Conference Paper

Upscaling of an Innovative Cogeneration CSP System

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An upscaling of an innovative concentrated solar power (CSP) technology for the cogeneration of electricity and desalinated water (CSP-DSW) to be integrated into the Cyprus power generation system is carried out. Further, a comparative study of the competitiveness of the CSP-DSW technology with the integration of natural gas combined cycle (CCGT) technology is carried out. For the simulations, the IPP v2.1 software is used for calculating the optimum cost of electricity produced from both conventional and CSP-DSW technologies. The results indicate that for high capacity factor levels, the CSP-DSW technology scenarios are more cost effective than the CCGT technology (base case natural gas technology price projection scenario) and become even more cost effective at very high capacity factor levels than the CCGT technology (low natural gas technology price projection scenario).

1. Introduction

Throughout history, Cyprus has experienced long periods of water scarcity. In recent years, this phenomenon occurs more due to the climate change. The overexploitation of the underground water resources and the reduction of the level of the surface water resources have brought the water resources at a critical point. The result of these factors is the shift in the desalination solution, which, although a method proven and technologically mature, still requires large amounts of energy, which in its majority is produced from conventional, polluting power plants. By increasing the water needs, there is an increase in the energy needs which are required for the operation of desalination units, which increases the impact in the environment. The cogeneration of electricity and desalinated water by concentrated solar power (CSP) technologies is an innovative approach for solving the above problems of water scarcity and energy production from sources that are not friendly to the environment [1].

In order to tackle these targets, a research project entitled Solar thermal Power Generation and Water (STEP-EW) has

been funded by the Cross-Border Cooperation Programme, Greece, Cyprus, 2007–2013 [2]. The project is based on a technoeconomic study carried out by the Cyprus Institute (CyI) in cooperation with Electricity Authority of Cyprus (EAC) and the Massachusetts Institute of Technology (MIT) and concerned the installation in Cyprus of cogenerated solar thermal plants with desalinated water [1, 3]. The main objective of STEP-EW project is the technical confirmation of the innovative idea of the cogeneration of electricity and desalinated water by using small-scale solar thermal plants in real conditions.

In this work, an up-scaling of the innovative CSP technology for the cogeneration of electricity and desalinated water (CSP-DSW) to be integrated into the Cyprus power generation system is carried out. Further, a comparative study of the competitiveness of CSP-DSW technology with the integration of natural gas combined cycle (CCGT) technology is carried out. For the simulations, the IPP v2.1 software is used for calculating the optimum cost of electricity produced from both conventional and CSP-DSW technologies [4]. For each scenario under investigation, the simulations take into

FIGURE 1: Cogenerated solar thermal plant with desalinated water.

account the capital cost, the fuel consumption and cost, the operation cost, the maintenance cost, the plant load factor, and so forth.

Section 2 gives a brief description of the STEP-EW project, whereas in Section 3, the optimization model used for the simulations is described. Section 4 concerns the simulation procedure and the results for the integration of large-scale CSP-DSW technologies in the Cyprus power generation system. Finally, the conclusions are summarized in Section 5.

2. The STEP-EW Project

The STEP-EW project has been funded by the Cross-Border Cooperation Programme, Greece, Cyprus, 2007–2013 [2]. The project is based on a technoeconomic study carried out by the CyI in cooperation with EAC and the MIT and concerned the installation of cogenerated solar thermal plants with desalinated water [1, 3]. The main objective of STEP-EW project is the technical confirmation of the innovative idea of the cogeneration of electricity and desalinated water by using small-scale solar thermal plants in real conditions. The consortium of project partners consists of the CyI, EAC, Cyprus Water Development Department, and the Act Network in Greece.

The CSP-DSW technology utilizes solar energy to generate electricity. The heat collected from converting solar energy to thermal energy is used in a conventional power cycle to generate electricity. The main components of a CSP-DSW technology are the energy collection system, the receiver system, the thermal energy storage, the desalination unit, and the typical components used in conventional power cycles (e.g., steam turbines and generators), as illustrated in Figure 1. The receiver system converts the solar energy that is intercepted and reflected by the collection system. In systems with energy storage capabilities, the thermal energy in the

receiver is first stored into a heat storage medium to manage the variations in the solar energy influx. The storage system may contain sufficient thermal energy to continue the power generation overnight, or during days with overcast weather. A heat transfer fluid (HTF), possibly different from the heat storage medium, transfers the energy from the storage medium to the steam generators in the power cycle.

The intensity of the solar energy received by the collectors is only a few $\text{kWh/m}^2/\text{day}$. To achieve higher intensities and ultimately higher operating temperatures, CSP technologies are used. In CSP systems, the surface area from which the heat losses occur, that is, the receiver aperture, is significantly less than the total surface area of the collectors. In the STEP-EW project, heliostats positioned on a south-facing hill reflect the light directly onto the receiver on the ground [5]. The solar receiver is the component that receives sunlight and converts it into heat. The heat is transferred through the HTF from the receiver to the storage unit, where it is accumulated for later use. The receiver unit is based on the technology of solar panels. With dimensions $1.5 \times 1.5 \text{ m}^2$, the receiver consists of a collector plate and manifold from where the HTF passes. Because of the high temperatures developed, the receiver will use synthetic oil as HTF resistant up to 400°C . Then the oil is transferred to the storage tank energy, as shown in Figure 2. The model predicts a yield of 65–70% for the receiver, which is considered satisfactory. The storage unit is designed so that the unit can operate for 24 hours at full capacity without additional energy from the sun. As a result, if there is a widespread lack of sunshine, such as during the night or on cloudy days, the unit can continue its normal operation [6].

Extraction turbines are assumed for the electricity generation. Process steam is extracted from the turbine at various pressures. The extracted steam can be used for heating the condensed steam in the steam cycle (through open or closed feedwater heaters) and seawater desalination (both optional). The heat collected at the lid is used for preheating

FIGURE 2: The receiver unit.

the desalinated feedwater [7]. For the desalination unit, the multieffect distillation (MED) is preferred. The MED process consists of several consecutive stages (or effects) maintained at decreasing levels of pressure (and temperature), leading from the first (hot) stage to the last one (cold), as illustrated in Figure 3.

Each effect mainly consists of a multiphase heat exchanger. Seawater is introduced in the evaporator side, and heating steam is introduced in the condenser side. As it flows down the evaporator surface, the seawater concentrates and produces brine at the bottom of each effect. The vapour raised by seawater evaporation is at a lower temperature than the vapour in the condenser. However, it can still be used as heating medium for the next effect where the process is repeated. The decreasing pressure from one effect to the next one allows brine and distillate to be drawn to the next effect where they will flash and release additional amounts

of vapour at the lower pressure. This additional vapour will condense into distillate inside the next effect. In the last effect, the produced steam condenses on a conventional shell and tubes heat exchanger. This exchanger, called distillate condenser, is cooled by seawater. At the outlet of this condenser, one part of the warmed seawater is used as make-up water, while the other part is rejected to the sea. Brine and distillate are collected from effect to effect, up to the last one from where they are extracted by pumps [6].

3. Optimization Model

In order to calculate the cost of electricity from the various candidate technologies, each plant operation is simulated using the IPP v2.1 software [8]. 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 given in Figure 4, 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 [4].

The technical and economic parameters of each candidate power generation technology are taken into account based on the cost function:

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

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 by

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

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, 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).

4. Simulations and Discussion of the Results

The main objective of this paper is to carry out an up-scaling of the innovative CSP-DSW technology to be integrated into the Cyprus power generation system. Further, a comparative study of the competitiveness of CSP-DSW technology with the integration of CCGT technology is carried out. The simulations are carried out using the IPP v2.1 software for calculating the optimum cost of electricity produced from both conventional and CSP-DSW technologies. Other works related to the integration of large-scale CSP plants in power generation systems can be found in [9–13].

FIGURE 3: Flow diagram for MED with thermal vapour compression.

FIGURE 4: Flow chart of the IPP optimization model.

In order to compare on equal basis the expected cost of electricity from the selected conventional and CSP-DSW technologies, the following generating technologies have been examined: (a) CCGT technology base case of natural gas technology price projection, (b) CCGT technology with low natural gas technology price projection, (c) CSP-DSW technology 5 MWe, (d) CSP-DSW technology 10 MWe, (e) CSP-DSW technology 25 MWe, and (f) CSP-DSW technology 50 MWe. For each scenario under investigation, the simulations take into account the capital cost, the fuel consumption and cost, the operation cost, the maintenance cost, the plant load factor, and so forth. In the case of the CSP-DSW technology scenarios, only the infrastructure required to operate the power block section is considered in the simulations.

4.1. Input Data and Assumptions. In order to compare on equal basis the expected cost of electricity from the selected conventional and CSP-DSW technologies, the technical and economic input data and assumptions tabulated in Tables 1 and 2 are used.

For all scenarios, the capacity factor of the plant varies from 50 to 90%, in steps of 10%, due to the fact that for the CSP-DSW technologies it is assumed 24 h of full daily operation. For the two scenarios of CCGT technologies, a plant of 220 MWe with 52.8% efficiency and with fuel net calorific value of 49.73% is used. Whereas, for the four scenarios of CSP-DSW technologies, a small plant of 5 MWe, a small to medium plant of 10 MWe, a medium plant of 25 MWe, and a large plant of 50 MWe are used with efficiencies that vary from 9.6% for the small plant up to 17% for the large plant.

Regarding the economic input data, for the two scenarios of CCGT technologies, the capital cost is assumed to be 1154 €/kWe, and, for the fixed O&M cost, an annual expenditure is assumed as 2.7% of the total investment cost for staff salaries, insurance charges, and fixed maintenance. The variable O&M cost is assumed as 1.78 €/MWh and includes the spare parts, chemicals, oils, consumables, and town water and sewage. As for the four scenarios of CSP-DSW technologies, the capital cost is assumed to reduce from 6337 €/kWe for the 5 MWe scenario to 5752 €/kWe for the 50 MWe scenario. The fixed O&M cost is assumed as an annual expenditure of 2% of the total investment cost, and the variable O&M cost is assumed to increase from 0.46 €/MWh for the 5 MWe scenario up to 1.8 €/MWh for the 50 MWe scenario.

The two scenarios of CCGT technologies concern two different cases of natural gas technology price projection, as illustrated in Figure 5.

The first case concerns a base case of natural gas technology price projection, which is based on [14] and the second one concerns a case with low natural gas technology price projection, in which the price of natural gas is reduced by 40% compared to the base case in each year.

In order to take into account, for the two scenarios of CCGT plants, the CO₂ emission trading scheme (ETS) cost, the CO₂ ETS price projection, which is illustrated in Figure 6,

TABLE 1: Technical input data and assumptions.

Scenario	Fuel type	Capacity (MWe)	Efficiency (%)	Fuel net calorific value (GJ/t)	Capacity factor (%)
CCGT base case	Natural gas	220	52.8	49.73	50–90
CCGT low NG cost	Natural gas	220	52.8	49.73	50–90
CSP-DSW 5 MWe	Solar energy	5	9.6	—	50–90
CSP-DSW 10 MWe	Solar energy	10	11.9	—	50–90
CSP-DSW 25 MWe	Solar energy	25	14.8	—	50–90
CSP-DSW 50 MWe	Solar energy	50	17.0	—	50–90

TABLE 2: Economic input data and assumptions.

Scenario	Specific capital cost (€/kWe)	Fixed O&M (€/kWe/month)	Variable O&M (€/MWh)
CCGT base case	1154	2.58	1.78
CCGT low NG cost	1154	2.58	1.78
CSP-DSW 5 MWe	6337	10.56	0.46
CSP-DSW 10 MWe	6093	10.16	1.02
CSP-DSW 25 MWe	5844	9.74	1.59
CSP-DSW 50 MWe	5752	9.59	1.80

FIGURE 5: Natural gas projection prices.

is assumed. Also, the economic life of the plants is assumed as 20 years. Throughout the simulations, a typical discount rate of 6% and a loan interest of 6% are assumed.

4.2. Results and Discussion. In order to compare on equal basis the expected cost of electricity from the selected conventional and CSP-DSW technologies, six scenarios have been examined. For each scenario under investigation, the simulations took into account the capital cost, the fuel consumption and cost, the operation cost, the maintenance cost, the plant load factor, and so forth. For each scenario, the electricity unit cost, as well as the specific capital cost, the specific fixed O&M cost, and the specific variable O&M cost were calculated.

FIGURE 6: CO₂ ETS price projection.

FIGURE 7: Comparison of the simulation results.

The results obtained concerning the electricity unit cost for the six scenarios in respect to the capacity factor of the plants are illustrated in Figure 7.

It can be observed that after a capacity factor of 58%, all the four scenarios of CSP-DSW technologies are cost effective with respect to the CCGT base case of natural gas technology price projection scenario. Also, for a capacity factor of more than 80%, the medium and the large CSP-DSW technology scenarios are even more cost effective than the CCGT with low natural gas technology price projection scenario, and, at 90% capacity factor, this observation is applied for all CSP-DSW technology scenarios.

FIGURE 8: Electricity unit cost breakdown for 80% capacity factor.

The electricity unit cost breakdown for 80% capacity factor for all six scenarios is illustrated in Figure 8. It can be observed that for the two scenarios of CCGT technologies, the most part of the total electricity unit cost is due to the specific fuel cost, which amounts to 74.5% for the CCGT base case of natural gas technology price projection scenario and 63.7% for the CCGT with low natural gas technology price projection scenario. Also, for these scenarios, a significant contribution to the total electricity unit cost has the specific CO₂ ETS cost. As for the four scenarios of CSP-DSW technologies, the specific capital cost, which is around 80.5%, contributes more than the specific O&M cost in the total electricity unit cost.

5. Conclusions

In this work, an up-scaling of the innovative CSP-DSW technology to be integrated into the Cyprus power generation system was carried out. Further, a comparative study of the competitiveness of CSP-DSW technology with the integration of CCGT technology was also carried out. In order to compare on equal basis the expected cost of electricity from the selected conventional and CSP-DSW technologies, six scenarios have been examined. For each scenario under investigation, the simulations took into account the capital cost, the fuel consumption and cost, the operation cost, the maintenance cost, the plant load factor, and so forth. For each scenario, the electricity unit cost, as well as the specific capital cost, the specific fixed O&M cost, and the specific variable O&M cost were calculated.

The results indicated that for high capacity factor levels, the CSP-DSW technology scenarios are more cost effective than the CCGT technology (base case of natural gas technology price projection scenario) and become even more cost effective at very high capacity factor levels than the CCGT technology (low natural gas technology price projection scenario). Furthermore, the most part of the electricity unit cost of the two scenarios of CCGT technologies is due to the

specific fuel cost, whereas for the four scenarios of CSP-DSW technologies, it is due to the specific capital cost.

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