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Research paper

Optimization of multiple fuel utilization options in Tri-generation systems

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ABSTRACT

This work investigates the design of optimal tri-generation systems for heat, power and water production via multiple fuel selections, thus aiming to reduce the reliance on fossil fuel consumption. Generally speaking, tri-generation systems are associated with high levels of carbon dioxide emissions to meet energy and water production requirements. Hence, a shift towards more renewable energy sources can assist in partially reducing the environmental damage associated with standard tri-generation operations. Since the switch from fossil fuels to renewable energy is very costly, hybrid energy systems were found an appealing solution that could allow a gradual reduction of carbon emissions. Hence, the novelty aspect of this work is the ability to generate cost-effective tri-generation systems that incorporate optimal hybrid energy selections and utility generation routes, subject to specific net carbon reduction targets (NCRT). As such, four different energy sources (natural gas, biomass, municipal solid waste (MSW) and Concentrated Solar Power (CSP) were investigated, together with five different routes for steam expansion and electricity production using a Mixed Integer Nonlinear Program (MINLP), including technical, economic and environmental constraints. In order to study the effect of different fuel selections, energy production operations, and water production routes on the performance of tri-generation systems, data from three different desalination plants (located in USA, Cyprus and Qatar) were used. The results obtained show that energy requirements for desalination greatly affects the order of selection of energy sources. In general, biomass was identified as the best alternative to replace natural gas at NCRT values below 40%. On the other hand, MSW incineration using grate-fired and fluidized bed boilers became more desirable for steam production when higher NCRT values were utilized. The water production costs (WPC) of a standalone CSP system integrated with each of the studied plants, having a feedwater salinity of 33.5, 41.8 and 45 g/L, were estimated at 1.739, 2.233 and 2.67 USD/m^3, respectively. In addition, an average incremental increase of 5.5% in the WPC has been observed during seasons that provide the lowest solar availability values.

1. Introduction

Cogeneration systems are often referred to as combined heat and power (CHP) systems, which allow the simultaneous process production of multiple energy streams, usually in the form of thermal energy (in the form of heat) and electrical energy (in the form of power). Since cogeneration systems are very well established and proven schemes for energy production, tri-generation systems are generally based on a pre-existing cogeneration setup, which then integrates additional units such as the presence of an absorption chiller or a desalination unit, so as to generate cooling/water simultaneously together with energy production (Uche et al., 2019). It has been reported that a 90% thermal efficiency could be achieved using tri-generation systems, especially for applications that involve commercial and industrial facilities (Liu et al., 2014).

Due to the high effectiveness of tri-generation systems in terms of producing multiple utility outlets simultaneously, the design and optimization of such systems is now emerging into an imminent research area, aiming for more sustainable designs (Tariq et al., 2022), including more renewable and environmentally friendly options (Rostami et al., 2021). However, the presence of many energy sources and utility generation routes makes the design of such systems complex and time consuming.

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Moreover, the shift towards carbon neutral systems is expensive due to the high costs of renewable energy technologies which requires the intervention of some cheaper energy sources that are characterized by lower carbon emissions than fossil fuels, such as biomass and municipal solid waste. Therefore, designing cost-effective hybrid tri-generation systems that could meet specific carbon reduction targets is vital.

The aim of this work is to design a hybrid tri-generation system that helps policy makers in selecting the best energy sources to be integrated tri-generation system, while meeting certain environmental constraints. Although the integration of concentrated solar power, biomass and fossil fuels with desalination has been widely studied and evaluated in literature, the optimization of a superstructure that includes a variety of technologies in each stage of the tri-generation process has not been tackled yet. In this context, Klaimi et al. (2021) first proposed an effective model for the design of tri-generation systems that involve three different pressure levels of steam, power and freshwater simultaneously, using a standalone CSP facility as the only possible energy source. Subsequently, Klaimi et al. (2022) introduced a selection of different energy sources for tri-generation systems, whilst fixing the steam expansion and power generation block. Unlike the previous work by Klaimi et al. (2022), this work allows the simultaneous optimization of different steam expansion and power generation options, whilst considering multiple energy source selections.

The novelty of this work is mainly manifested through the ability to optimize the fuel selections for energy production in addition to optimizing the technologies used within the tri-generation system (a three-stage process for steam, power and water production), simultaneously. According to Klaimi et al. (2022), optimal solution for a fixed tri-generation configuration were found very sensitive to the specifications of the embedded technologies and many other parameters related to the location of the desalination plant, solar availability, land footprint, and fuel costs. It was reported that any change in one of these parameters would ultimately result in a different optimal configuration of the system (Klaimi et al., 2022). As such, the effects of incorporating various energy sources, including natural gas, biomass and municipal solid waste to the CSP integrated tri-generation system presented by Klaimi et al. (2021), were considered while simultaneously exploring five different energy production routes for steam expansion and power generation.

2. Literature review

Many studies in literature have addressed and assessed tri-generation systems from different perspectives (Petrillo et al., 2021). For instance, Jafary et al. (2021) compare two solar powered tri-generation systems from both energetic and exergetic viewpoints. Li et al. (2022a) have worked on the thermo-economic assessment and optimization of a geothermal driven tri-generation system for power, cooling and hydrogen production. A weather-based energy system consisting of a tri-generation unit, photovoltaics and water-cooled chiller was proposed by Chen et al. (2022). Jamaluddin et al. (2022) have addressed transmission losses associated with tri-generation systems, which is a significant problem due to the presence of friction in pipelines and the electric grid during the distribution of energy from a total site to end users. You et al. (2022) presented the design and analysis of a solar energy driven tri-generation plant for power, heating and refrigeration. A detailed thermodynamics model has been developed in this work to determine the performance of the plant for many different conditions. Tariq et al. (2022) proposed a holistic analytical and smart management approach to investigate the performance of a renewable based tri-generation system generating power, cooling and domestic hot water. In their work, Tariq et al. (2022) consider economics, reliability, as well as risk and environmental aspects. Besides power, heating and cooling, various studies have combined desalination technologies with tri-generation systems for freshwater production. Abdelhay et al. (2022) presented an innovative tri-generation system integrating a combined nano filtration-multi effect desalination system to absorption chiller, steam Rankine cycle, parabolic trough collector and auxiliary natural gas-fired heater. A novel small-scale combined desalination, heating and power system has also been proposed by Saini et al. (2021). Li et al. (2022b) developed a two-objective optimization model for a hybrid solar-geothermal system with thermal energy storage that involves power, hydrogen and freshwater production. Similarly, Abdolalipouradl et al. (2020) conducted a thermodynamic and exergo-economic analysis for two novel tri-generation cycles that can generate power, hydrogen and freshwater using geothermal energy. Anand and Murugavelh (2019) utilized a concentrated photovoltaic/ thermal collector together with a hybrid system design for the production of power and water. Anand and Murugavelh (2019) analyzed the performance of their system throughout the day during summer and winter, and investigated the effect of meteorological variables such as PV efficiency, desalination yield, hot water and chilled air temperatures, onto the system performance.

The aforementioned studies investigated the integration of various energy sources into tri-generation systems. However, solar driven multi-generation systems remain the most preferred type of energy systems to be used as a renewable energy option, due to their ability to meet carbon emission reduction targets while meeting heat and power demands. More specifically, concentrated solar power is one of the most integrated solar systems together with seawater desalination, due to its exceptional capability of generating both thermal and electrical energy for desalination. However, as it is well known, CSPs are associated with several challenges. Those include high capital costs, large land requirements and solar intermittency. Therefore, many research studies have addressed both standalone and hybrid CSP systems, from such perspectives. As such the need to consider other waste-derived fuel types, such as biomass and municipal solid waste (MSW) for energy production in tri-generation systems, becomes a necessity for overcoming some challenges associated with CSP (Menikpura et al., 2013). Omar et al. (2021) presented a techno-economic optimization of a cascade multi-effect distillation system integrated with a CSP-sCO_2 power plant. Jamshidian et al. (2022) assessed a hybrid RO-MED desalination plant coupled with a solar CSP system from technical and economic perspectives. Klaimi et al. (2021) proposed a cost-effective design of a CSP tri-generation system integrated with a hybrid RO-MSF desalination plant. As for hybrid energy systems, Khosravi et al. (2021) investigated the energy and economic performance of a novel biomass–solar hybrid system for electricity and water production in Brazil. Similarly, Algieri and Morrone (2022) studied a solar–biomass hybrid energy cogeneration system, while Xu et al. (2022) investigated a poly-generation system for electricity, hydrogen and freshwater generation from biomass. Dajnak and Lockwood (2000) presented the benefits of using a MSW-based desalination system by evaluating the amount of freshwater generation from a reverse osmosis unit that is integrated with a municipal solid waste incineration and a gasification unit. Najjar et al. (2021) conducted a feasibility study to assess the integration of RO together with a hybrid energy system based on the anaerobic digestion of organic fractions in municipal solid waste. Similarly, de Sá Moreira et al. (2022) presented an energetic and economic feasibility analysis for a municipal solid waste incineration driven desalination plant in Brazil.

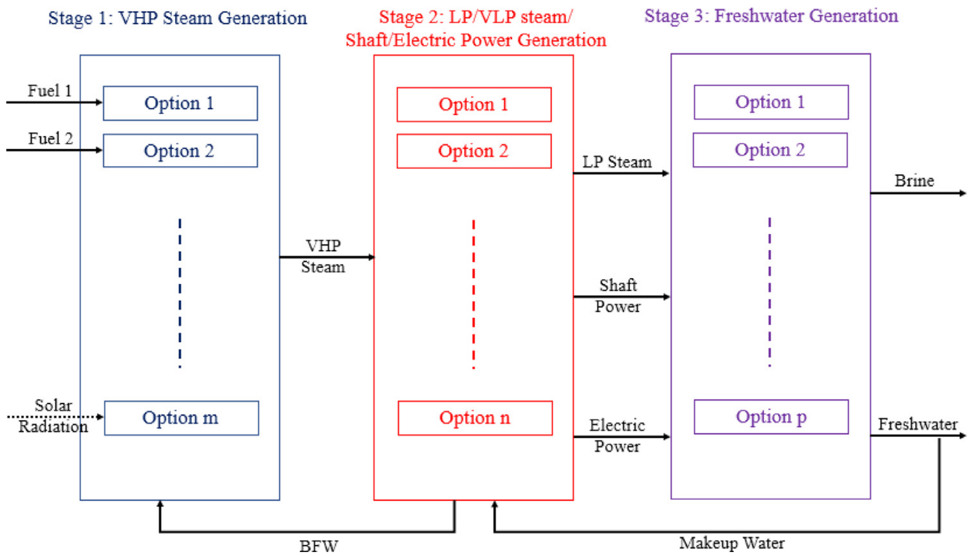

Fig. 1. General structure of tri-generation system.

As previously mentioned, one of the fundamental incentives for investing in solar energy is the significant reduction in CO_2 emissions, unlike the unrestricted fossil fuel consumption which is always correlated with increased GHG emissions. Moreover, government agencies and scientific communities have identified the energy and desalination sectors as the most critical sectors that need immediate attention for meeting decarbonization objectives (Jimenez-Navarro et al., 2020). Therefore, many studies have investigated the environmental benefits associated with multi-generation systems, especially the integration of renewable energy technologies with various processes. For instance, a PV-RO system coupled with a backup diesel generator that was proposed by Fthenakis et al. (2016) proved that it prevent up to 832 million tons of CO_2 annually. Mannan et al. (2019) also identified different scenarios for coupling MSF desalination with renewable energy in Qatar. They found that a 13% reduction in CO_2 emissions is attainable, by using a 20% contribution of solar power for thermal energy generation. Klaimi et al. (2019) presented an optimization model that couples renewable and hybrid energy options together with desalination systems, for carbon footprint reduction. In this work, Klaimi et al. (2019) mainly focused on the possible use of energy sources that are mainly for water production routes, without any co-generation of heat and power within the process. Tariq et al. (2022) performed a lifecycle assessment to analyze the environmental implications of a proposed solar driven tri-generation system, which in turn indicated a CO_2 saving potential of 6646, 4883, and 2878 tons/year in comparison to coal, fuel oil, and natural gas based systems, respectively.

Previous studies were found to be very limited in terms of the fuel options and energy generation technologies that were incorporated in tri-generation system. More specifically, exploring different steam and power technologies in tri-generation systems were primarily as conducted as standalone projects, and very few studies considered more than one fuel. As such, this work addresses a variety of technical, economic and environmental aspects in the design of tri-generation systems integrated, with multiple types of fuel and energy generation technologies involved.

3. Process description

The general structure of the tri-generation system, shown in Fig. 1, is divided into three main sections: (1) Very high pressure (VHP) steam generation section, (2) steam expansion and power generation section, and (3) freshwater generation section. Each of these sections present various options which are the different technologies that could be utilized for the production of the target utility. For instance, a combination of conventional and renewable energy sources can be incorporated within the first section of the system to generate VHP steam. Moreover, steam generation could take place using different technologies for the same type of fuel. Hence, this section presents a significant number of potential technologies for steam generation. This steam is expanded in the second section of the system for the generation of low pressure (LP) and very low pressure (VLP) steam. This expansion could happen through different routes and technologies depending on the required properties and amounts of LP and VLP steam. In addition, the expansion of VHP steam is associated with the generation of electric and shaft work when turbo-generators and drivers are utilized for this process. The utilities produced in the second section of the system are needed to drive the desalination process taking place in the freshwater generation section. On the other hand, the VLP steam produced is condensed, deaerated and redirected to the first section of the system as a boiling feedwater (BFW) stream. Finally, various thermal and membrane desalination technologies can be embedded within the third section for freshwater generation, while a small fraction of the generated water can be utilized as a makeup stream for BFW.

As previously mentioned, the design of stage 2 and 3 has been adopted from Klaimi et al. (2021). All the technologies and utilities generation routes that are considered in this work are combined into one superstructure, represented in Fig. 2, to be optimized based on the specifications of the desalination plant integrated with the system. Therefore, a mathematical model was formulated to solve for the optimal configuration of the tri-generation system through the selection of the most appropriate and cost-effective technologies, in addition to the flowrates of all respective inlet and outlet streams while meeting the requirements of the system. A summary of the mathematical formulation has been provided in the supplementary material file.

4. Case study

The proposed superstructure which was presented in Section 3, has been investigated using three different operating desalination plants. The three selected plants for which the model

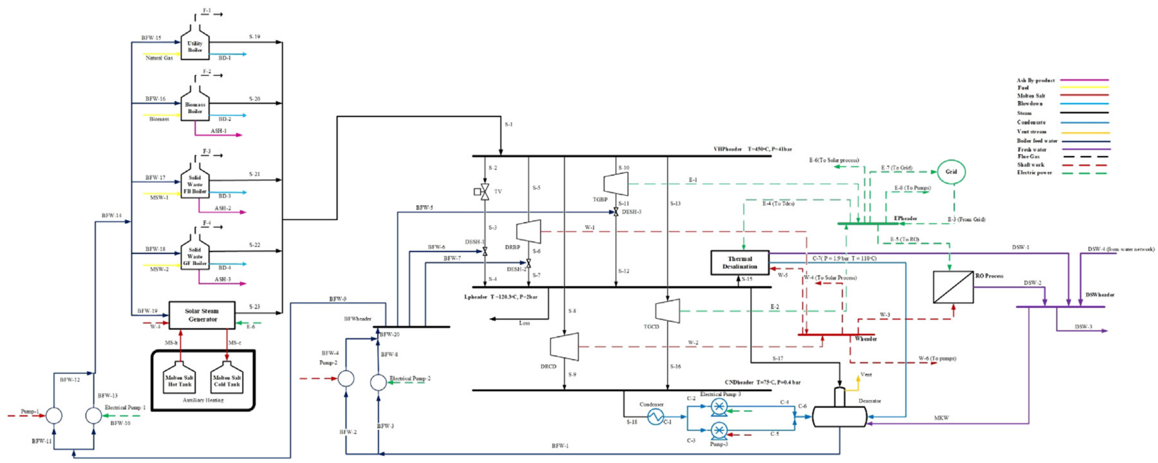

Fig. 2. Superstructure of tri-generation system.

was implemented are: (1) Carlsbad desalination plant in USA, (2) Dhekelia desalination plant in Cyprus, and (3) Ras Abu Fontas (RAF) A2 desalination plant in Qatar. The plants that were chosen for this case study were selected as representative cases for different desalination technologies and operating conditions. Moreover, those plants are located across several different regions that are characterized by different seawater salinity and direct normal irradiance (DNI) conditions. Those differences were then used to study the effect of several important parameters (such as the plant capacity, the feedwater salinity, the DNI values, and the desalination technologies) on the optimal selection of energy sources, and on the optimal configuration of the tri-generation system to be integrated. Direct normal irradiance is defined as the amount of solar radiation received per unit area by a surface that is held perpendicular to the rays that come in a straight line from the direction of the sun (Cleveland and Morris, 2013), and it is one of the most crucial aspects when assessing the technical concept for a CSP plant, since it determines the maximum amount of heat that could be generated from a CSP facility per unit area.

Regarding desalination technologies, the reverse osmosis (RO) technology is used in both Carlsbad and Dhekelia plants. On the other hand, the RAF plant was the only desalination plant that employs a thermal desalination technology using multi-stage flash (MSF), amongst those three. Hence, the energy requirements of RAF is expected to be slightly different when compared to the other two plants, since thermal desalination is well-known for being energy intensive and requires thermal and electrical energy, while RO operates using electrical energy only. Such differences will certainly help in understanding the effects of using different desalination technologies on the selection of the optimal energy sources and power block technologies, when subjected to a specific carbon reduction target. Since seawater salinity and direct normal irradiance are two very important parameters that are highly dependent on the location of the desalination plant, and since those plants are located in different regions, it was also very important to incorporate the effects of such aspects onto the overall performance of the model. Hence, an efficient comparison between the optimal desalination system configurations that are generated from the proposed model allows the identification of the most appropriate energy technologies to be embedded within the tri-generation system, based on different seawater salinities and solar availabilities.

All the parameters and costs related to the technologies and fuels involved in this study are provided in the supplementary material of this work. Table S.1 summarizes all the process, economics and environmental data related to the three

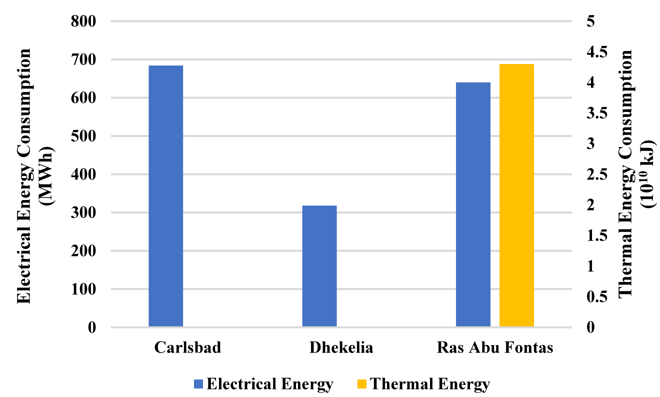

Fig. 3. Daily energy requirements of desalination plants.

described plants above. Table S.2 represents the maximum available amounts of biomass and municipal solid waste that are available in each respective regions for every plant, which in turn could be utilized as part of the integrated energy system. In addition, the maximum and minimum monthly averaged DNI values are also provided, which correspond to the best and worst case scenarios for each plant location, respectively. Fig. 3 also provides the daily thermal and electrical energy requirements for each desalination plant.

The amount of electrical energy required by Carlsbad and RAF plants are very close, as shown in Fig. 3. The higher product water capacity of Carlsbad combined with its lower energy consumption per unit of water when compared with RAF yielded similar electrical energy consumption values. On the other hand, although the capacity of Dhekelia is approximately one third of Carlsbad, the amount of electrical energy required by the Cypriot plant represents 47% of the amount required by Carlsbad, due to the higher feedwater salinity which necessitated an additional amount of electrical energy for desalination. Since RAF is the only thermal plant, it requires a daily amount of thermal energy estimated at 4300 GJ, while no thermal energy was required for Carlsbad and Dhekelia.

As mentioned in the process description, there exist five different steam generation technology options that are available to operate the desalination energy system of each plant. Those five different technologies are: (1) the natural gas boiler, (2) the biomass boiler, (3) the MSW fluidized bed boiler, (4) the MSW grate fired boiler and (5) the CSP option. The proposed model is capable of choosing the optimal energy mix for each desalination setup. Table S.3 summarizes the main parameters related to the different fuel options available, while Table S.4 represents the capital and operating costs of the different boiler options, as well as the corresponding fuel costs for each. All costs related to the CSP facility have been obtained from Gunawan et al. (2019). It should be noted that for the grate firing system option, disposal plants in several countries usually receive a fee for the to-be-treated waste (Hasan and Ahsant, 2015). Therefore, the waste cost associated with this particular technology was assumed to be negative.

First off, the effect of incorporating all different energy sources simultaneously within the tri-generation system, on the water production cost was investigated, using the Carlsbad desalination plant as an example. The results of which are summarized in Section 4.1. Sections 4.2–4.4 then include a more detailed discussion for the optimal tri-generation configurations that have been identified for each selected desalination plant in this study (Carlsbad, Dhekelia, and RAF), based on a prescribed net carbon reduction target.

4.1. Incorporating all energy sources simultaneously

Whether the aim is to switch from conventional to non-polluting renewable energy, or to reduce carbon dioxide emissions of an energy system by a certain factor, the notion of incorporating different energy sources simultaneously within a single tri-generation system might not always be a good strategy to adopt. Hence, it is always favored to test out which of the available energy sources are optimal for each case, especially when those cases are based on differing carbon reduction targets. The effects of combining different energy sources together on the overall design of a desalination system is also reflected in the overall water production cost. Capturing such effects are very useful, especially when the desalination plant is in a transitional period, and it is required to understand which of the different energy source are favored while making a transition to cleaner fuels, so as to reduce the net carbon emissions from desalination activities. In order to clarify this aspect, it has been assumed that a tri-generation system is integrated with the Carlsbad desalination plant. In this scenario, a minimum energy contribution has been equally imposed on all energy options simultaneously, and the design of the system was investigated for a series of energy contributions ranging from 0 to 25%. The results obtained are shown in Fig. 4, in which two NCRT cases have been presented (0% and 60%), while the water production cost and carbon reduction corresponding to each case have been specified. Each of those NCRT cases have been carried out using different minimum energy contributions.

At 0% NCRT, when no minimum energy contribution was imposed on the energy sources, the results showed that natural gas is the optimal option. Therefore, it was the only fuel selected to cover the energy requirements of the desalination plant resulting in a WPC of 0.715 USD/m^3. When a minimum energy contribution of 5% was imposed on all sources, the water production cost increased to 0.779 USD/m^3. This increase was due to the contribution of biomass, solid waste and CSP in energy generation as they are all more expensive than natural gas. Since no carbon reduction was required in this case, the contributions of these three sources were exactly equal to the minimum imposed fraction of 5%, while the remaining 85% of energy was generated from natural gas. This confirms that the selection of biomass, MSW and CSP was forced by the system in order to satisfy the constraint of minimum contribution. When the minimum contribution was further increased to 10, 15, 20 and 25%, the same selection of energy options was noted, meaning that, in all these cases, biomass, MSW and CSP only generate the minimum fraction of energy, while natural gas covers the remaining amount needed. Moreover, the WPC increased by almost 44% when the minimum energy contribution was set to 25%. Although all the studied cases were conducted under 0% NCRT, the energy production from biomass, MSW and CSP was associated with a carbon reduction which was found to be proportional to their contribution. In fact, a 56% carbon reduction could be achieved from an equal energy contribution of 25%.

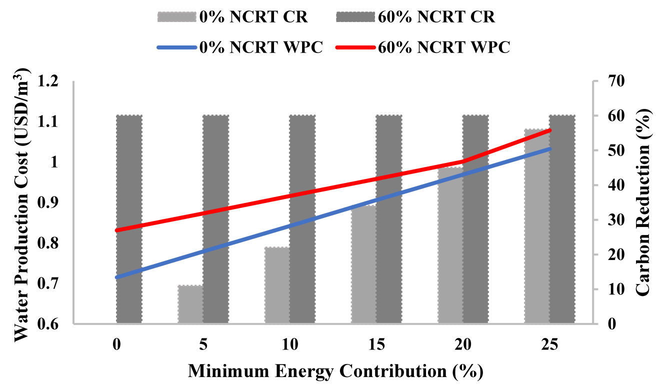

Fig. 4. WPC and carbon reduction of artificial case.

At 60% NCRT, Fig. 4 shows that the water production cost follows the same behavior as that with no carbon reduction target. However, the main difference between the two cases lies in the optimal energy sources that were selected for each minimum energy contribution value. Since a 60% carbon reduction was required, natural gas was not an appealing option anymore due to the high carbon emissions associated natural gas fuel combustion. Therefore, when no minimum contribution was imposed on the system, a combination of biomass and MSW resulted in the lowest WPC estimated at 0.831 USD/m^3. Similarly, when a minimum equal contribution was required from all available sources, the contribution of natural gas and CSP was forced to satisfy the minimum amount, while the remaining amount of energy was covered by biomass and MSW. On the other hand, it is important to note that there was a slight change in the linear behavior of the WPC values obtained up until 20%. Increasing the minimum energy contribution value from 20% to 25% resulted in the selection of a fluidized bed boiler for MSW incineration instead of grate fired boiler. This change in the type of boiler allows the system to meet its carbon reduction target at 60%, since fluidized bed emissions are much lower than the grated fired boiler option. This new selection in the type of boiler chosen was associated with additional costs, hence resulting in a total WPC of 1.078 USD/m^3. Another interesting feature of the 60% NCRT cases was also realized. The optimal solutions that were attained at 60% NCRT always achieved a higher carbon reduction for each minimum contribution percentage that was studied, unlike the 0% NCRT cases.

4.2. Carlsbad plant case

The Claud "Bud" Lewis Carlsbad desalination plant is located in the state of California. It is the largest, most technologically advanced and energy-efficient seawater desalination plant in the nation (Carlsbad Desalination, 2017). This plant delivers nearly 190,000 m^3 of fresh desalination water daily to San Diego county using a total of 16,000 RO membranes. The main energy supplier of Carlsbad desalination plant is San Diego Gas and Electric (SDG&E) plant which currently generates 45% of its energy from solar panels and 55% from natural gas (Elmer, 2021). On the

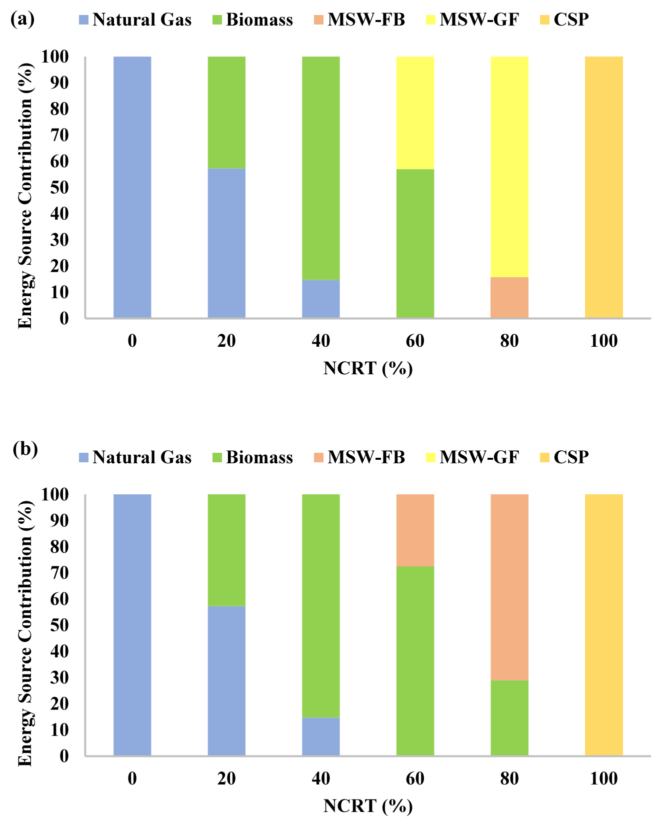

Fig. 5. Carlsbad's energy sources contribution (a) Scenario 1 and (b) Scenario 2.

other hand, Carlsbad plant has incorporated a solar power generation system on its rooftop that could generate 777 MWh annually (Carlsbad Desalination, 2017).

The proposed model has been implemented by assuming that a tri-generation system with multiple energy. Moreover, two different scenarios have been investigated. Scenario 1 involves the identification of the optimal energy configuration in the tri-generation system under different NCRT values (ranging from 0 to 100%) based on the technology costs provided in Table S.3 while accounting for any additional revenue outlets from the incineration unit. Scenario 2 ignores any revenue generated from the incineration of MSW using grate fired boiler. The results of the studied scenarios are presented in Fig. 5.

When no carbon reductions has been applied on the system for scenario 1, natural gas was the only selected source of energy, since it was found to be the cheapest energy source compared to the other available energy options. The amount of natural gas consumed to produce the required amount of electricity for desalination was 254 t/d. On the other hand, the flowrate of VHP steam generated from natural gas combustion was estimated by 3337 t/d. The major portion of this steam (93%) was utilized for the production of electricity using a condensing turbo-generator (TGCD), whereas the remaining fraction was utilized for the production of LP steam, required for deaeration, and electricity using a back-pressure turbo-generator (TGBP). The total amount of electricity produced by the system was estimated at 29.06 MW, from which 28.8 MW were utilized for desalination and 0.26 MW for driving the electrical pumps within the system. The total amount of CO_2 emissions corresponding to this case was 109,103 t/y, while the total water production cost (WPC) was found to be 0.715 USD/m^3.

When a net carbon reduction target of 20% has been imposed on the system, a new energy source was selected besides natural gas. This new source is biomass which has a relatively lower CO_2 emissions compared to natural gas. The optimal configuration of this case showed that almost 57% of thermal energy produced was from natural gas and 43% from biomass. This resulted in the reduction in CO_2 emissions to 87,282 t/y. Since the same amount of VHP steam was produced, no changes were noticed in the power production section regarding the selected steam expansion technologies and steam and electricity distribution within the system. On the other hand, the water production cost associated with this case was estimated at 0.748 USD/m^3.

The 40% NCRT case in scenario 1 showed a similar configuration of the previous case in terms of the technologies selected within the system. However, as the carbon reduction target became more stringent, the energy contribution of natural gas decreased to 15% while that of biomass increased to 85%, which resulted a WPC increase to 0.781 USD/m^3. On the other hand, when the NCRT value was further increased to 60%, steam production from natural gas was no longer a good option, so MSW incineration using the grate fire boiler was selected over fossil fuel. Although MSW incineration using the grate fired boiler results in higher carbon emissions when compared to the fluidized bed option, the former was selected due to the revenue stream associated with the volume reduction of MSW. Hence, approximately 2.75% of the available biomass and 0.29% of the available MSW were utilized to produce the required energy to operate the system, at 57% and 43%, respectively. The WPC of this case was reported at 0.831 USD/m^3. However, in case no revenue was made from MSW incineration, this cost would increase by 11.8%.

At an NCRT of 80%, MSW incineration using grate fired and fluidized bed boilers were the two optimal options for energy generation for desalination. The increase in the NCRT value from 60 to 80% resulted in an increase in the contribution of grate fired boiler to 84%, while the remaining energy fraction was generated from fluidized bed boiler. The carbon emission and WPC associated with MSW incineration were estimated at 21,820 t/y and 0.918 USD/m^3, respectively, while the revenue from MSW incineration using the grate fired boiler was 19.55%. The system resulted in a WPC 1.739 USD/m^3, in the period with the highest average DNI of 6.07 kWh/m^2/d, and 1.766 USD/m^3 in the period with the lowest average DNI of 4.74 kWh/m^2/d. Moreover, the required receiver areas for each of the best and worst case scenarios were estimated at 71.3 and 91.3 ha, respectively.

The results of the first set of cases showed that the main reason behind the selection of MSW incineration using grate fired boiler in the 60% and 80% NCRT cases was the revenue stream associated with this option. However, the revenues generated per unit of solid waste are different for each location being investigated. Moreover, such a revenue feature might not be even be an option in certain countries. Therefore, it was important to investigate whether the same energy streams would be selected in the absence of any revenue generation from grate fired incineration. In this regard, Fig. 5b represents scenario 2 results, in which different energy source contributions are selected with no revenue options. The same NCRT cases that were investigated in scenario 1, were re-investigated using the same NCRT values, but this time after eliminating the revenue option that was earned from selecting the MSW incineration using the grate fired boiler that was enabled in scenario 1.

The results of scenario 2 confirmed the assumption previously made regarding the reason behind the selection of grate fired incineration option. Fig. 4 shows that this option was not selected in any of the previous cases. This is due to the low heating value of MSW utilized in grate fired heating, which necessitates large amounts of solid waste for combustion. This in turn results in significant emissions. Therefore, all cases involving a grate

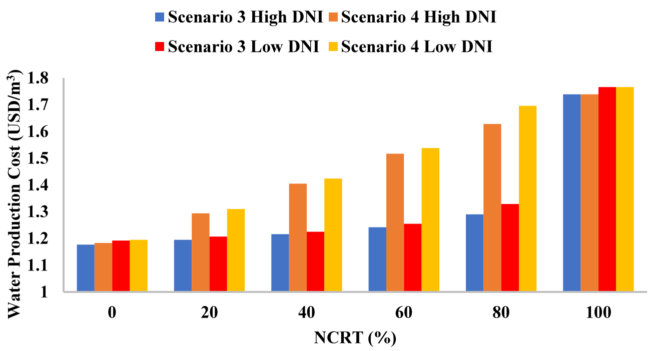

Fig. 6. Variation of WPC with NCRT for scenarios 3 and 4.

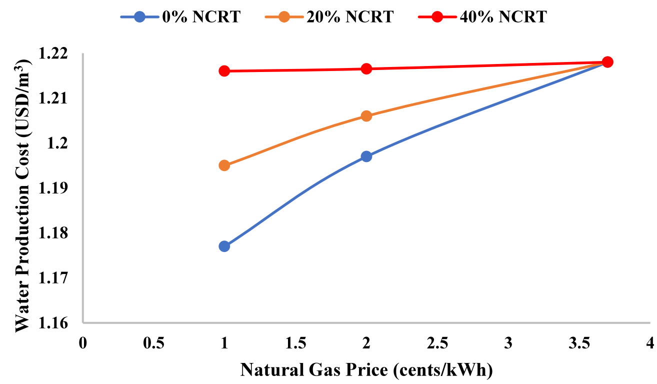

Fig. 7. Variation of WPC with natural gas price.

fired boiler alongside biomass in scenario 1 were replaced by the fluidized bed option, alongside biomass. MSW incineration using fluidized bed is associated with lower carbon emissions when compared to the biomass boiler for the same amount of energy produced. Therefore, the contribution of biomass into the optimal energy mix selections for scenario 2 witnessed a decrease from 73 to 29%, while that of MSW increased from 27 to 71% when NCRT was increased from 60 to 80%. Consequently, higher costs have been incurred for energy production in scenario 2, when compared to scenario 1. Table S.5 summarizes the main parameters in scenario 2 optimal configurations of Carlsbad case at different NCRT values.

In all the above cases (both for scenarios 1 and 2), CSP has not been selected as an optimal energy source for desalination unless a very stringent carbon reduction target has been imposed on the system. This is mainly due to the high capital cost and land requirements of CSP which make this technology the most expensive compared to the other available sources. However, Carlsbad desalination plant currently secures 45% of its energy requirements from solar energy (corresponding to a WPC of 1.3 USD/m^3), with 59,234 tons of CO_2 being emitted annually. Hence, to stay in-line with the current situation, an extra constraint has been added onto the mathematical model, in which a minimum energy contribution of 45% was allocated to the CSP energy option. Upon doing so, two new scenarios have been created, scenario 3 and scenario 4. Scenario 3 considers all energy sources (natural gas, biomass, MSW and CSP) to be available while scenario 4 only considers natural gas and CSP energy sources. It should be noted that scenario 4 replicates the current energy supplier to Carlsbad, by SDG&E. To summarize the results obtained for scenarios 3 and 4, Fig. 6 illustrates the variation of WPC with NCRT for the best case DNI (high) and the worst case DNI (low) as per the plant's location (found in Table S.2), while Table S.6 summarizes the energy selection for both scenarios.

The results of scenario 3 showed that the WPC at 0% NCRT is 1.177 USD/m^3 at high DNI values and 1.192 USD/m^3 at low DNI values. This would result in an average WPC of 1.185 USD/m^3 which is close to the actual water production cost of the plant (1.3 USD/m^3) reported in Table S.1. The total receivers areas required in the best and worst periods in terms of solar energy availability were estimated at 33.8 and 42.7 ha, respectively. On the other hand, the WPC increased by 10% at high DNI, and by 12% at low DNI, when the NCRT requirement was increased to 80%. During this phase, the selection of energy sources followed the same order as that observed in scenario 1. As such, biomass was the best option to be integrated with CSP and natural gas at 20% NCRT, while a further increase in NCRT resulted in a shift towards MSW incineration using grate fired boilers, followed by the integration of fluidized bed boilers at even higher NCRTs. After reaching the 100% NCRT requirement, CSP becomes the only energy option chosen. The difference in the water production cost between the high and low DNI cases ranges from 1.3 to 3%, at 100% NCRT.

As for scenario 4, in which natural gas and CSP were the only available energy sources for desalination, the change in the WPC were found to be proportional to the set NCRT values. This is mainly due to the fact that higher carbon reduction targets necessitates a reduction in natural gas consumption. As such CSP becomes the only alternative energy source to be utilized for steam generation. Therefore, with every increase in NCRT, a larger solar field area for CSP is required which results in a higher water production cost. Comparing both scenarios 3 and 4, one can easily conclude that scenario 3 is more economically attractive, since there is a significant difference between the WPCs attained, with scenario 3 being approximately 26% less costly than scenario 4, at an NCRT value of 80%. However, in some cases, it may be more appropriate to favor scenario 4 over scenario 3, especially when the target is to achieve a zero-carbon tri-generation system over a short period of time. Although WPC values of scenario 4 are always higher than that of scenario 3, the latter includes different energy sources that must be integrated with the system while shifting from 0 to 100% NCRT. Such frequent shifts in the energy sources may turn out to be very costly and expensive in the short run. Moreover, when an ultimate NCRT target of 100% is required, both scenarios lead to the same final configuration at similar costs, meaning that there is no need to incur additional costs from embedding different energy sources within the system, especially if the ultimate goal is to eventually have a standalone CSP system in the short run. Scenario 3 becomes more attractive and convenient when the overall goal of achieving a zero-carbon system could be achieved in the long run. Alternatively, when shorter transitional periods are considered, scenario 4 would be more appropriate to make a quick shift towards a cleaner tri-generation system.

Since the global natural gas price is prone to fluctuations, it is important to understand how an increase in this price would affect the design of tri-generation systems in terms of the optimal energy sources and water production cost. In order to do so, a sensitivity analysis on natural gas price has been carried for 0, 20 and 40% NCRT values using scenario 3. Fig. 7 below represents the variation of WPC with natural gas price for the three studied cases.

Based on the findings of the sensitivity analysis, when natural gas price increases from 0.998 c/kWh, which is the price considered in all the studied scenarios, to 2 c/kWh, the WPC witnessed an increase in the three NCRT cases. However, the optimal configurations showed no change in the type and contribution of the optimal energy sources. For instance, at 0% NCRT, natural gas remains the only selected source besides CSP, while at 20 and 40% NCRT, natural gas and biomass were selected besides CSP, and the same energy contributions were attained, as those that were reported in scenario 3. This means that the increase in WPC was related to the natural gas price, not because of the switch to other energy sources. Moreover, it should be noted that the variation in water production cost was affected by the contribution of natural gas to the overall energy mix. This explains the increase in WPC at higher NCRT values. For instance, at 0% NCRT, the contribution of natural gas was 55%, while at 40% NCRT, the natural gas contribution was only 7% only, hence resulting in a higher WPC value.

A further increase in natural gas price beyond 2 c/kWh showed the same optimal configuration for the three NCRT cases. This remains the case until the natural gas price reaches 3.7 c/kWh. At this value, natural gas was no longer the cheapest energy source. Therefore, the system switched to biomass as a new optimal energy source to be used in the energy mix of the tri-generation system, after such a change in the natural gas price takes place. Since the carbon footprint of biomass is lower than natural gas, the amount of CO_2 emitted from the system operating using 55% biomass and 45% CSP was estimated at 31,866 tons annually, which corresponds to 46% in carbon emission reduction. Therefore, all three cases converged to the same optimal configuration, yielding a WPC of 1.216 USD/m^3, since the carbon reduction of this configuration is higher than the target value. Hence, an increase in natural gas price to 3.7 c/kWh resulted in alternative optimal energy source selections that do not involve natural gas option for the case of Carlsbad desalination plant. Moreover, since natural gas price currently hits a higher average value of 9.64 c/kWh due to the Russia–Ukraine conflict (EIA, 2022), the optimal configuration that corresponds to the current situation is similar to the one that the three cases have converged to in Fig. 7.

4.3. Dhekelia plant case

The Dhekelia plant is located on the Mediterranean Sea in Cyprus. This plant also uses the Reverse Osmosis (RO) technology for a daily freshwater production of 60,000 m^3. Besides its lower capacity, the main difference between Dhekelia and Carlsbad is the higher feedwater salinity of 41.8 g/L in Dhekelia's case, which necessitates a higher electrical energy supply per unit of water. Moreover, the maximum solar radiation in Cyprus is relatively high, exceeding that in California, which makes CSP a very attractive energy option for driving the desalination plant. However, the difference between the highest and lowest DNI values, which are reported for Cyprus, is large. This means that the water production cost may be significantly affected when CSP becomes the main energy contributor for desalination. On the other hand, the total amount of electrical energy required by the system is estimated at 318 MWh per day. This energy is currently generated using fuel oil having a CO_2 emission factor of 0.67 kg/kWh (Xevgenos et al., 2021), resulting in an annual carbon emission of 77,767 tons. In the following, the proposed model has been implemented on a tri-generation system that is assumed to be integrated with the Dhekelia desalination plant. Fig. 8 represents the energy source contributions at different NCRT values for scenarios 1 and 2.

A comparison between the results obtained for Dhekelia plant and those reported for Carlsbad desalination plant (Fig. 5) shows a similar selection of optimal energy sources with exactly same contribution of each source at each NCRT value. Natural gas, being the cheapest energy option, has been selected as the only energy source for desalination at 0% NCRT. It is important to mention that the utilization of natural gas instead of fuel oil could

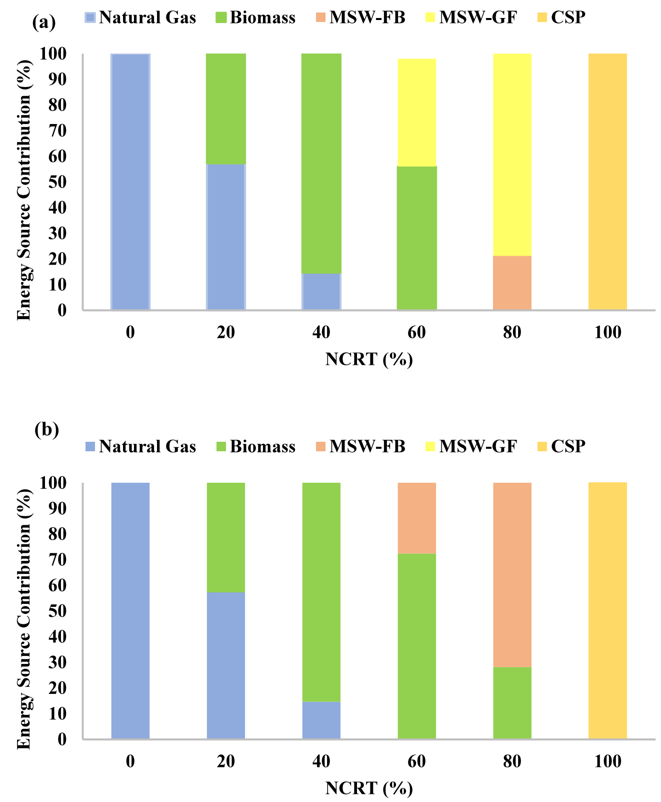

Fig. 8. Dhekelia's energy sources contribution (a) scenario 1 and (b) scenario 2.

reduce carbon emissions by 34.6%, to 50,804 tons annually. In the following, the carbon reduction target will be based on this amount.

When the carbon reduction target was further increased, new sources have been selected to meet the maximum allowable CO_2 emission. Consequently, biomass was selected besides natural gas at 20 and 40% NCRT, while a more stringent carbon reduction resulted in the selection of MSW incineration using the grate fired the fluidized bed boiler option. At 100% NCRT, CSP was the only energy supplier to the system with a required solar receivers area of 24.77 and 58.89 ha, respectively, for the best and worst case scenarios. Moreover, when no revenue was associated with MSW incineration in grate fired boiler in scenario 2, this option was not selected at 60 and 80% NCRT, similar to Carlsbad case. Regarding the power block section, the optimal steam and electricity generation technologies selected for Dhekelia are a throttling valve and a condensing turbo-generator. The estimated amount of VHP steam required for electricity production is 1618 t/d. The major portion of this steam (94%) was allocated to the turbo-generator for the production of 13.53 MW of electric power to drive the RO unit and the electrical pumps within the system. The remaining fraction was fed into a throttling valve to produce LP steam required for the deaeration of condensed VLP steam. Hence, the comparison between the optimal configurations of Carlsbad and Dhekelia plants shows that for higher capacity and electric power requirements, back-pressure turbo-generator is the best technology to be utilized for LP steam generation due to its ability of generating electricity simultaneously with steam. However, throttling valve turned to be the best fit for LP steam generation when the condensing turbo-generator provides all the electric power required by the system for lower desalination capacities as in the case of Dhekelia plant. The main parameters

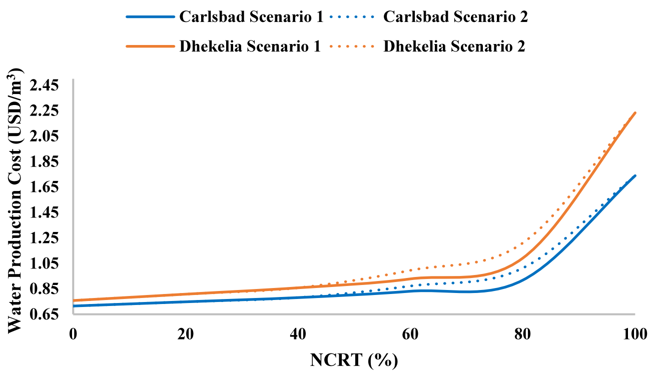

Fig. 9. Variation of WPC with NCRT of Carlsbad and Dhekelia.

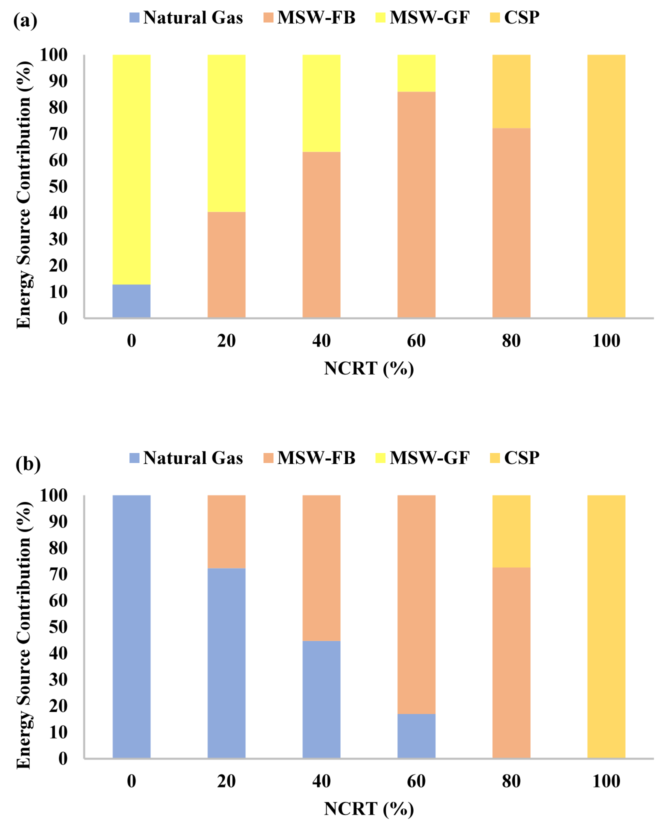

Fig. 10. RAF's energy sources contributions for (a) scenario 1 and (b) scenario 2.

in the optimal configuration of scenario 2 for Dhekelia case are provided in Table S.7.

The change in water production cost of the optimal configurations of Dhekelia plant followed the same behavior as that of Carlsbad. This cost was estimated at 0.758 USD/m^3 when no carbon reduction was imposed on the system. As the carbon reduction target becomes more stringent, WPC increased to reach 2.233 USD/m^3 at 100% NCRT. However, the difference between the required receivers area in the best and worst case DNI cases resulted in a 6.5% increase in the WPC, when the DNI of the location is the lowest, reaching 2.378 USD/m^3. Fig. 9 represents the variation in water production cost with NCRT for tri-generation systems integrated with Carlsbad and Dhekelia plants based on scenarios 1 and 2.

According to Fig. 9, one can note the change in WPC which follows the same trend for both desalination plants due to the similar contributions of energy sources at each NCRT value. However, the WPC of Dhekelia's case is always higher than that of Carlsbad because of the lower capacity and higher salinity of the former plant. This resulted in a higher cost per unit of desalinated water for Dhekelia's case. Moreover, the significant difference in WPC of CSP driven desalination, represented by 100% NCRT costs, confirms the fact that concentrated solar power is more economically viable for large-scale desalination, which is also supported by previous studies (Klaimi et al., 2021).

4.4. RAF plant case

In order to study the effect of the desalination type on the optimal configuration of tri-generation system and water production cost, the proposed model was implemented on a thermal desalination plant located in Qatar. Ras Abu Fontas A2 seawater desalination plant is located in Qatar, about 10 km south of Doha. The plant operates using multi-stage flashing desalination and produces 160,000 m^3/d of potable water that is supplied to the country's national power and water grid operator (KAHRAMAA) (Verdit Media, 2022). The relatively high feedwater salinity (45 g/L) and the type of desalination involved justify the high energy demand of the process, estimated at 11.94 GWh and 640 MWh of daily thermal and electrical energy requirements, respectively. The power required for running the facility is supplied from the 597 MW RAF B2 power plant which is currently operating using natural gas. The resulting carbon emission from this process are significant, since it is energy intensive, and mainly utilizes fossil fuel for its operation. Given that the annual carbon emission of this plant is about 505,744 tons, the aim of this case study is identifying a cost-effective tri-generation system, when subjected to a specific carbon reduction target. Therefore, scenarios 1 and 2 that were defined in the previous cases have also been applied here, for the RAF desalination plant. However, it is important to note that due to the nature of the country, major biomass sources in Qatar are municipal solid waste and sewage sludge (Al-Moftah et al., 2021). The MSW option which has been considered by our model as an energy fuel option for tri-generation in this work will be applied in this case, whereas the biomass fuel option that was mainly assumed to come from wood and forestry feelings will not be incorporated for the case of the RAF plant in Qatar, since the presence of forests are quite rare in Qatar. Thus, the available energy sources which were investigated for this case were natural gas, MSW and CSP only, for scenario 1. Fig. 10 shows the contribution of energy sources selected in the optimal configurations of the tri-generation system integrated with RAF at different NCRT values for scenarios 1 and 2.

Since the natural gas option is cheaper than MSW, it was the only selected energy source for Carlsbad and Dhekelia cases when no carbon reduction was required in scenario 2. However, the obtained results for scenario 1 show that at 0% NCRT, nearly 90% of MSW incineration using grate fired boiler is combined with to natural gas, due to the revenue generated from this energy option. MSW incineration using grate fired boiler was chosen for most NCRT values cases, up until the 60% NCRT target in scenario 1. One of the main differences between RAF and the other two plants is its high energy demand. Therefore, the selection of MSW at this NCRT value was mostly due to the high revenue generated, which results in a relatively larger MSW integration into the energy mix, when compared to the other plants. Moreover, since the biomass option was not considered in this case, this resulted in the selection of both the MSW grate fired heating and fluidized bed options into the energy source mix at various NCRT values. Moreover, the revenue stream from grate fired heating, allows MSW incineration to be a profitable option. Hence, all the available amount of MSW has been utilized for steam generation resulting in a total contribution of 87.2%. The remaining required amount of steam was generated from natural gas, being the cheapest among the available options, resulting in a very low WPC of 0.091 USD/m^3 due to the high generated revenue. Therefore, the selection of the grate fired option was highly affected by the total amount of energy required by desalination.

It very interesting to note that when the NCRT value was set to 20%, the contribution of grate fired boiler was reduced to 40.4%, when compared to the 0% NCRT case for scenario 1. Moreover, the fluidized bed boiler was selected to generate the remaining amount of steam in scenario 1. The switch from grate fire to fluidized bed boiler allowed for a reduction of 101,149 tons of CO_2 annually. However, a lower revenue has been generated due to the lower contribution of grate fire boiler. Therefore, a drastic increase has been observed in the WPC values, which was estimated at 0.778 USD/m^3 in this case. A further increase in NCRT necessitated a higher reduction in carbon emission from grate fired, hence the contribution of fluidized bed boiler increased with NCRT while that of grate fire decreased until 80% NCRT. At this value, CSP appeared for the first time as an optimal energy supplier besides the fluidized bed. In the previous two RO desalination plants, CSP was not selected until it was forced by the system at 100% NCRT, since it is the only non-emitting carbon source. However, in this case, this option was selected at 80% NCRT in RAF case due to the high energy demand for desalination which makes from CSP an appropriate option. Moreover, CSP was previously proven to be economically viable for large-scale desalination systems by Klaimi et al. (2021). The integration of CSP and fluidized bed boiler with the tri-generation system increased the water production cost to 2.145 USD/m^3. This WPC value was further increased when CSP was the only energy supplier at 100% NCRT. Moreover, the required receivers areas for meeting the energy requirements were estimated at 386.36 and 517.44 ha for the highest and lowest DNI values, respectively. Consequently, the WPC associated with these two cases was 2.67 (for high DNI) and 2.90 USD/m^3 (for low DNI). These costs are relatively high compared to those obtained for the Carlsbad and Dhekelia plant integrated with CSP due to the high salinity of feedwater.

The results of scenario 2 represented in Fig. 10b showed a similar order of selection of energy sources as Carlsbad and Dhekelia cases. However, the only difference in the results of the three desalination plants was the absence of biomass option in RAF superstructure, which led to a direct switch from natural gas at 0% NCRT to MSW using fluidized bed option at 20% NCRT. Natural gas and MSW remained the two optimal energy sources up until the 60% NCRT case, with an increasing contribution of MSW and a reduction in that of natural gas. Beyond this value, the energy sources options and contributions were similar to those of scenario 1, since they were not affected by the removal of revenue from the grate fired option. Table S.8 shows the energy selection, fuel consumption, carbon emissions and WPC of the optimal configurations in scenario 2 of RAF case.

Regarding the technologies selected in the power block, the optimal configurations showed that a back-pressure driver and a throttling valve were utilized for LP steam production, whereas a condensing driver was used for VLP steam generation. Since the amount of thermal energy required by MSF is much higher than that of electric power, 94% of VHP steam produced by the system was expanded to LP steam for desalination, while the remaining fraction was expanded into VLP steam using a condensing driver. As a result, no electrical energy was produced, and shaft work was the only type of energy generated to drive all pumps within the system. Table S.9 shows the optimal technologies selected in the power block section of each desalination plant, while Table S.10 summarizes the water production costs of the optimal tri-generation systems integrated with each of the three studied desalination plants.

When closely observing the results attained, the optimal solutions were found very sensitive to the specifications of the embedded technologies. This aspect was also observed by the work performed by Klaimi et al. (2022) using five different parameters in a tri-generation system. It should be pointed out that unlike the previous work by Klaimi et al. (2022), this work allows the simultaneous selection of different steam expansion and power generation options for each case, whilst considering multiple energy sources. Previously, the optimal configuration of the steam expansion and power generation options were kept fixed, and the effects of key parameters were only observed for a fixed steam expansion and power generation configuration. Even then, when the configuration was fixed, the optimal solutions were found sensitive to the specifications of the embedded technologies. The results obtained in this work were able to back up many of the previous findings by Klaimi et al. (2022), while simultaneously exploring the five different routes steam expansion and power generation on the attained results.

It should be noted that the selection of many different types of energy sources is certainly not practical and not very cost-efficient. Even though the proposed mathematical model does not place any limits on the number of energy sources that can be selected, the incorporation of all energy sources into one system simultaneously was studied. The results attained show a significant increase in water production cost with the increase in the energy contribution of all energy sources. Moreover, a maximum of two energy sources was observed in the optimal solutions of the three case studies in Sections 4.2–4.4 which also confirms the unpracticality of selecting many different types of energy sources simultaneously.

5. Conclusion

This work proposes a design of a hybrid tri-generation system for simultaneous production of thermal energy, power and freshwater. The tri-generation system has been designed under specific carbon reduction targets which helps in switching from fossil-based to zero carbon. Moreover, different scenarios have been presented for this purpose regarding the selection and contribution of energy sources and technologies. The novelty of this work lies in the incorporation of a wide number of utilities generation routes into a single superstructure that can be optimized based on a several types of constraints and process requirements. Moreover, the control of carbon emissions is an important aspect of this work, as the world moves towards renewable energy sources and carbon neutrality. The energy streams involved in the superstructure are natural gas, biomass, municipal solid waste and concentrated solar power, whereas steam expansion and power generation can take place using back-pressure and condensing drivers and turbo-generators, in addition to throttling valves. The proposed model has been implemented on three different operating desalination plants. Each of those plants involve different desalination capacities and are located in across several different regions. The following points summarize the main findings of this work:

- In the absence of any carbon reduction constraint, natural gas was identified as the optimal energy source for desalination, with associated water production costs ranging from 0.715 USD/m^3 for RO to 0.841 USD/m^3 for MSF desalination.

- A gradual increase in the carbon reduction target resulted in the selection of biomass for thermal energy generation. As NCRT values increase, the system starts to favor municipal solid waste over biomass. CSP was selected as the primary energy source only for very stringent NCRT values.
- The association of energy recovery from municipal solution waste using the grate fired option with a revenue stream greatly affected the optimal energy sources as it resulted in lower water production costs.
- High CSP costs were the main reason behind its selection only when no emissions were desired using the RO technology. Since MSF requires more thermal energy, when compared to RO, the results showed the selection of CSP starting from 80% NCRT values.
- The water production cost of a CSP driven desalination plant ranges from 1.739 USD/m^3 for an RO desalination plant (with a feedwater salinity of 33.5 g/L), to 2.67 USD/m^3 for MSF desalination (with a feedwater salinity of 45 g/L).
- At low DNI values, larger solar field areas were required to meet the energy requirements for desalination. This resulted in an average water production cost increase of 5.5%.
- The selection of steam expansion and power generation technologies were greatly affected by the amount of steam and power required by the system:
    - Turbo-generators were primarily selected by RO, since it requires higher amounts of electric power compared to MSF, while drivers were identified as the best option for thermal energy generation in MSF.
    - Throttling valves were selected by RO and MSF to generate the required LP steam for deaeration.

This work studies the design of hybrid tri-generation systems under specific carbon reduction targets which helps in switching from fossil-based to zero carbon systems. Moreover, different scenarios have been presented for this purpose regarding the selection and contribution of energy sources and technologies. Future work can potentially account for the life cycle assessment (LCA) aspect of the individual plants to assess the environmental impact of desalination plants, which would ultimately help in improving the design of sustainable tri-generation systems.

Nomenclature

Acronyms	
DRBP	Back-pressure driver
DRCD	Condensing driver
FB	Fluidized bed
GF	Grate fired
MSF	Multi-stage flashing
RO	Reverse osmosis
TGBP	Back-pressure turbo-generator
TGCD	Condensing turbo-generator
TV	Throttle valve
Parameters	
A	Solar field area (m^2)
DNI	Direct normal irradiance (kWh/m^2)
G	Mass flowrate (kg/h)
h	Specific enthalpy (kJ/kg)
K	Cost (USD/year)
NCRT	Net Carbon Reduction Target
x	Composition (%)
Y	Binary variable (0,1)
Greek Symbols	
η	Efficiency (%)
Sets	
I	Fuels
J	Technologies
Superscripts	
BC	Base Case
BFW	Boiling feed water
c	component
DSW	Desalinated seawater
F	Flue gas
in	Inlet to a unit
max	Maximum
min	Minimum
OM	Operating and maintenance
op	Optical
out	Outlet from a unit
rec	Solar receiver
SF	Solar field
Subscripts	
i	Fuel i
j	Technology j

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.egyr.2022.12.025.

References

Abdelhay, A.O., Fath, H.E., Nada, S., 2022. Enviro-exergo-economic analysis and optimization of a nanofiltration-multi effect desalination, power generation and cooling in an innovative trigeneration plant. Case Stud. Therm. Eng. 31, 101857.
Abdolalipouradl, M., et al., 2020. Thermodynamic and exergoeconomic analysis of two novel tri-generation cycles for power, hydrogen and freshwater production from geothermal energy. Energy Convers. Manage. 226, 113544.
Al-Moftah, A.M.S., Marsh, R., Steer, J., 2021. Life cycle assessment of solid recovered fuel gasification in the state of Qatar. Chem. Eng. 5 (4), 81.
Algieri, A., Morrone, P., 2022. Thermo-economic investigation of solar-biomass hybrid cogeneration systems based on small-scale transcritical organic Rankine cycles. Appl. Therm. Eng. 210, 118312.
Anand, B., Murugavelh, S., 2019. A hybrid system for power, desalination, and cooling using concentrated photovoltaic/thermal collector. Energy Resour. 44 (1), 1416–1436.
Carlsbad Desalination, 2017. Claud bud lewis carlsbad desalination plant. Available from: https://www.carlsbaddesal.com/.
Chen, Y., et al., 2022. Optimization of a weather-based energy system for high cooling and low heating conditions using different types of water-cooled chiller. Energy 252, 124094.
Cleveland, C.J., Morris, C.G., 2013. Handbook of Energy: Diagrams, Charts, and Tables, Vol. 1. Newnes.
Dajnak, D., Lockwood, F., 2000. Use of thermal energy from waste for seawater desalination. Desalination 130 (2), 137–146.

de Sá Moreira, M., et al., 2022. Energy and economic analysis for a desalination plant powered by municipal solid waste incineration and natural gas in Brazil. Environ., Dev. Sustain. 24 (2), 1799–1826.
EIA, 2022. Highlights: 2022. Available from: https://www.eia.gov/electricity/monthly/update/print-version.php.
Elmer, M., 2021. SDG & E Walks back claim it delivers 45 percent renewable energy. Voice San Diego.
Fthenakis, V., et al., 2016. New prospects for PV powered water desalination plants: case studies in Saudi Arabia. Prog. Photovolt., Res. Appl. 24 (4), 543–550.
Gunawan, A., et al., 2019. Techno-economics of cogeneration approaches for combined power and desalination from concentrated solar power. J. Solar Energy Eng. 141 (2).
Hasan, B., Ahsant, A., 2015. A Comparison Between Two Different Methods of Combustion, Grate-Fired and Fluidized Bed, Applied To a CHP-Plant with MSW As Fuel. KTH School of Industrial Engineering and Management Stockholm.
Jafary, S., et al., 2021. A complete energetic and exergetic analysis of a solar powered trigeneration system with two novel organic Rankine cycle (ORC) configurations. J. Clean. Prod. 281, 124552.
Jamaluddin, K., et al., 2022. Design of Total Site-Integrated TrigenerationSystem using trigeneration cascade analysis considering transmission losses and sensitivity analysis. Energy 252, 123958.
Jamshidian, F.J., Gorjian, S., Shafieefar, M., 2022. Techno-economic assessment of a hybrid RO-MED desalination plant integrated with a solar CHP system. Energy Convers. Manage. 251, 114985.
Jimenez-Navarro, J.-P., et al., 2020. Coupling the heating and power sectors: The role of centralised combined heat and power plants and district heat in a European decarbonised power system. Appl. Energy 270, 115134.
Khosravi, A., Santasalo-Aarnio, A., Syri, S., 2021. Optimal technology for a hybrid biomass/solar system for electricity generation and desalination in Brazil. Energy 234, 121309.
Klaimi, R., Alnouri, S.Y., Stijepović, M., 2021. Design and thermo-economic evaluation of an integrated concentrated solar power–Desalination tri-generation system. Energy Convers. Manage. 249, 114865.
Klaimi, R., Alnouri, S.Y., Stijepović, M., 2022. Investigation of seasonal variations and multiple fuel options in a novel tri-generation CSP integrated hybrid energy process. Energy 125338.
Klaimi, R., et al., 2019. Optimization techniques for coupling renewable/hybrid energy options with desalination systems for carbon footprint reduction. Chem. Eng. Res. Des. 151, 270–1422.
Li, J., Zoghi, M., Zhao, L., 2022a. Thermo-economic assessment and optimization of a geothermal-driven tri-generation system for power, cooling, and hydrogen production. Energy 123151.
Li, H., et al., 2022b. Two-objective optimization of a hybrid solar-geothermal system with thermal energy storage for power, hydrogen and freshwater production based on transcritical CO2 cycle. Renew. Energy 183, 51–1422.
Liu, M., Shi, Y., Fang, F., 2014. Combined cooling, heating and power systems: A survey. Renew. Sustain. Energy Rev. 35, 1–1422.
Mannan, M., et al., 2019. Examining the life-cycle environmental impacts of desalination: A case study in the State of Qatar. Desalination 452, 238–1422.
Menikpura, S.N.M., Sang-Arun, J., Bengtsson, M., 2013. Integrated Solid Waste Management: an approach for enhancing climate co-benefits through resource recovery. J. Clean. Prod. 58, 34–1422.
Najjar, E., et al., 2021. Life Cycle Assessment of a seawater reverse osmosis plant powered by a hybrid energy system (fossil fuel and waste to energy). Energy Rep. 7, 448–1422.
Omar, A., et al., 2021. Techno-economic optimization of coupling a cascaded MED system to a CSP-sCO2 power plant. Energy Convers. Manage. 247, 114725.
Petrillo, A., et al., 2021. Experimental study and Life Cycle Assessment of biomass small-scale trigeneration plant. J. Clean. Prod. 326, 129234.
Rostami, S., Rostamzadeh, H., Fatehi, R., 2021. A new wind turbine driven trigeneration system applicable for humid and windy areas, working with various nanofluids. J. Clean. Prod. 296, 126579.
Saini, P., Singh, J., Sarkar, J., 2021. Novel combined desalination, heating and power system: Energy, exergy, economic and environmental assessments. Renew. Sustain. Energy Rev. 151, 111612.
Tariq, S., Safder, U., Yoo, C., 2022. Exergy-based weighted optimization and smart decision-making for renewable energy systems considering economics, reliability, risk, and environmental assessments. Renew. Sustain. Energy Rev. 162, 112445.
Uche, J., et al., 2019. Analysis of a domestic trigeneration scheme with hybrid renewable energy sources and desalting techniques. J. Clean. Prod. 212, 1409–1422.
Verdit Media, 2022. Ras Abu Fontas (RAF) A2 Seawater Desalination Plant. Available from: https://www.water-technology.net/projects/ras-abu-fontas-raf-a2-seawater-desalination-plant/.
Xevgenos, D., et al., 2021. Aspects of environmental impacts of seawater desalination: Cyprus as a case study. Desalin. Water Treat..
Xu, Y.-P., et al., 2022. Optimization of a biomass-driven Rankine cycle integrated with multi-effect desalination, and solid oxide electrolyzer for power, hydrogen, and freshwater production. Desalination 525, 115486.
You, D., et al., 2022. Design and analysis of a solar energy driven tri-generation plant for power, heating, and refrigeration. J. Energy Resour. Technol. 144 (8).