**Supplementary Material**

**Mathematical Formulation:**

The tri-generation problem has been converted into a mathematical model, specifically a Mixed Integer Nonlinear Program (MINLP). It should be noted that all the equations related to the design of the second and third sections of the system can be found in Klaimi et al. [1].

First off, two sets have been defined as follows:

Set = which represents the set of fuel options utilized by the system

Set = which represents the set of different technology options embedded within the system

The objective function, described in Eq. (1), includes the summation of the investment and operating costs of all technologies in the system, in addition to fuel cost. Moreover, an additional cost, , is added to the system for any power or water import from the grid.

The water unit price can take different values depending on the production cost of water unit. Therefore, the revenue generated from the system was not included in the cost objective function in order to reflect the actual water production cost. However, we would like to mention that the effect of accounting for such revenues has been assessed in the work (Klaimi et al., 2021), for fixed tri-generation configurations.

|  |  |
| --- | --- |
|  | (1) |

The equality constraints cover the material and energy balances on all headers and technologies within the system [1, 2]. It should be noted that these equations are not case-specific, and the same equations have been used for all cases that were studied. As for the inequality constraints, they can be of several types:

1. Capacity constraints, which place a limit on the inlet feed flowrate allowed to a certain technology
2. Production constraints, which impose a minimum or maximum production rate of the generated utilities (freshwater, thermal energy, electrical energy)
3. Performance constraints, which set specific requirements on some technologies, such as the prevention of temperature cross-over from taking place in the solar steam generator
4. Composition constraints, which place a restriction on the concentration of a specific component in the inlet or outlet stream of a technology or waste generated, such as the salinity of freshwater and brine streams
5. Fuel availability constraints, which set a cap on the amount of fuel available for energy recovery
6. Land footprint constraint, which places a restriction on the maximum available land area for CSP facility
7. Environmental constraint, which imposes a minimum net carbon reduction target on the emissions resulted from the combustion of fuels in the VHP steam generation section

Eq. (2-9) below describe all the inequality constraints of the proposed model. The capacity constraint is represented in Eq. (2), where denotes the flowrate of inlet stream to technology , and are the minimum and maximum flowrates directed to technology , and is a binary variable associated with the existence of technology in the optimal configuration of the system.

|  |  |
| --- | --- |
|  | (2) |

To ensure a freshwater production equal to the capacity of the desalination plant, Eq. (3) used, where is the total flowrate of desalinated water generated by the system, while is equal to the capacity of the desalination plant. On the other hand, solar availability consists a significant constraint for CSP as it determines the maximum amount of thermal energy that could be produced in a unit area at a specific day. This constraints is described in Eq. (4), where is the flowrate of BFW inlet to the solar steam generator, and are the specific enthalpies of the inlet and outlet streams of the solar steam generator, and are the optical efficiency of heliostat and solar receiver efficiency, while and represent the direct normal irradiance and required solar field area, respectively.

|  |  |
| --- | --- |
|  | (3) |
|  | (4) |

The performance constraint associated with the solar steam generator is defined by a temperature cross-over checking equation, in which there must be a minimum temperature difference between the boiling temperature of BFW and the molten salt temperature when the boiling feed water starts to boil [1]. The composition constraints are represented in Eq. (5-6), where and are the composition of component in the inlet and outlet streams of technology , respectively, which must lie between minimum and maximum values based on the specifications of the technology and process requirements.

|  |  |
| --- | --- |
|  | (5) |
|  | (6) |

Eq. (7) and (8) represent the fuel availability and land footprint constraints, respectively, where is the required flowrate of fuel , is the available amount of fuel , and is the available solar field area for CSP.

|  |  |
| --- | --- |
|  | (7) |
|  | (8) |

In order to control the total amount of carbon emissions from the system, a net carbon reduction target (NCRT) has been considered. Hence, the summation of all carbon flowrates emitted as a result of the combustion of fuels, , must not exceed the allowable amount of emissions, , based on a base case scenario to be determined by the user. This environmental constraint is described in Eq. (9) below.

|  |  |
| --- | --- |
|  | (9) |

The proposed Mixed Integer Non-Linear Problem (MINLP) was implemented using “What’sBest 17.0” LINDO Global solver for MS-Excel 2016 via a laptop with Intel Core i5 Duo processor, 8 GB RAM and a 64- bit operating system.

**Table S.1: Summary of desalination plants data**

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Carlsbad** | **Dhekelia** | **Ras Abu Fontas** |
| Location | California, USA [3] | Larnaca, Cyprus [4] | RAF, Qatar [5] |
| Year of Operation | 2015 [3] | 1997 [4] | 2015 [5] |
| **Process** [3, 4, 6-10] | | | |
| Technology | RO | RO | MSF |
| Capacity | 190,000 m3/d | 60,000 m3/d | 160,000 m3/d |
| Feedwater Salinity | 33.5 g/L | 41.8 g/L | 45 g/L |
| Brine Salinity | 67 g/L | 83.6 g/L | 85 g/L |
| Water Recovery | 50% | 50% | 25% |
| Energy Consumption | 3.6 kWh/m3 | 5.3 kWh/m3 | 4 kWh/m3  270 kJ/kg |
| **Economics** [3, 5, 10, 11] | | | |
| Project Cost | 650 Million USD | 29 Million USD | 502 Million USD |
| Cost of water | 1.321 USD/m3 | 0.89 USD/m3 | 1.94 USD/m3 |
| Selling Price of water | 1.6 USD/m3 | >1.14 USD/m3 | 1.21-1.92 USD/m3 |
| **Environment** [5, 6, 8, 10, 12, 13] | | | |
| Energy Supplier | San Diego Gas and Electric | - | 597 MW RAF B2 Power Plant |
| Energy Resource | PV  45% Solar & Wind  55% Natural Gas | Oil | Natural Gas |
| CO2 Footprint | 59,234 tons/year | 77,767 tons/year | 505,744 tons/year |

**Table S.2: Energy sources capacities and DNI of desalination plants locations**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Plant | Biomass Capacity (tons/year) | MSW Capacity (tons/year) | Average Monthly DNI  (kWh/m2) [14] | |
| Highest DNI | Lowest DNI |
| Carlsbad | 6,400,000 [15] | 77,500,000 [16] | 188.1 | 147 |
| Dhekelia | 9,974,000 [17] | 578,484 [18] | 262 | 110.2 |
| Ras Abu Fontas | 0 [19] | 2,500,000 [20] | 173.9 | 115.6 |

**Table S.3: Summary of fuel parameters**

|  |  |  |  |
| --- | --- | --- | --- |
| Fuel/Technology | Moisture Content  (%) | Heating Value (MJ/kg) | CO2 Footprint |
| Natural Gas | - | 48.5 [2, 13] | 0.433 kg CO2/kWh [21] |
| Biomass | 20 [2, 22] | 16 [2, 22] | 0.23 kg CO2/kWh [21] |
| MSW (fluidized bed) | 5 [23] | 16.6 [23] | 23.75 kg CO2/t MSW [23] |
| MSW (grate fired) | 5 [23] | 9.15 [23] | 47.24 kg CO2/t MSW [23] |

**Table S.4: Technologies and fuel costs**

|  |  |  |  |
| --- | --- | --- | --- |
| Technology | Capital Cost  [23-25] | Operating Cost  [23-25] | Fuel Cost  [23, 25, 26] |
| Natural gas boiler | 119.43 USD/kWth | 0.32 c/kW | 0.998 c/kWh |
| Biomass boiler | 1,880 USD/kW | 0.2 c/kWh | 15 USD/ton |
| MSW fluidized bed boiler | 8,095 USD/kW | 27.04 USD/ton | 12.27 USD/ton |
| MSW grate fired boiler | 11,522 USD/kW | 10.77 USD/ton | -35.03 USD/ton |

**Table S.5: Summary of main parameters in Carlsbad scenario 2 results**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| NCRT  (%) | Energy Sources | Fuel Consumption (ton/y) | CO2 Flowrate  (ton/y) | WPC  (USD/m3) |
| 0 | Natural Gas | 96,142 | 109,103 | 0.715 |
| 20 | Natural Gas | 53,176 | 62,560 | 0.748 |
| Biomass | 131,078 | 24,723 |
| 40 | Natural Gas | 13,614 | 16,016 | 0.781 |
| Biomass | 262,158 | 49,446 |
| 60 | Biomass | 222,745 | 42,012 | 0.872 |
| MSW-FB | 68,601 | 1,629 |
| 80 | Biomass | 94,226 | 17,375 | 1.013 |
| MSW-FB | 187,167 | 4,445 |
| 100 | CSP | - | 0 | 1.739 |

**Table S.6: Summary of energy selection and contribution of scenarios 3 and 4**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| NCRT (%) | Scenario 3 | | Scenario 4 | |
| Energy Source | Contribution (%) | Energy Source | Contribution (%) |
| 0 | CSP | 45 | CSP | 45 |
| Natural Gas | 53.5 | Natural Gas | 55 |
| Biomass | 1.5 |  |  |
| 20 | CSP | 45 | CSP | 56.6 |
| Natural Gas | 30.4 | Natural Gas | 43.4 |
| Biomass | 24.6 |  |  |
| 40 | CSP | 45 | CSP | 67.4 |
| Natural Gas | 7.2 | Natural Gas | 32.6 |
| Biomass | 47.8 |  |  |
| 60 | CSP | 45 | CSP | 78.2 |
| Biomass | 30.6 | Natural Gas | 21.8 |
| MSW-GF | 24.4 |  |  |
| 80 | CSP | 45 | CSP | 89.1 |
| MSW-FB | 10.8 | Natural Gas | 10.9 |
| MSW-GF | 44.2 |  |  |
| 100 | CSP | 100 | CSP | 100 |

**Table S.7: Summary of main parameters in Dhekelia scenario 2 results**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| NCRT  (%) | Energy Sources | Fuel Consumption (ton/y) | CO2 Flowrate  (ton/y) | WPC  (USD/m3) |
| 0 | Natural Gas | 44,947 | 50,804 | 0.758 |
| 20 | Natural Gas | 25,773 | 29,131 | 0.808 |
| Biomass | 63,529 | 11,512 |
| 40 | Natural Gas | 6,598 | 7,458 | 0.858 |
| Biomass | 127,058 | 23,024 |
| 60 | Biomass | 107,765 | 19,528 | 0.995 |
| MSW-FB | 33,404 | 793 |
| 80 | Biomass | 42,967 | 8,055 | 1.21 |
| MSW-FB | 88,660 | 2,106 |
| 100 | CSP | - | 0 | 2.233 |

**Table S.8: Summary of main parameters in RAF scenario 2 results**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| NCRT  (%) | Energy Sources | Fuel Consumption (ton/y) | CO2 Flowrate  (ton/y) | WPC  (USD/m3) |
| 0 | Natural Gas | 466,725 | 505,744 | 0.841 |
| 20 | Natural Gas | 337,573 | 365,816 | 1.127 |
| MSW-FB | 347,248 | 38,779 |
| 40 | Natural Gas | 208,405 | 225,888 | 1.41 |
| MSW-FB | 694,350 | 77,558 |
| 60 | Natural Gas | 79,307 | 85,960 | 1.695 |
| MSW-FB | 1,041,524 | 116,337 |
| 80 | MSW-FB | 932,767 | 101,149 | 2.121 |
| CSP | - | 0 |
| 100 | CSP | - | 0 | 2.67 |

**Table S.9: Summary of optimal technologies in power block section**

|  |  |  |  |
| --- | --- | --- | --- |
| Desalination Plant | Type of desalination | Capacity (m3/d) | Selected Technologies |
| Carlsbad | RO | 190,000 | TGBP, TGCD |
| Dhekelia | RO | 60,000 | TV, TGCD |
| RAF | MSF | 160,000 | TV, DRBP, DRCD |

**Table S.10: Summary of WPC of all studied cases**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| NCRT (%) | WPC of Scenario 1 (USD/m3) | | | WPC of Scenario 2 (USD/m3) | | |
| Carlsbad | Dhekelia | RAF | Carlsbad | Dhekelia | RAF |
| 0 | 0.715 | 0.758 | 0.091 | 0.715 | 0.758 | 0.841 |
| 20 | 0.748 | 0.808 | 0.778 | 0.748 | 0.808 | 1.127 |
| 40 | 0.781 | 0.858 | 1.215 | 0.781 | 0.858 | 1.41 |
| 60 | 0.831 | 0.928 | 1.621 | 0.872 | 0.995 | 1.695 |
| 80 | 0.918 | 1.091 | 2.121 | 1.013 | 1.21 | 2.121 |
| 100 | 1.739 | 2.233 | 2.67 | 1.739 | 2.233 | 2.67 |

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