basically made up of a 1 m diameter fan blowing air either in induced or forced draft mode across an array of condenser tubes, located in the tube bundle section of the module, shown in Figure 1(b), through which the output steam of the turbine flows.

The optimum MACC system size will consist of multiple modules, the exact number of which needs to be identified. In addition, the optimum MACC system configuration will correspond to a specific tube geometry design consisting of a unique set of tube rows, columns, and taxonomy.

In this work, a technical and economic comparative optimization assessment is carried out in order to identify the competitiveness of the optimum MACC system in relation to conventional dry-cooled or water-cooled condensers. Specifically, the techno-economic performance of the CCGT technology, the parabolic trough CSP (PT-CSP) technology, and the solar tower CSP (ST-CSP) technology are compared when all are integrated (a) with a MACC condenser of an

optimum tube geometry and size, (b) with a conventional water-cooled condenser, and (c) with a conventional dry-cooled condenser.

In Section 2, the methodology and the software optimization tool that are used for the comparative optimization assessment are described. Then, the input data used in the analysis and the scenarios investigated are presented in Section 3. The results of the comparative optimization assessment are discussed in Section 4, while the conclusions are summarized in Section 5.

2. Methodology and Simulation Procedure

In order to perform the technical and economic comparative optimization assessment of the MACC system competitiveness compared to conventional dry-cooled or water-cooled condensers, the optimum MACC system tube geometry and size has to be first identified. The optimum MACC system geometry and size essentially incurs the lowest plant electricity unit cost because it corresponds to the optimum tradeoff between increased plant operating costs (associated with high MACC system fan speeds) and increased plant capital costs (associated with high heat transfer surface area and essentially MACC system size) [11, 12]. The optimum MACC system identification analysis has already been the scope of work of previous studies [13, 14], which were conducted on seventeen individual MACC system configurations with different tube geometries and on a total of eight different MACC sizes. The analysis has shown that the plate-finned MACC system geometry is the optimum geometry, with an optimum size of 955 modules [14], and will be used in the current comparative optimization assessment analysis.

For the purposes of this analysis, the operation of the CSP technology is simulated and the electricity unit cost is calculated based on the following algorithm: (a) calculation of solar radiation in plane of parabolic trough solar field, (b) calculation of electrical energy delivered by the CSP technology, (c) calculation of system losses, (d) calculation of electrical energy delivered to the grid, (e) calculation of required area for parabolic trough solar field, (f) calculation

of required area for the installation of the solar thermal power plant, and (g) calculation of electricity unit cost assuming that the initial investment year is year 0; the costs are given in year 0 terms; thus any inflation rate (or the escalation rate) is applied from year 1 onwards, and the timing of cash flows occurs at the end of the year.

In order to perform the simulations required for the above optimization analysis of the electricity generation technologies, that is, the CCGT, the PT-CSP, and the ST-CSP technologies, the IPP v2.1 software tool is employed [15]. The software emerged from a continued research and development in the field of software development for the needs of power industry. This user-friendly software tool, the flowchart of which is shown in Figure 2, can be used for the selection of an appropriate least cost power generation technology in competitive electricity markets.

The software takes into account the capital cost, the fuel consumption and cost, the operation cost, the maintenance cost, the plant load factor, and so forth. All costs are discounted to a reference date at a given discount rate. Each run can handle 50 different candidate schemes simultaneously. Based on the above input parameters for each candidate technology, the algorithm calculates the least cost power generation configuration in real prices and the ranking order of the candidate schemes. The technical and economic parameters of each candidate power generation technology are taken into account based on the cost function:

$$\begin{aligned} \min \left(\frac{\partial c}{\partial k} \right) \\ = \min \left\{ \left(\sum_{j=0}^N \left[\left(\frac{\partial C_{Cj}}{\partial k} + \frac{\partial C_{Fj}}{\partial k} + \frac{\partial C_{OMFj}}{\partial k} + \frac{\partial C_{OMVj}}{\partial k} \right) \right. \right. \right. \\ \left. \left. \left. \times ((1+i)^j)^{-1} \right] \right) \right. \\ \left. \times \left(\sum_{j=0}^N \left[\frac{\partial P_j / \partial k}{(1+i)^j} \right] \right)^{-1} \right\}, \end{aligned} \quad (1)$$

where c is the final cost of electricity in €/kWh, in real prices, for the candidate technology k , C_{Cj} is the capital cost function in €, C_{Fj} is the fuel cost function in €, C_{OMFj} is the fixed O&M cost function in €, C_{OMVj} is the variable O&M cost function in €, P_j is the total electricity production in kWh, $j = 1, 2, \dots, N$ is the periods (e.g., years) of installation and operation of the power generation technology, and i is the discount rate. The least cost solution is calculated as follows:

$$\text{least cost solution} = \min \left[\frac{\partial c}{\partial k} \right]. \quad (2)$$

During the simulations procedure, the following financial feasibility indicators based on the individual case examined may be calculated: (a) electricity unit cost or benefit before tax (in €/kWh), (b) after-tax cash flow (in €), (c) after tax NPV (net present value: the value of all future cash flows,

FIGURE 2: Flowchart of the IPP optimization model.

discounted at the discount rate, in today's currency), (d) after-tax IRR (internal rate of return: the discount rate that causes the NPV of the project to be zero and is calculated using the after tax-cash flows; note that the IRR is undefined in certain cases, notably if the project yields immediate positive cash flow in year zero), and (e) after-tax PBP (payback period: the number of years it takes for the cash flow, excluding debt payments, to equal the total investment which is equal to the sum of debt and equity).

3. Input Data and Scenarios

For the purposes of the comparative optimization analysis, the electricity generation technologies to be investigated are a 420 MWe CCGT natural gas technology (with a fuel net calorific value of 46.3 GJ/t and a fuel carbon content of 76.24%) at a 75% capacity factor, a 50 MWe PT-CSP technology, and a 17 MWe ST-CSP technology. Both CSP technologies are not integrated with thermal storage capability.

Regarding the CCGT technology analysis, two cases were examined, namely, the base case and the alternative case, each using different natural gas prices. Specifically, the natural gas price projections used in the analysis for the base and the alternative case are shown in Figure 3. Essentially, in the alternative case, the price of natural gas is reduced by 40% compared to the base case in each year. Moreover, in order to account for the unpredictability of the electricity generation when the CCGT technology is integrated with the MACC cooling system, since such a system is not yet commercialized and its actual behavior is not as yet well predicted in existing

FIGURE 3: Annual price projections of natural gas (nominal values).

software design tools, the efficiency of the CCGT technology system was varied at 56% (low), 57% (medium), and 58% (high) in both the base and alternative cases.

The input data and scenarios used in the CCGT technology comparative optimization analysis are shown in Table 1.

Regarding the CSP technologies, since the MACC system would be integrated as the main cooling system in a 50 MWe PT-CSP and a 17 MWe ST-CSP technology systems, an annual direct normal irradiance (DNI) factor of 2000 kWh/m² typical of Larnaca, Cyprus, which is considered as a normal DNI level for the Mediterranean region, is used for the analysis. However, in order to study the effect of varying DNI levels on the competitiveness of the MACC system, two additional DNI levels were also studied, namely, a high DNI level of 2500 kWh/m² typical of Luxor, Egypt, and a low DNI level of 1500 kWh/m² typical of Athens, Greece. The input data and scenarios used in the CSP technologies comparative optimization analysis are shown in Table 2 for the PT-CSP technology and in Table 3 for the ST-CSP technology. Regarding the analysis of the PT-CSP and ST-CSP technologies when integrated with the MACC system, the overall CSP technology system efficiency was varied, for reasons already explained above. Specifically, for the PT-CSP technology, the efficiency was varied between 12.5% (low), 13.5% (medium), and 14.5% (high), while for the ST-CSP technology, it was varied between 14.5% (low), 15.5% (medium), and 16.5% (high). The input data regarding the ST-CSP technology was based on the PS10 and PS20 solar tower CSP plants that are currently in operation in Spain, since the Gemasolar solar tower CSP plant is integrated with thermal storage capability through an innovative 24 h storage technology with molten salt [16].

Throughout the simulations, a typical discount rate of 6% is assumed. In order to calculate the after-tax cash flows and after-tax financial indicators, a single 10% income tax rate is assumed that is constant throughout the project life and applied to net income. Also, the economic life of the CCGT and the two CSP systems is assumed at 20 years. The

FIGURE 4: Annual price projections of CO₂ ETS price (real values).

simulations consider a CO₂ emission trading scheme (ETS) price projection, as shown in Figure 4, to account for the environmental cost of the CCGT technology. The simulations do not consider any feed-in tariff or other subsidy scheme for the application of CSP technologies.

4. Results and Discussion

In this section, the results of the comparative optimization analysis are discussed. The electricity unit cost of each scenario investigated is used as the sole criterion in order to assess the competitiveness of the MACC system.

4.1. CCGT Technology Electricity Unit Cost Comparison. The results concerning the electricity unit cost of the 420 MWe CCGT technology when integrated with a conventional water-cooled condenser, dry-cooled condenser, and with the innovative MACC system are shown in Figure 5. The comparison of each scenario shows that the electricity unit cost of the CCGT technology integrated with the MACC

TABLE 1: Input data and scenarios for CCGT technology comparative analysis.

Scenario	Capacity MWe	Specific capital cost €/kW	Efficiency %	Fixed O and M €/kW/month	Variable O and M €/MWh
CCGT, water cooling, base case	420	665	57.20	2.34	1.62
CCGT, dry cooling, base case	420	737	56.30	2.34	1.62
CCGT, MACC cooling, base case, 56% efficiency	420	666	56.00	2.37	1.62
CCGT, MACC cooling, base case, 57% efficiency	420	666	57.00	2.37	1.62
CCGT, MACC cooling, base case, 58% efficiency	420	666	58.00	2.37	1.62
CCGT, water cooling, alternative case	420	665	57.20	2.34	1.62
CCGT, dry cooling, alternative case	420	737	56.30	2.34	1.62
CCGT, MACC cooling, alternative case, 56% efficiency	420	666	56.00	2.37	1.62
CCGT, MACC cooling, alternative case, 57% efficiency	420	666	57.00	2.37	1.62
CCGT, MACC cooling, alternative case, 58% efficiency	420	666	58.00	2.37	1.62

TABLE 2: Input data and scenarios for PT-CSP technology comparative analysis.

Scenario	Capacity MWe	Specific capital cost €/kW	Efficiency %	Fixed O and M €/kW/month	Variable O and M €/MWh	Capacity factor %
PT-CSP, water cooling, high DNI	50	4943	14.00	9.90	2.48	29.10
PT-CSP, water cooling, normal DNI	50	4943	14.00	9.90	2.48	22.50
PT-CSP, water cooling, low DNI	50	4943	14.00	9.90	2.48	17.50
PT-CSP, dry cooling, high DNI	50	5059	12.70	9.90	2.48	27.30
PT-CSP, dry cooling, normal DNI	50	5059	12.70	9.90	2.48	21.50
PT-CSP, dry cooling, low DNI	50	5059	12.70	9.90	2.48	16.60
PT-CSP, MACC cooling, high DNI, 12.5% efficiency	50	4970	12.50	9.93	2.48	25.98
PT-CSP, MACC cooling, high DNI, 13.5% efficiency	50	4970	13.50	9.93	2.48	28.06
PT-CSP, MACC cooling, high DNI, 14.5% efficiency	50	4970	14.50	9.93	2.48	30.14
PT-CSP, MACC cooling, normal DNI, 12.5% efficiency	50	4970	12.50	9.93	2.48	20.09
PT-CSP, MACC cooling, normal DNI, 13.5% efficiency	50	4970	13.50	9.93	2.48	21.70
PT-CSP, MACC cooling, normal DNI, 14.5% efficiency	50	4970	14.50	9.93	2.48	23.30
PT-CSP, MACC cooling, low DNI, 12.5% efficiency	50	4970	12.50	9.93	2.48	15.63
PT-CSP, MACC cooling, low DNI, 13.5% efficiency	50	4970	13.50	9.93	2.48	16.88
PT-CSP, MACC cooling, low DNI, 14.5% efficiency	50	4970	14.50	9.93	2.48	18.13

system is in all cases lower than that of the same technology integrated with the dry-cooled condenser. This means that the MACC system can be considered as a cost-competitive alternative to the conventional dry-cooled condenser, to be integrated with the CCGT technology.

Specifically, in the base case, the results show that when the efficiency of the CCGT technology integrated with the MACC system is 56% or 57%, its electricity unit cost is lower than that of the same technology integrated with the dry-cooled condenser but remains slightly higher than

that of the CCGT technology integrated with the water-cooled condenser. For example, the electricity unit cost of the CCGT technology with the MACC system at a 56% efficiency is 10.59€/c/kWh, while with the water-cooled condenser is 10.39€/c/kWh, and with the dry-cooled condenser it is 10.63€/c/kWh. However, as the efficiency of the CCGT technology with the MACC system increases to 58%, the respective electricity unit cost decreases even further. In fact, at 58% efficiency, the CCGT technology integrated with the MACC system is more economical than both the CCGT

TABLE 3: Input data and scenarios for ST-CSP technology comparative analysis.

Scenario	Capacity	Specific capital cost	Efficiency	Fixed O and M	Variable O and M	Capacity factor
	MWe	€/kW	%	€/kW/month	€/MWh	%
ST-CSP, water cooling, high DNI	17	6471	16.08	9.20	2.48	22.40
ST-CSP, water cooling, normal DNI	17	6471	16.08	9.20	2.48	17.30
ST-CSP, water cooling, low DNI	17	6471	16.08	9.20	2.48	13.30
ST-CSP, dry cooling, high DNI	17	6587	14.86	9.20	2.48	21.20
ST-CSP, dry cooling, normal DNI	17	6587	14.86	9.20	2.48	16.60
ST-CSP, dry cooling, low DNI	17	6587	14.86	9.20	2.48	12.70
ST-CSP, MACC cooling, high DNI, 14.5% efficiency	17	6482	14.50	9.23	2.48	20.20
ST-CSP, MACC cooling, high DNI, 15.5% efficiency	17	6482	15.50	9.23	2.48	21.59
ST-CSP, MACC cooling, high DNI, 16.5% efficiency	17	6482	16.50	9.23	2.48	22.99
ST-CSP, MACC cooling, normal DNI, 14.5% efficiency	17	6482	14.50	9.23	2.48	15.60
ST-CSP, MACC cooling, normal DNI, 15.5% efficiency	17	6482	15.50	9.23	2.48	16.68
ST-CSP, MACC cooling, normal DNI, 16.5% efficiency	17	6482	16.50	9.23	2.48	17.75
ST-CSP, MACC cooling, low DNI, 14.5% efficiency	17	6482	14.50	9.23	2.48	11.99
ST-CSP, MACC cooling, low DNI, 15.5% efficiency	17	6482	15.50	9.23	2.48	12.82
ST-CSP, MACC cooling, low DNI, 16.5% efficiency	17	6482	16.50	9.23	2.48	13.65

water-cooled and the dry-cooled technologies, showing that the MACC system integrated in a CCGT technology can become a cost-competitive alternative to the conventional water-cooled condenser as well.

The results in the CCGT alternative case provide the same observations as above, in that the innovative MACC system is a cost-competitive alternative to a conventional dry-cooled condenser and that in higher efficiencies it can even become cost competitive to the conventional water-cooled condenser. Clearly, the electricity unit cost range in the alternative case (which is between 7.13€/kWh and 7.39€/kWh) is lower than that of the base case due to the lower natural gas price projections considered.

4.2. PT-CSP Technology Electricity Unit Cost Comparison. The results concerning the electricity unit cost of the 50 MWe PT-CSP technology when integrated with a conventional water-cooled condenser, dry-cooled condenser and with the innovative MACC system are shown in Figure 6. The comparison of each scenario shows that the competitiveness of the MACC system, compared to the conventional water-cooled and dry-cooled condensers, depends heavily on the PT-CSP technology efficiency level. This observation applies to all DNI cases examined, that is, low, normal, and high. Specifically, at the low 12.5% efficiency level, the PT-CSP technology with the MACC system has an electricity

unit cost higher than both of the PT-CSP technologies with water-cooled and dry-cooled condensers. Therefore, at such efficiency level, the MACC system is not considered a competitive condensing technology to be integrated in a PT-CSP technology. However, at the higher efficiencies examined, the MACC system offers more competitive results. At the medium-efficiency level, the MACC system is cost competitive only to the dry-cooled condenser, while at the high-efficiency level, the MACC system is cost competitive to both water-cooled and dry-cooled condensers.

For example, in the high DNI case, at 12.5% efficiency, the electricity unit cost of the PT-CSP technology integrated with the MACC system is 24.52€/kWh, while with the water-cooled condenser is 21.81€/kWh, and with the dry-cooled condenser is 23.70€/kWh. However, at the high 14.5% efficiency, the PT-CSP technology integrated with the MACC system has lower electricity unit cost than both of the PT-CSP technologies integrated with water-cooled and dry-cooled condensers. Specifically, the electricity unit cost of the PT-CSP technology integrated with the MACC system is 21.17€/kWh, lower than both the 21.81€/kWh of the water-cooled and the 23.70€/kWh of the dry-cooled condensers. Therefore, at such efficiency level, the MACC system can be considered as a competitive condensing technology to be integrated in a PT-CSP technology as an alternative to both water-cooled and dry-cooled condensers.

FIGURE 5: MACC system competitiveness integrated in CCGT technology.

FIGURE 6: MACC system competitiveness integrated in PT-CSP technology.

4.3. ST-CSP Technology Electricity Unit Cost Comparison. The results concerning the electricity unit cost of the 17 MWe ST-CSP technology when integrated with a conventional water-cooled condenser, dry-cooled condenser, and with the innovative MACC system are shown in Figure 7. The comparison of each scenario shows that, as in the case of

the PT-CSP technology, the competitiveness of the MACC system, compared to the conventional water-cooled and dry-cooled condensers, depends heavily on the ST-CSP technology efficiency level. This observation applies to all DNI cases examined, that is, low, normal, and high. Specifically, at the low 14.5% efficiency level, the ST-CSP technology integrated

FIGURE 7: MACC system competitiveness integrated in ST-CSP technology.

FIGURE 8: Comparison of electricity generation technologies integrated with the MACC system.

with the MACC system has an electricity unit cost higher than both of the ST-CSP technologies with water-cooled and dry-cooled condensers. Therefore, at such efficiency level, the MACC system is not considered a competitive condensing

technology to be integrated in a ST-CSP technology. However, at the higher efficiencies examined, the MACC system offers more competitive results. At the medium-efficiency level, the MACC system is cost competitive only to the dry-cooled condenser, while at the high-efficiency level, the MACC system is cost competitive to both water-cooled and dry-cooled condensers.

For example, in the high DNI case, at 14.5% efficiency, the electricity unit cost of the ST-CSP technology with the MACC system is 38.44€/kWh, while with the water-cooled condenser is 34.63€/kWh, and with the dry-cooled condenser is 37.12€/kWh. However, at the high 16.5% efficiency, the ST-CSP technology integrated with the MACC system has lower electricity unit cost than both the ST-CSP technologies integrated with water-cooled and dry-cooled condensers. Specifically, the electricity unit cost of the ST-CSP technology with the MACC system is 33.81€/kWh, lower than both the 34.63€/kWh of the water-cooled and the 37.12€/kWh of the dry-cooled condensers. Therefore, at such efficiency level, the MACC system can be considered as a competitive condensing technology to be integrated in a ST-CSP technology as an alternative to both water-cooled and dry-cooled condensers.

4.4. Comparison of Technologies Integrated with the MACC System. Finally, an overall comparison of the competitiveness of each of the three types of electricity generation technologies examined, that is, CCGT, PT-CSP, and ST-CSP, when integrated with the MACC system, is provided in Figure 8. In the x -axis, the labels A, B, and C refer, respectively, to

the low-, medium-, and high-efficiency levels in the efficiency range examined individually for each generation technology. For example, in the case of the PT-CSP technology, A would refer to 12.5%, B to 13.5%, and C to 14.5% efficiency. The comparison shows that the CCGT technology integrated with the MACC system is the most competitive of the three types of technologies, exhibiting the lowest electricity unit costs. Depending on the efficiency, the electricity unit cost ranges around 7€/kWh in the alternative case and 10€/kWh in the base case.

The electricity unit cost of the CSP technologies integrated with the MACC system depends on the efficiency of each technology and the DNI level. Comparison-wise, the PT-CSP technology generally exhibits lower electricity unit costs than the ST-CSP technology, ranging from around 25€/kWh to 40€/kWh in the low-efficiency case (depending on the DNI level) and from 20€/kWh to 35€/kWh in the high-efficiency case, while the ST-CSP technology has from around 38€/kWh to 65€/kWh in the low-efficiency case and from 34€/kWh to 57€/kWh in the high-efficiency case. Importantly though, the ST-CSP technology at high DNI level has lower electricity unit costs across all efficiency levels than the PT-CSP technology at low DNI level.

In terms of classification, the three most competitive scenarios of CSP technology integrated with the MACC system are the PT-CSP at high DNI, followed by the PT-CSP at normal DNI and the ST-CSP at high DNI level.

5. Conclusions

In this work, a technical and economic comparative optimization assessment is carried out using the IPP v2.1 software package in order to identify the optimum MACC system competitiveness in relation to conventional dry-cooled or water-cooled condensers. Specifically, the techno-economic performance of the CCGT technology, the parabolic trough CSP (PT-CSP) technology, and the solar tower CSP (ST-CSP) technology are compared when all are integrated (a) with a MACC condenser of an optimum tube geometry and size, (b) with a conventional water-cooled condenser, and (c) with a conventional dry-cooled condenser.

Based on the input data and assumptions made, the comparative optimization analysis shows that, in the case of the CCGT technology, the MACC system is a cost-competitive technology to the conventional dry-cooled condenser. In addition, at higher efficiencies, the MACC system can even become cost competitive to the conventional water-cooled condenser. In the case of the PT-CSP and ST-CSP technologies, the results show that, irrespective of the location's DNI level, the competitiveness of the MACC system, compared to the conventional water-cooled and dry-cooled condensers, depends heavily on the efficiency level. At low CSP technology efficiency levels, the MACC system is not considered a competitive condensing technology to either the conventional water- or dry-cooled condensers. However, at higher efficiency levels, the MACC system begins to become cost competitive first to the dry-cooled condensers and then, at even higher efficiency levels, to the water-cooled condensers as well.

Finally regarding the competitiveness of each of the three types of electricity generation technologies examined (i.e., CCGT, PT-CSP, and ST-CSP), when integrated with a MACC system, the most cost-competitive technology is the CCGT technology (alternative and base cases). Concerning the CSP technologies, the three most cost-competitive scenarios are the PT-CSP at high DNI, followed by the PT-CSP at normal DNI, and the ST-CSP at high DNI level.

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