Switching from fossil fuel-based to concentrated solar power driven tri-generation systems: an optimization model

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Abstract

In light of the increase in the consumption of fossil fuels in tri-generation systems integrated with desalination plants and the associated environmental damage, switching into renewable energy sources became a necessity. Various technologies have been identified as potential energy sources for tri-generation systems, among which concentrated solar power (CSP) was found an appealing and viable option for driving large-scale desalination plants. However, CSP is well known for its high investment cost, which makes the switching process very expansive. In order to address this challenge, different types of fuel with lower carbon emission than conventional energy sources could be utilized in a transient phase allowing for a gradual reduction in carbon emissions. This work presents a Mixed Integer Nonlinear mathematical model that can be used for planning the shift from fossil fuels to CSP. The model is capable of identifying the optimal combination of fuels to be utilized besides CSP in the transient phase for a tri-generation system integrated with a reverse osmosis (RO) unit. Hence, the aim is to determine the best fuel options to be integrated with CSP, in addition to their corresponding energy contributions using a series of different net carbon reduction targets (NCRT) ranging from 0 to 100%. The fuel options incorporated into the model include natural gas, biomass and municipal solid waste (MSW). Moreover, two different technologies for MSW incineration are involved: grate fired and fluidized bed boilers. The model has been implemented on a tri-generation system integrated with Carlsbad desalination plant in California for illustration purposes. The optimal fuel source(s) and technologies during the transition from fossil fuels to a concentrated solar power-based desalination system have then been identified. It was found that when the NCRT levels are below 40%, biomass emerges as the most suitable fuel option, whereas for higher NCRT values, solid waste incineration is the preferred choice.

**Keywords:** Tri-generation systems, desalination, concentrated solar power, biomass, municipal solid waste

* 1. Introduction

Thermal and electrical energy generation from conventional fossil fuels is becoming expansive, and it is associated with many detrimental effects on health and environment. In 2018, a significant rise in power consumption produced from fossil fuel sources of energy was reported, while carbon dioxide emissions reached a critical level of 33.5 Gt. Although a decline in power sector emissions in developing countries was observed in the following year, global CO2 emissions showed a very small reduction of less than 1% (Ma’aji et al., 2022). On the other hand, desalination processes are well known for their high thermal and electrical energy demand and fossil fuels consumption. Therefore, the past half-century witnessed the integration of various concentrated solar power (CSP) technologies with desalination units coupled with tri-generation systems. For instance, Klaimi et al. (2021) have presented a Mixed Integer Non-linear mathematical model for designing a standalone CSP-desalination tri-generation system producing three pressure levels of steam, power and freshwater simultaneously, while Ma’aji et al. (2022) have proposed a design of a tri-generation plant for electricity, freshwater production and district heating in Lagos, Nigeria. One of the main challenges associated with CSP is the high investment cost. Therefore, the integration of other energy sources with CSP was found a great strategy to overcome this challenge. For instance, an energy and economic analysis of a novel biomass-solar hybrid system presented by Khosravi et al. (2021) showed a minimum attainable levelized cost of energy of 7.865 cents/kWh. Klaimi et al. (2022a) have presented a multi-period model for designing a CSP-desalination tri-generation system integrated with a natural gas boiler, while Najjar et al. (2021) have studied the energy generation from the anaerobic digestion of municipal solid waste (MSW) to drive a reverse osmosis unit. Moreover, Klaimi et al. (2022b) have investigated seasonal variations and multiple fuel options (natural gas, biomass and MSW) in a novel tri-generation CSP integarted hybrid energy process. Although the backup energy sources of CSP could significantly reduce the cost of the system, their existence is associated with carbon dioxide emissions. Therefore, these sources could not be utilized when the target is to design a carbon neutral system. However, it is recommended to incorporate such sources in a transient phase while switching from fossil fuels to CSP allowing a gradual reduction in CO2 emissions. This paper assess different types of fuel and technologies to be utilized in a tri-generation system during the transient phase subject to a specific net carbon reduction target. The novelty of this work lies in the incorporation of a wide number of fuels and technologies which helps policy makers in selecting the appropriate energy sources based on the specifications of the system.

* 1. Methodology

The proposed CSP-desalination hybrid tri-generation system is depicted in Figure 1. This system is divided into three stages: 1) Very high pressure (VHP) steam generation section, 2) Low pressure (LP) steam, very low pressure (VLP) steam, shaft and electric power generation section, and 3) Freshwater generation section. The first section includes a natural gas boiler, a solar steam generator and an additional boiler specific to the fuel to be utilized in the transient phase. The fuels that will be considered in this work are biomass and municipal solid waste. Moreover, two different boilers will be investigated for the incineration of solid waste: a fluidized bed (FB) boiler and a grate-fired (GF) boiler. The main difference between the two boilers lies in the type of solid waste incinerated and the amount of carbon emissions which allows a more controlled incineration when the process takes place in a fluidized bed boiler. VHP steam at 41 bars and 450 oC is produced in this section and fed to the next stage of the system. The second stage includes a throttling valve (TV), a back-pressure driver (DRBP) and turbo-generator (TGBP) for the production of LP steam at 2 bars, in addition to a condensing driver (DRCD) and turbo-generator (TGCD) for the production of VLP steam at 0.4 bar. The VLP steam produced is condensed, pumped and deaerated before being relocated as boiling feed water (BFW) to the first section, while the shaft and electric power produced are distributed to the desalination technologies in the following section. Two different desalination technologies are incorporated in this system: thermal desalination using multi-stage flashing (MSF) and membrane desalination using reverse osmosis (RO). A portion of freshwater stream generated is recycled back as makeup water to the deaerator in order to compensate for any loss of steam during VHP steam expansion and deaeration.

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Figure 1: Proposed tri-generation system structure

* 1. Mathematical Model

The proposed tri-generation system has been converted into a Mixed Integer Non-linear Problem (MINLP) that aims at minimizing the total cost of the system. The objective function is described in Eq. (1) below, where *Costsec1* is the VHP steam generation cost from the different energy sources and technologies embedded in section 1 of the system, *Costsec2* is the cost of utilities (LP and VLP steam, electric and shaft work) generated in section 2 of the system for desalination purposes, and *Costsec3* is the cost of desalination process which takes place in the third section of the system.

$Minimize Cost^{sec1}+Cost^{sec2}+Cost^{sec3}$ (1)

Equality and inequality constraints have been added to the model. The equality constraints cover the material and energy balances around all technologies and headers in the system. For instance, Eq. (2-5) represents the mass balances on natural gas boiler, solar steam generator, back-pressure turbo-generator and reverse osmosis unit, respectively, while the energy balances of the same technologies are represented in Eq. (6-9), respectively. In these equations, the variables *G*, *H*, *Q* and *W* denote the mass flowrate, specific enthalpy, thermal energy and electric power, respectively, while the subscripts *B*, *S*, *SG*, *TB*, *RO*, *DSW* and *NG* refer to boiler, steam, steam generator, turbo-generator, reverse osmosis, desalinated water and natural gas, respectively. Moreover, *HV*, *η* and λare the parameters corresponding to the calorific value of natural gas, technology efficiency and electric power requirement per unit of water, respectively.

$G\_{BFW-B}=G\_{S-B}+G\_{blowdown}$ (2)

$G\_{BFW-SG}=G\_{S-SG}$ (3)

$G\_{TB-in}=G\_{TB-out}$ (4)

$G\_{RO-in}=G\_{RO-brine}+G\_{RO-DSW}$ (5)

$\left(G\_{BFW-b}H\_{BFW-b}+G\_{NG}HV\_{NG}\right) η\_{B}=G\_{S-B}H\_{S-B}+G\_{blowdown}H\_{blowdown}$ (6)

$Q\_{absorbed}=η\_{SG} Q\_{released}$ (7)

$W\_{TB}=η\_{power }η\_{TB }ΔH\_{TB} $(8)

$W\_{RO}=λ\_{RO} G\_{RO-DSW}$ (9)

On the other hand, the inequality constraints, described in Eq. (10-13) below, address the limitations on certain aspects of the system, such as the capacities of technologies, solar availability, minimum freshwater production and maximum allowable CO2 emissions subject to a net carbon reduction target (NCRT) imposed on the system. In these equations, *b* represents a binary variable, $A\_{SF}$ is the required solar field area, *DNI* is the average direct normal irradiance, while $G\_{NG}^{CO2}$, $G\_{TF}^{CO2}$, and $G^{CO2, BC}$ are the carbon dioxide emissions from natural gas boiler, transient fuel boiler and total CO2 emissions of a base case scenario, respectively.

$b G\_{min}\leq G\leq b G\_{max}$ (10)

$G\_{S-SG}\left(H\_{S-SG}-H\_{BFW-SG}\right)\leq A\_{SF} DNI$ (11)

 $G\_{DSW,min}\leq G\_{DSW}$ (12)

$G\_{NG}^{CO2}+G\_{TF}^{CO2}\leq \left(1-NCRT\right) G^{CO2, BC}$ (13)

* 1. Case Study

The proposed model was implemented on a trigeneration system integrated with Carlsbad desalination plant in California, USA. This plant operates using reverse osmosis (RO) membranes with a total capacity of 160,000 m3/d and inlet seawater salinity of 33.5 g/L. Moreover, the energy consumption of RO was estimated at 3.5 kWh/m3. The main energy supplier of Carlsbad plant is San Diego Gas and Electric (SDG&E) plant which currently generates 55% of its energy from natural gas and 45% from solar panels and wind (Klaimi et al., 2022c). Since the aim of this study is to assess the utilization of various fuel options and technologies in a transient phase towards a carbon neutral system, two base case scenarios will be considered. In the first scenario, the net carbon reduction target will be based on the amount of CO2 emitted from a system that is operating on natural gas only, whereas the second base case scenario is similar to the current situation. As previously mentioned, biomass and municipal solid waste are the transient fuels to be investigated in this work, while the technologies that will be incorporated are biomass boiler, grate-fired boiler and fluidized bed boiler. Moreover, the option of making some revenues through the selection of grate-fired boiler was added to the model, since this policy is adopted in many countries to reduce the total volume of generated solid waste. On the other hand, in order to determine the maximum amount of energy that could be generated from CSP, an average monthly DNI value of 168 kWh/m2 was considered. The MINLP optimization problem has been implemented using “Whats’Best 17.0” LINDO Global Solver for MS-Excel 2016. Figure 2 below shows the variation of total water production cost (WPC) using different transient fuels and technologies at a series of NCRT values ranging from 0 to 100% based on the first scenario.

Figure 2: Water production cost vs NCRT for different fuel options

The obtained results showed that water production cost of a tri-generation system operating using natural gas only (0% NCRT) is 0.715 USD/m3, while the amount of CO2 emissions associated with the utilization of natural gas is estimated at 299 tons/day. This WPC varies differently with increasing NCRT values depending on the type of transient fuel and technology. Figure 2 shows that biomass is the most appropriate fuel to be selected in the transient phase for NCRT values below 40%. At low NCRT values, energy generation from biomass was found the cheapest among the available options, followed by MSW incineration using grate fired boiler with revenues (MSW-GFR). However, when the revenues from the utilization of grate fired boiler are ignored (MSW-GFWR), the fluidized bed boiler (MSW-FB) becomes the most suitable technology for the incineration of MSW. This is mainly due to the high amount of CO2 emissions resulted from the incorporation of a grate fired boiler which necessitates a significant contribution of CSP in this case in order to meet the carbon reduction target. Thus, a higher WPC was observed due to the high investment cost of CSP. Similarly, when NCRT exceeds 40%, the high emissions from biomass combustion require a higher contribution of CSP. This resulted in a drastic increase in WPC when biomass is selected as a transient fuel. In addition, MSW incineration option using grate fired boiler with revenue was preferred over biomass for a NCRT beyond 40%, while the fluidized bed and grate fired boiler without revenues become more desirable at NCRT values of 50% and 60%, respectively. On the other hand, when a 100% carbon reduction is required, the WPC of a system operating using CSP only was found 1.75 USD/m3.

The capital and investment costs of the investigated technologies were not the only reason behind the results observed in Figure 2. The amount of carbon emissions associated with the combustion of transient fuels could also affect the water production cost of the system. Higher CO2 emissions result in the selection of CSP as a secondary energy source for desalination which increase the WPC. Since the transient fuels have different carbon emission factors, it should be noted that CSP technology appeared for the first time in the optimal configurations at different NCRT values depending on the type of transient fuel involved. Table 1 below summarizes the NCRT values at which CSP was selected for the first time, the contribution of this energy source and WPC for the studied fuels.

Table 1: Summary of CSP related results

|  |  |  |  |
| --- | --- | --- | --- |
| Transient Fuel | NCRT (%) | CSP Contribution (%) | WPC (USD/m3) |
| Biomass | 60 | 24 | 1.39 |
| MSW-GFR | 80 | 11 | 0.98 |
| MSW-GFWR | 80 | 11 | 1.21 |
| MSW-FB | 100 | 100 | 1.75 |

All NCRT values were based on a carbon emission flowrate of 162 tons/day. Surprisingly, the results showed the same trend of WPC variation with NCRT for the different fuels and technologies. The only difference was found in the values of WPC which were higher in the second case due to the higher contribution of CSP as a result of the stringent allowable carbon emissions. Thus, it can be concluded that fuel optimality does not depend on the base case scenario, whereas the water production cost does.

* 1. Conclusion

This study has presented an assessment strategy for detrmining the most appropriate fuel and technology to be adopted in a transient phase while switching from fossil fuel to concentrated solar power based desalination system. The results showed that biomass is the best fuel to be utilized for this purposes at NCRT values below 40%, whereas solid waste incineration is preferred at higher NCRT values.

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