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# Thermo-economic analysis of conventional combined cycle hybridization: United Arab Emirates case study

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ABSTRACT

Extensive investigations have been conducted to find a replacement for fossil fuels and natural gases in power generation industries. Solar energy is one of the most promising solution to a more environmentally friendly power production technology. In particular, concentrated solar power technologies are displaying significant potential for electricity production. United Arab Emirates hot and sunny climate is an indication of the great potential it possesses for hybrid and solar only power plant implementation. In this paper, power plant hybridization feasibility in the United Arab Emirates is taken under extensive investigation. Moreover, a thermo-economic optimization is performed for the installment of a new 50 MWe hybrid conventional combined cycle power plant in the United Arab Emirates. In addition, hybridization of an already existing conventional combined cycle power plant is comprehensively investigated by utilizing levelized cost of electricity, payback period, life cycle saving, and net present value approaches. The hybrid conventional combined cycle power plant optimum levelized cost of electricity and net present value are 77.7 US$/MWh and −34.918 MUS$, respectively. Additionally, the plant solar share and specific carbon dioxide emission are 8.87% and 371.9 $kgCO_2$/MWh, respectively.


## 1. Introduction

There are several studies available in literature investigating different aspects of renewable energy integration. For instance, techno-economic assessment of a ground source heat pump system in eastern Turkey is accomplished by Esen et al. [1] whereas experimental analysis for a solar assisted ground source heat pump system is presented by Esen et al. [2]. Moreover, techno-economic evaluations of ground-coupled and air-coupled heat pump systems are carried out by Esen et al. [3]. Additionally, comparative and experimental evaluations for different renewable energy sources employment in greenhouse heating are accomplished by Esen and Yuksel [4]. Furthermore, cost-effective design of ringwall storage hybrid power plants is presented by Weibel and Madlener [5]; while, tri-generation based hybrid power plants with energy storage are investigated by Pazheri [6]. Compressed air energy storage is proposed for bulk storage of electric energy in solar and wind systems by Safaei and Keith [7]. Besides, Sandler et al. [8] utilize solar thermal energy to generate steam for thermal enhanced oil recovery. Moreover, penetration of solar power without utilizing any type of storage is investigated by Stodola and Modi [9]. In another study, modeling and optimization of a new hybrid solar thermoelectric system utilizing a thermosyphon are presented by Miljkovic and Wang [10]. Finally, a new concept of wave energy conversion capable of trapping ocean wave energy into a basin is introduced by Saadat et al. [11].

Solar energy is one of the most promising solutions to a more environmentally friendly power production technology. In particular, CSP employs solar radiation to initially heat up a fluid (water, synthetic oil, or air) which will eventually result in electricity generation. In a study by Jacobson and Delucchi [12], a ranking for different renewable energy technologies are presented. Based on the reported ranking, CSP technology has the second highest potential for power generation. One of the advantages of the CSP technology is its capability to be utilized as a primary or secondary source of energy within fossil fuel and natural gases power plants. In other words, part of the required thermal input can be supplied by the CSP technology. Therefore, an existed fossil fuel or natural gases power plant can be partially converted into a solar thermal power plant utilizing CSP technology as a source of energy. This process is referred to as the hybridization of the power plant.

While hybridization of a power plant cannot be considered as a long term solution, it is certainly a temporary solution to the difficulties associated with renewable energy integrations such as intermittency and storage [13]. Hybridization will increase power

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## Nomenclature

| | |
|---|---|
| $a_1 \cdots a_n$ | dimensionless NASA polynomial curve fit coefficients |
| $c_p$ | specific heat capacity (kJ/kg K) |
| *dsep* | additional separation distance between adjacent heliostats (m) |
| *DM* | heliostat characteristic diameter (m) |
| *f* | factor |
| *i* | loan interest rate |
| *LHV* | lower heating value (kJ/kg) |
| *LH* | heliostat height (m) |
| *LW* | heliostat width (m) |
| $\dot{m}$ | mass flow rate (kg/s) |
| *N* | number, number of years |
| $\dot{Q}$ | rate of thermal energy (kWth) |
| *R* | gas constant (kJ/kg K), radial distance (m) |
| $r_{ins}$ | insurance rate |
| $s^0$ | temperature dependent specific entropy (kJ/kg K) |
| *T* | temperature (K) |
| *W* | generated electricity (MWh) |
| $\dot{W}$ | power (kWe) |
| *w* | specific work (kJ/kg) |
| *Z* | capital investment cost (US$) |

*Abbreviations*

| | |
|---|---|
| BCPR | bottoming cycle pressure ratio |
| CCC | conventional combined cycle |
| CEPCI | chemical engineering plant cost index |
| CSP | concentrated solar power |
| DNI | direct normal radiation |
| DOSH | degree of superheating |
| GTIT | gas turbine inlet temperature |
| HRSG | heat recovery steam generator |
| LCOE | levelized cost of electricity |
| TMY | typical meteorological year |
| TCPR | topping cycle pressure ratio |
| UAE | United Arab Emirates |

*Greek symbols*

| | |
|---|---|
| $\alpha$, $\beta$ | thermo-economic coefficients |
| $\Delta R$ | radial increment (m) |
| $\Delta T$ | temperature difference (K) |
| $\varepsilon_T$ | tower unit vector elevation angle (rad) |
| $\eta$ | efficiency |
| $\rho$ | mirror reflectivity |
| $\omega$ | solar radiation incident angle (rad) |

*Subscripts*

| | |
|---|---|
| *1* | first |
| *a* | air |
| *ann* | annual |
| *at* | attenuation |
| *B* | bottoming |
| *b* | blocking |
| $CO_2$ | carbon dioxide |
| *c* | compressor |
| *civil* | civil engineering |
| *con* | construction |
| *cont* | contingency |
| *cos* | cosine |
| *dec* | decommissioning |
| *ele* | electrical |
| *eqp* | equipment |
| *ex* | exhaust |
| *f* | fuel, field |
| *G* | generator |
| *g* | gas |
| *i* | $i^{th}$ |
| *if* | indirect factor |
| *ins* | installation |
| *inv* | investment |
| *j* | $j^{th}$ |
| *lab* | labor |
| *M* | mechanical |
| *mai* | maintenance |
| *min* | minimum |
| *NGS* | natural gas branching |
| *net* | net |
| *opt* | operation, optical |
| *pinch* | pinch |
| *pump* | pump |
| *ref* | reference |
| *s* | steam |
| *sat* | saturated |
| *sh* | superheater |
| *sol* | solar |
| *sp* | spillage |
| *s&b* | shading and blocking |
| *T* | topping |
| *t* | turbine |
| *w* | water, weighted |

plant efficiency (compared with solar only plants) and enable the plant to operate for 24 h a day. Moreover, CSP has a low environmental impact regarding construction materials as compared to the other renewable energy technologies [14]. Hybrid solar power plants can be competitive with conventional fossil fuel power plants in high insolation areas. United Arab Emirate (UAE) hot and sunny climate is an indication of the great potential it possesses for hybrid or solar only power plant implementation. Extensive research has been accomplished in regard to the employment of CSP technology in UAE. In 2010, a joint study by Petroleum Institute and the University of Maryland estimated the average direct normal radiation (DNI) for Abu Dhabi to be 400 W/m$^2$ during a year [15,16]. Thus, studies on the implementation of CSP technology in the UAE is highly regarded as a step toward a cleaner future.

Introduction of gas turbine in 1937 presented a new method of power production [17]. Gas turbine exhaust gases contain considerable amount of waste heat which can be utilized to operate a waste heat recovery bottoming cycle. Rankine (steam turbine) cycle is the most popular and widely implemented bottoming cycle coupled with a topping gas turbine cycle. Low operating temperature of the steam turbine cycles makes it the most appropriate cycle for waste heat recovery purposes. This configuration which is referred to as the conventional combined cycle (CCC) is the most efficient combined configuration. Several investigations were conducted on different aspects and potentials of CCC power plants. Pelster [18] proposed a CCC plant with $CO_2$ separation option. Additionally, the author provided detailed thermo-economic and environmental analyses of the aforementioned plant. An