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Lifetime optimisation of integrated thermally- and electrically-driven solar desalination plants

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Abstract

We compare the performance across different locations of systems employing photovoltaic (PV) panels, flat-plate and evacuated-tube solar-thermal (ST), and hybrid photovoltaic-thermal (PV-T) collectors to fulfil the energy demands (both thermal and electrical) of multi-effect distillation (MED) desalination plants. We consider large- (1700 m³/day), medium- (120 m³/day) and small-scale (3 m³/day) MED plants. We find a strong dependence of both the capacity and configuration of the solar collectors used on both the cost of sourcing electricity from the grid and the specific collector employed. We find mean grid-electricity fractions range from 47%, for the lowest grid-cost location, to 2.5% for the highest grid-cost location. We find that systems using PV-T and ST collectors meet between 49% and 62% of the hot-water demand at these locations, respectively. We find lifetime costs for the smallest-, medium- and largest-scale plants' energy-generation systems as low as 0.209, 3.35 and 50.8 million USD, respectively, corresponding to specific costs of 6.37, 2.55 and 2.74 USD/m³. We find that systems using solar collectors, when optimised for the lowest specific cost, result in associated CO₂eq emissions equal to, or higher than, those associated with grid-driven reverse osmosis. These results

highlight the need to consider the environmental footprint of these systems, not only their cost, to ensure that desalination is in-line with the United Nations' Sustainable Development Goal 6 (SDG6).

Keywords: desalination, multi-effect distillation, PV, PV-T, solar energy

1 Introduction

As of 2018, the United Nations Children's Fund (UNICEF) estimates that one in three people globally are without access to clean water [1] whilst the number without access to electricity is set to rise for the first time in decades [2]. At the same time, the demands for power [3–5] and clean water [6, 7] have continued to increase globally, both as populations rise [6, 8–10] and also as lower-income countries develop economically [11] and increase their standards of living [12–14]: current freshwater withdrawals range by a factor of over 60 between low-income and high-income countries, from 20.90 litres/capita-day in the Democratic Republic of the Congo to 1342 litres/capita-day in the United States of America as of 2020 [15]. Desalination, the process of converting saline water into potable water [16], currently accounts for around 0.6% of global greenhouse gas emissions [17] with only about 1% of desalination currently powered by renewable energy [18]. Estimates put the energy-associated emissions of an MED desalination plant in the UAE operating for a 30-year lifetime at over 90% of the total lifetime emissions of the plant [19]. With the demand for desalination set to rise by 40–50% by 2050 [10], novel technologies need to be assessed and deployed to communities which currently lack a reliable source of clean drinking water in line with Sustainable Development Goal (SDG) 6, “clean water and sanitation for all” [20].

This paper aims to present an open-source modelling tool for optimising the configuration of photovoltaic (PV), photovoltaic-thermal (PV-T) and solar-thermal (ST) collectors, along with battery storage and a grid connection, for powering a desalination plant. We apply this framework to three case-study MED plants to assess whether PV-T collectors are a cost-effective means of producing drinking water at three different scales when compared against the industry-standard of PV and grid-powered RO desalination [21, 22], across four different case-study locations. By doing so, this paper aims to assess whether PV-T collectors can be cost-effective over the lifetime of a desalination plant for producing clean drinking water. In the following sections, we outline the technologies considered, namely PV-T collectors and MED desalination.

Hybrid PV-T solar panels produce both electricity and heat from the same collector [23]. The most-common PV-T collector tends to be a thermally-coupled, non-concentrating collector. A thermally-coupled collector consists of photovoltaic (PV) modules, responsible for electricity generation, in direct thermal contact with the solar-thermal (ST) absorber material. These are generally non-concentrating in design due to the risk of damaging the PV

modules when run at high heat-transfer fluid (HTF) temperatures [24, 25]. Most commercially-available PV-T collectors are non-concentrating flat-plate collectors (FPCs) due to these being the easiest to manufacture [26].

Traditionally, PV-T collectors were seen as advantageous over conventional PV modules as they provided a means to cool the PV cells, avoiding PV-related issues such as damage from overheating, as well as reducing the operating temperature of the PV modules and hence increasing their electrical efficiency. More recently, the ability to extract both heat and electricity from the same collector has become one of the major drivers towards the adoption of PV-T collectors [27]. As many desalination technologies require both electricity and heat for their operation, PV-T collectors integrated with desalination plants have the potential to provide synergistic benefits over standalone PV- and solar-thermal-powered systems [28].

There are two main types of desalination: membrane-based and thermally-driven. As of 2020, 20% of renewable-energy-powered desalination was thermally driven where the main process of desalination was driven by heat [29]. Whilst there are some membrane-based technologies which utilise heat at some stage [30, 31], thermally-driven technologies present the greatest potential for integrations which utilise the efficiency benefits associated with PV-T collectors due to the combination of electrical and thermal needs [32].

As of 2019, reverse osmosis (RO), an electrically-driven process, accounted for 69% of installed desalination plants globally, with thermally-driven multi-stage flash (MSF) and multi-effect distillation (MED) plants the second and third most common technologies, with 18% and 7% shares respectively [21, 22]. RO is a membrane-based approach which uses electricity as its main power source. Although heated feedwater brings performance benefits to RO, around a 3% increase in freshwater-production rate per degree of temperature, there is a greater rate of membrane degradation [33, 34]. As such, it cannot utilise the synergistic benefits of PV-T collectors.

MSF desalination is the second most widely installed desalination technology [21]. MSF plants are usually large in scale and supply between 50,000 and 70,000 tonnes of water per day [35], equivalent to the the drinking-water needs of 500,000 to 1.4 million people respectively [36]. As such, they are generally well suited for district-scale applications [37]. There are issues surrounding the practical implementation of MSF plants, including corrosion from high operating temperatures, practicalities with maintenance in rural environments, and large up-front investment costs [38].

MED desalination is the third most widely installed desalination technology worldwide, the second most widely implemented thermally-driven approach, with just under half as many plants installed as compared with MSF plants [21]. The electrical and heat requirements of MED plants lend them well to PV-T systems where both electricity and heat are generated [39]. Further, the lower electrical [40, 41] and thermal [30, 41] energy requirements, combined with their lower embedded emissions [37], when compared to the more widely-adopted MSF technology, allow for higher-efficiency plant installations.

Further, the lower operating temperature of MED plants, compared to MSF installations, results in a lower risk of scaling [42]. MED plants also have the potential for smaller-capacity installations, supplying as little as 1.14 tonnes of clean water per day [43], which lends MED-driven desalination well to off-grid, community-scale contexts where access to clean drinking water [44] and electricity are likely to be lower [45].

Hybrid solar PV-T collectors, in combination with well-established ST and PV collectors, therefore, have the potential to provide sustainably-generated clean drinking water through the use of MED desalination in line with SDG 6. Further, small-scale standalone systems have the potential of addressing rural clean-water and electricity-access needs to help meet the goals of SDGs 6 and 7, “access to affordable, reliable, sustainable and modern energy for all,” whilst minimising carbon emissions in line with SDG 13, “urgent action to combat climate change and its impacts.”

Thus far in the literature, the majority of PV-T-powered MED installations tend to consider only a single technology for energy generation, either concentrating [46, 47] or non-concentrating PV-T collectors [48], with most considering concentrating designs [28]. Further, before constructing an MED installation, the optimum and necessary number of collectors needs to be assessed, and there exists a gap in the existing open-source and licensable modelling tools available when assessing PV-T-driven desalination systems, with most either considering only a single technology [49, 50] or having no scope for desalination and drinking-water demands [51, 52]. There is hence a need to develop a reliable methodology for assessing the performance of various renewable technologies beyond standard PV setups, including PV-T collectors alongside more commonplace standalone PV and ST systems, for desalination.

In this work, we assess the performance of systems consisting of PV, PV-T and ST collectors for providing heat, in the form of hot water, and electricity to power MED desalination plants. We compare across four different case-study locations, and three different plant capacities, as well as different technological options. We find a strong dependence of the results on the specific model of collector used as well as the price of grid-sourced electricity across the case-study locations. We find that regions with a higher price of grid-sourced electricity rely more heavily on the grid as a source of power, with PV collectors and batteries fulfilling demand during the day. We find that MED plants in regions with a lower price of grid-sourced power utilise PV-T and ST collectors for the synergistic production of off-grid electricity and hot water.

2 Methods

We consider a combination of PV-T, PV and ST collectors, in conjunction with electrical and hot-water storage, and a grid connection, for the provision of electricity and heat for an MED desalination plant. An air-water heat pump is used to meet auxiliary heating demands.

We developed an integrated model of the solar collectors with hot-water storage tanks to determine their electrical and thermal outputs. We consider here only ST flat-plate collectors (FPCs) and evacuated-tube collectors (ETCs). We make our software open-source and available online so other designs can be explored [53].

We implemented an optimisation algorithm, making multiple target variables, including the lowest lifetime cost and emissions, available [53]. We utilised this to determine system configurations and technologies that resulted in the lowest total cost over the lifetime of selected MED plants. For the total cost, we included the costs of the initial energy-generation equipment and any replacements necessary, as well as the costs of grid electricity. Additional costs associated with the plants were not included as they are plant-dependent and are not affected by the size of the energy-generation system installed. We include these as an error-bar adjustment to the final results.

For the carbon dioxide equivalent (CO₂eq) emissions associated with the MED plants, we consider both the embedded emissions in the technologies installed, as well as the ongoing emissions arising from electricity sourced from the grid. Where uncertainty exists in the literature, we have considered upper- and lower-bound estimates on these values. The embedded emissions in the plants have also been considered, though these are not calculated as part of the optimisation tool as they are independent of the energy-generation system and are, instead, added afterwards.

In the next sections, we present the details of the modelling and input parameters used to assess the performance of the PV, PV-T and ST collectors as well as the electrical battery storage considered.

2.1 Solar technologies

We here model ST, PV-T and PV collectors. For hot-water generation, we consider PV-T and ST collectors, either connected in series (PV-T followed by ST collectors) or as independent technologies. Thermally-coupled PV-T collectors are limited in their fluid temperatures compared with thermally-decoupled designs. For thermally-coupled collectors, higher fluid temperatures result in both a lower electrical efficiency as well as a greater risk of damage to the PV cells [54, 55]. Thermally-decoupled spectral-splitting collectors [56], or partially-laminated collectors [57], are two approaches to mitigate these issues. One recent solution that utilises readily available collectors employs PV-T and ST collectors connected in series such that high output temperatures from the collector system can be achieved whilst reducing the output temperature of the PV-T collectors and hence the temperature of the PV cells [58].

The same approach is used to model the thermal performance of the PV-T and ST collectors. This is outlined in Section 2.1.1. The electrical performance of the PV-T and PV panels is modelled differently. These approaches are outlined in Section 2.1.2.

Table 1: Technical parameters of the flat-plate and evacuated-tube ST collectors selected from Olympios et al. [60] as being representative of the space of available collectors. “N/A” denotes that information was not provided by the manufacturer.

Manufacturer	Solar Technologie International GmbH	soldardirekt24 GmbH	Augusta Solar
Model	FKF 240 V CuCu	Eurotherm Solar Pro 20	AS 100 DF
Collector type	FPC	ETC	ETC
Zeroth-order heat-loss coefficient (a_0)	0.710	0.44	0.55
First-order heat-loss coefficient (a_2) / W/K	-3.63	-1.01	-1.03
Second-order heat- loss coefficient (a_2) / W/K ²	-0.0106	-0.0104	-0.0052
Area / m ²	2.22	1.87	1.11
Cost / USD/component	494	631	925
$\dot{m}_{\text{htf,min}}$ / kg/h	37.8	N/A	N/A

2.1.1 Thermal collector performance

To consider the performance of ST and PV-T collectors, a simple reduced quadratic curve is used to model the ST collectors as is common throughout both literature and among manufacturers [59]. The thermal efficiency of ST and PV-T collectors can be modelled with a quadratic performance curve in reduced temperature,

$$\eta_{\text{th}} = a_0 + a_1 \frac{(T_{\text{m}} - T_{\text{amb}})}{GA} + a_2 \frac{(T_{\text{m}} - T_{\text{amb}})^2}{GA}, \quad (1)$$

where T_{m} is the average temperature of the collector, T_{amb} is the ambient temperature, G is the solar irradiance, A the surface area of the collector, and a_0 , a_1 and a_2 are coefficients which are unique to the collector and govern its performance characteristics.

For the ST collectors within our system, we considered flat-plate and evacuated-tube collector designs, taking parameters for collectors close to the mean thermal-efficiency curve from Olympios et al. [60]. We identified an FPC and two ETCs which were closest to these mean curves. The performance data for these collectors selected are given in Table 1. The average exchange rate between the currency used by Ref. [60] and United States Dollars (USD) for 2022, given in Table 2, has been applied [61].

We took values for the PV-T collectors considered from Olympios et al. [60], with collectors selected based on having the lowest standard deviation from the mean electric-performance curve, as well as the availability of up-to-date cost information, and are given in Table 3.

Table 2: Currency exchange rates used to adjust financial inputs.

Exchange rate	Value
British-pound-to-dollar / USD/British Pound (GBP)	1.38 [62, 63]
Euro-to-dollar / USD/Euro (EUR)	1.05 [61]
UAE-Dirham-to-dollar / USD/Arab Emirates Dirham (AED)	0.27 ¹

¹The exchange rate between Arab Emirates Dirhams and United States Dollars has been fixed since 2014 when the UAE Dirhama was pegged to the dollar.

Table 3: Technical parameters of the hybrid photovoltaic-thermal collectors selected from Olympios et al. [60] as being representative of the space of available collectors.

Manufacturer Model	Dualsun (insulated) Spring 300M	Dualsun (insulated) Spring 400M	Solimpeks Powervolt
Thermal coefficient (β) / °C ⁻¹	0.0039	0.0034	0.0045
Reference electrical efficiency (η_{ref})	0.183	0.213	0.151
Zeroth-order heat-loss coefficient (a_0)	0.852	0.621	0.475
First-order heat-loss coefficient (a_1)	-10.8	-7.4	-8.4
Second-order heat-loss coefficient (a_2)	0	0	-0.59
Collector area (A_{ap}) / m ²	1.64	1.88	1.33
Cost / USD/component	556 [64]	1020 [65]	545
Reference power (P_r) / W _p	300	400	325
Stagnation temperature (T_{stag}) / °C	76	90	101

Assuming that the temperature rise across the collector is approximately linear, an approximation valid provided that the operating temperature is below the stagnation temperature for the collectors, we can substitute this,

$$T_m = \frac{T_{c,\text{in}} + T_{c,\text{out}}}{2}, \quad (2)$$

where $T_{c,\text{in}}$ and $T_{c,\text{out}}$ are the temperatures of the HTF entering and leaving the PV-T or ST collector respectively, into Equation 1 along with an expression for the thermal efficiency in terms of the useful heat gain of the HTF,

$$\eta_{\text{th}} = \frac{\dot{m}_{\text{htf}} c_{\text{htf}} (T_{c,\text{out}} - T_{c,\text{in}})}{x_c y_c A G}, \quad (3)$$

where x_c and y_c are the width and length of the collector respectively and $\dot{m}_{\text{htf}}$ and c_{htf} give the mass flow rate and specific heat capacity of the HTF respectively, to obtain an overall expression for the performance of the collector which is quadratic in temperature.

2.1.2 Electrical collector performance

We consider here both PV and PV-T collectors as sources of electricity within our model. For PV-T collectors, once the outlet temperatures of the collector have been solved for, the average module temperature of the collector, T_m , can be calculated using Equation 2. This can then be used to determine the electrical efficiency of the collector:

$$\eta_{el} = \eta_{el,ref} (1 - \beta (T_m - T_{ref})), \quad (4)$$

where η_{el} is the electrical efficiency of the collector, $\eta_{el,ref}$ the reference electrical efficiency, β the thermal coefficient and T_{ref} the reference temperature at which the reference efficiency of the collector is determined.

For the standalone PV modules installed, we develop a steady-state one-dimensional energy-balance model for the collectors,

$$Q_{sun} = Q_{env} \quad (5)$$

where Q_{sun} denotes the energy inputted to the PV panels from solar irradiance,

$$Q_{sun} = \alpha_{pv} x_{pv} y_{pv} G (1 - \eta_{el,ref} (1 - \beta (T_{pv} - T_{pv,ref}))), \quad (6)$$

where α_{pv} is the absorptivity of the PV module, x_{pv} and y_{pv} give the width and height of the module respectively, T_{pv} denotes the temperature of the PV module, and $T_{pv,ref}$ the reference temperature of the PV module. Q_{env} denotes the energy transferred from the PV panels to the environment,

$$Q_{env} = \dot{q}_{pv,air} (T_{air} - T_{pv}) + \dot{q}_{pv,sky} (T_{sky}^4 - T_{pv}^4), \quad (7)$$

where T_{sky} the radiative temperature of the sky and $\dot{q}_{pv,air}$ and $\dot{q}_{pv,sky}$ the conductive and radiative heat fluxes between the module and the air and sky respectively. We assume that the PV panels are close to the ground such that heat transfer from the rear of the collectors can be neglected. We ignore the edge heat-transfer effects.

The value for the convective heat-transfer coefficient between the PV collector and the air can be related to the convective heat-transfer coefficient,

$$\dot{q}_{pv,air} = h_{air} x_{pv} y_{pv}, \quad (8)$$

where h_{air} is the convective heat-transfer coefficient, with units W/m^2K , between the module and the air,

$$h_{air} = 3.97v_w + 6.90, \quad (9)$$

an expression valid for low wind speeds [66], where v_w is the wind speed over the collector and the uncertainty in the constants are given in parentheses.

We selected a mono- (m-Si) and a poly-crystalline (p-Si) PV panel, with performance characteristics taken from Olympios et al. [60], having reference efficiencies and thermal coefficients close to the mean values of those in the data set. We took values for the absorptivity of the collectors to be the average for silicon panels of 0.93 [23, 67]. The performance characteristics for these collectors, along with their relevant optical data, are given in Table 4. We adjusted cost information for inflation and the average annual exchange rate for 2021 given in Table 2.

Table 4: Technical parameters of the photovoltaic collectors selected from Olympios et al. [60] as having the lowest standard deviation in efficiency and thermal coefficient compared to the average collector whilst being close to the lowest cost.

Manufacturer Model	REC 325 N-Peak Mono	Sharp ND-AF 330 C
Type	m-Si	p-Si
Absorptivity (α_{pv})	0.93	0.93
Thermal coefficient (β) / $^{\circ}\text{C}^{-1}$	0.00325	0.00380
Reference electrical efficiency (η_{ref})	19.5	17.0
Collector area (A) / m^2	1.67	1.94
Cost / USD/component	154.54 ¹	111.74 ¹
Annual fractional degradation (d_{pv}) / %/year	1.1 ² [68]	1.1 ² [68]
Lifetime / years	30 ³	30 ³
Reference power (P_r) / W	325	330

¹The costs shown were accurate at the time of writing and are reported at the level of precision included within the modelling.

²The degradation rates of PV modules vary greatly based on climactic conditions [68]. A value of 1.1% was used as this is representative of the climactic conditions in the case-study locations considered [68].

³The lifetime of the PV panels is taken to be 30 years such that no replacements of PV or PV-T collectors need be considered during the lifetime of the plants. This is based on a combination of 25-year lifetimes, common throughout the literature [69, 70], which we extend to a 30-year lifetime, as reported in some studies [71, 72], for ease of modelling.

The nature of this approach allows for any type of ST or PV-T collector whose thermal performance can be reduced to a quadratic curve in reduced temperature, or PV module whose reference characteristics and optical properties are known, to be considered as part of the wider system model. In this way, any of the ST collectors assembled in Olympios et al. [60], or any other collectors for which performance curves can be experimentally or theoretically obtained, can be modelled using this approach. We make our model open-source for stakeholders to consider their own collectors [53].

2.2 Desalination

We outline the configuration of the MED desalination plant considered.

2.2.1 Desalination plant configuration

A schematic of the desalination plant and solar generation system is shown in Figure 1. We consider an MED desalination plant such that hot water from a buffer tank is drawn through a pipe within the first effect. We assume continuous operation of the plant. Hence, a steady amount of water is drawn from the buffer tank and passed through the first effect of the MED system before returning to the buffer tank at a cooler temperature. If the temperature of the water leaving the buffer tank is less than the desired hot-water temperature of the plant, it is heated using an electrically-driven heat pump, the specifics of which are described in Section 2.2.2.

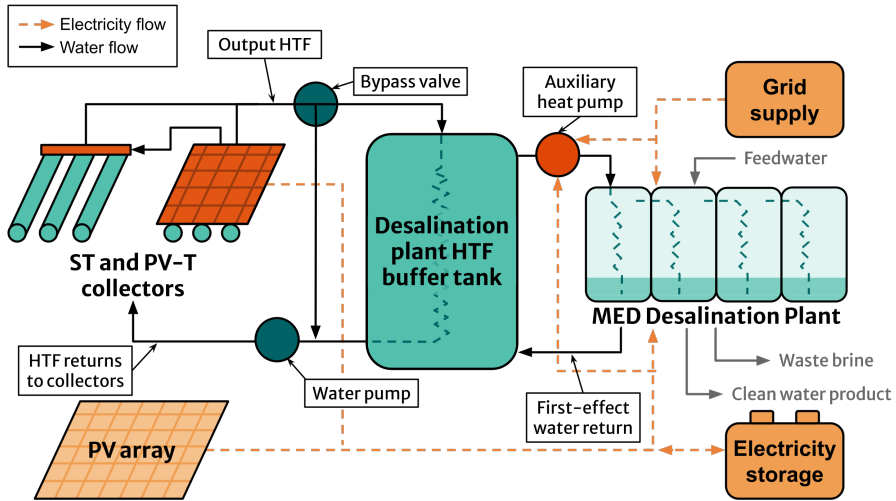


Fig. 1: MED plant considered in the study. Schematic showing the system configuration for the MED plant modelled. A series of PV-T and ST collectors are connected in series such that a HTF, taken in this case to be water, first passes through the PV-T and then the ST collectors. The HTF passes through a buffer tank containing water which is then used to supply heat to the MED desalination plant. A PV array, if present, in conjunction with the electrical output from the PV-T collectors, supplies the electrical needs of the plant, with electrical storage in the form of batteries stores excess power generated. A grid supply meets any shortfall in the electrical power supplied by the renewable PV and PV-T collectors.

PV-T and ST collectors, if present, are used to heat the water within the buffer tank. An HTF passes through the PV-T (if present) and ST (if present) collectors in turn. If the HTF leaving the collector system is higher in temperature than the fluid within the buffer tank, it flows through a heat exchanger and transfers heat to the tank. Otherwise, a bypass valve redirects the fluid back through the collector system.

We here consider lithium-ion (Li-ion) batteries, the characteristics for which are given in Table 5. Any shortfall in electrical demand, which cannot be met directly with PV- or PV-T-generated electricity or from battery storage, is made up by supply from the grid, the costs of which vary between locations and which are given in Table 9. Grid-infrastructure costs are neglected due to these varying significantly from country to country and between locations, though, should these be needed by stakeholders, scope is provided to include these in the open-source model [53]. We assume a 30-year plant lifetime, common across the type of plants considered.

Table 5: Technical parameters of the Lithium-Ion battery used in the modelling [73].

Manufacturer Model	Renogy 12V 100Ah
Capacity ($Q_{\max}$) / kWh	1.28
Charging efficiency	0.95 ¹ [74]
C-rate, charging (cr_{chg})	0.58
C-rate, discharging ($cr_{\text{d-chg}}$)	1.0
Cost / USD/component	494.90 ¹ [73]
Cycle lifetime (N_L) / cycles	2000
Depth of discharge (DoD) / %	80
Discharging efficiency	0.95 ² [74]
Leakage / %/hour	0.00417
Lifetime capacity loss d_L / %	0.241 ³ [75, 76]

¹The costs shown were accurate at the time of writing and are reported at the level of precision included within the modelling.

²An efficiency of 95% was used for both charging and discharging, resulting in a roundtrip efficiency of 90%. This is higher than values obtained by Bobanac et al. [74], who accounted for columbic efficiency, for a c-rate of 0.6, but will vary greatly between manufacturers and due to cycling conditions [77], so is taken here as a reflective estimate.

³Lifetime capacity loss based on 24% degradation for 500-cycle batteries reported by Spotnitz et al. [75] and <20% for 4500-cycle batteries reported by Yang et al. [76].

We considered three different capacities of desalination plants, capable of producing 3, 120, and 1700 m³ of freshwater per day respectively. The properties of these plants are given in Table 6. The electrical power consumption of the plants is calculated based on their daily freshwater-output capacities and the average specific MED power consumption [40, 41].

2.2.2 Heat-pump model

To assess the electrical load placed on the system by heat-pump-driven auxiliary heating, we convert the thermal load placed on the heat pump into an

Table 6: Specifications of the case-study multi-effect distillation (MED) desalination plants used.

Name	$\dot{m}_{\text{prod}}$, m ³ /day	P , kW _{el}	$\dot{m}_{\text{hw}}$, kg/s	T_{hw} , °C	$T_{\text{hw,r}}$, °C
Small [78]	3	0.288	0.919	75	65
Medium [79]	120	11.5	3.75	77	31
Large [80]	1700	107	100	80	54

electrical load. The coefficient of performance (COP) of an electrically-driven heat pump relates the thermal output to its electrical power consumption [81],

$$COP = \frac{\dot{Q}_{\text{th}}}{w_{\text{el}}}, \quad (10)$$

where COP is the coefficient of performance of the heat pump, $\dot{Q}_{\text{th}}$ its thermal output and w_{el} its electrical load. The condensation temperature of the heat pump's heat-exchange fluid is fixed by the requirements of the plant. Due to varying environmental conditions, the evaporation temperature of the heat pump's heat-exchange fluid, taken as ambient temperature, will vary throughout the day and from location to location. Hence, the heat pump COP needs to be related to its system efficiency,

$$COP = \eta_{\text{sys}} \frac{T_{\text{cond}}}{T_{\text{evap}}}, \quad (11)$$

where η_{sys} is the system efficiency of the heat pump, T_{cond} its condensation temperature, and T_{evap} the evaporation temperature, taken to be the ambient temperature. The cost information for the heat pumps is calculated using fitted data from Olympios et al. [82] for the capital costs whilst the costs of electricity utilised are considered by increasing the electrical demands of the plant accordingly. We select an ammonia-based heat pump and make other technologies from Ref. [82] available in our open-source software [53].

2.3 Component costs

Component costs for the various collectors used are given in Tables 1, 3 and 4. The costs of the hot-water tanks installed, electrical storage, and solar-power inverters used are given in Table 7. We selected the battery based on typical costs and capacities for Li-ion based batteries, and costed the inverter based on typical inverter costs [83] and selected a lifetime of 13 years based on that for a dry-and-hot climate [84]. We selected the hot-water tank used based on the lowest standard deviation from the mean cost per unit energy stored, as found by Olympios et al. [60], and among the lowest values for the seasonal daily heat loss. The model is able to size the hot-water storage system by altering the number of these tanks installed.

Table 7: Capacities and costs of the batteries, hot-water tank(s) and inverter(s) installed.

Component	Heat-transfer fluid pump	Hot-water tank	Inverter
Manufacturer Model	Grundfos CRNF 15-1 A-CA-A-E-HQQE	Grant HPMONO/IND150	Solis S5-GR1P6K 5G
Capacity	20.5 m ³ /h	150 l	6 kW
Cost / USD/component	4170	1250 [60]	890 [83]
Reference	[85]	[60]	[84]

2.4 Component degradation

We degrade the electrical performance of the PV and PV-T collectors and the installed batteries over their lifetime using an average degradation rate of 1.1 %/year in efficiency for PV modules [68] and manufacturer-specific degradation values for the batteries considered. Details on the methods employed are given in the Supplementary Information (S.I.).

In the next sections, we outline the case-study locations considered, including the costs associated with grid-sourced electricity in each location, as well as the nature of the optimisation process employed. Details on the benchmarks used for assessing the performance of the MED systems against the more-commonly-employed RO desalination follow.

2.5 Case-study locations and environmental conditions

We took four case-study locations which rely on desalination to meet a portion of their clean-water demands and which varying proportions of fossil fuels within their energy mixes: Tijuana and La Paz in Mexico, Dubai in the United Arab Emirates (UAE), and Gando on Gran Canaria, Spain. We selected this range of locations to study the effect of grid and component costs, as well as the ambient temperature and solar irradiance, details of which are given in Table 8, on the optimum system.

Table 8: Summary of weather information for the four case-study locations.

Location	Mean temp. / °C	Daily temp. standard deviation / °C	Seasonal temp. standard deviation / °C	Max. irradiance ¹ / W/m ²
Abu Dhabi	28.1	2.92	6.19	945
Gando	20.3	0.25	2.18	856
Tijuana	16.2	2.08	3.27	844
La Paz	23.9	4.13	4.42	932

¹The average daily irradiance is utilised in the modelling. The maximum hourly irradiance achieved is given as an indicator of the peak summer-time solar resource available.

Due to the high variability in the price of grid electricity throughout Mexico [86], we selected two locations within the states of Baja California and Baja California Sur which represented the extreme grid-electricity costs across the country [86, 87], Tijuana and La Paz, both of which have a high risk of suffering from droughts [88] and have high and medium water-scarcity indices respectively [89, 90]. Further, Tijuana remains the site of an unbuilt government-priority desalination plant [91]. We took up-to-date grid-cost information from the website of the Comisión Federal de Electricidad [87].

We use the site of an existing solar-thermal-powered desalination plant near Abu Dhabi, capable of producing 120 m³/day of fresh water as the source of our UAE-based environmental data [79], the specifics of which are given in Table 6. With the sixth-highest per-capita carbon emissions as of 2021, [92], and the fourth-lowest per-capita renewable-water resource as of 2018 [93], the UAE relies on seawater desalination to satisfy over 50% of its freshwater demand [21].

There is variability in the primary source of drinking water across the Canary Islands, with the easternmost islands, including Gran Canaria, reliant on desalination as their primary source of drinking water [94]. Despite a shift towards renewable energy-generation technologies, only 16% of the electricity demand of Gran Canaria was generated renewably in 2019 [95]. The remaining share was met through carbon-intensive fuel- and gas-oil plants. Fewer than 1% of desalination plants across the archipelago were powered by at-site renewable technologies as of 2019 [96].

We obtained weather data, along with optimum panel tilt angles, for the various locations chosen using the publicly-available PVGIS database [97]. This, along with the latitude and longitude of sites used and the cost of grid electricity, is given in Table 9. Exchange rates to the USD have been applied for British Pounds, Euros and Abu Dhabi Dhirs. These are given in Table 2. We obtained the latest grid-cost information for Tijuana and La Paz from the Comisión Federal de Electricidad [87]. The tiered pricing structure used is given in Table 10 for Tijuana and La Paz.

The price of grid-sourced electricity changes over time, both as markets fluctuate [98], and as the renewable-electricity mix changes [99]. Due to uncertainties in predicting future electricity prices, we took the costs of grid-sourced electricity to be constant throughout the lifetime of the plant. Similarly, we chose not to apply discount rates to the batteries and solar inverters modelled to be in-keeping with our approach to grid costs.

Table 9: Position, grid-cost and solar-collector tilt values for locations studied.

Location	Latitude / °N	Longitude / °E	Grid cost / USD/kWh _{el}	Tilt / °
Abu Dhabi, UAE	24.44	54.49	0.078 [100]	24 [97]
Gando, Gran Canaria	27.94	-15.37	0.146 [101]	25 [97]
Tijuana, Mexico	32.49	-117.11	See Table 10	32 [97]
La Paz, Mexico	24.17	-110.29	See Table 10	24 [97]

Table 10: Tiered grid-cost structure used for case-study locations, Tijuana and La Paz, in Mexico, obtained from the Comisión Federal de Electricidad. The costs shown were accurate at the time of writing and are reported at the level of precision included within the modelling.

Location	Tariff	P_p / kW	C_f^1 / USD/month	C_{cons}^2 / USD/kWh	C_{cap}^3 / USD/kW _p
Tijuana	PDBT	< 25	59.85	2.466	0
Tijuana	GDBT	> 25	598.55	0.826	499.39
La Paz	PDBT	< 25	59.85	3.817	0
La Paz	GDBT	> 25	598.55	2.907	454.36

¹ C_f is a fixed monthly cost for a commercial connection to the national grid network.

² C_{cons} is a consumption-based cost per unit electricity consumed, charged monthly.

³ C_{cap} is a capacity-based cost, charged based on the peak power demand within a month.

2.6 Optimisation

We aim to optimise the energy-generation system, consisting of PV, PV-T and ST collectors with electrical and hot-water storage, for the lowest lifetime cost. We do so by varying the capacities of components installed, and hence the reliance on grid-sourced electricity and auxiliary heating, whilst fixing component costs and environmental conditions. We allow for a variable and optimisable global mass flow rate through the thermal-collector system as well as a varying buffer-tank capacity.

We undertook an analysis of optimisation algorithms and selected two based on their ability to successfully determine the optimum component sizes for the system when compared with the results of a global optimisation: the Nelder-Mead (N-M) [102] and Limited-memory Broyden-Fletcher-Goldfarb-Shanno (L-BFGS-B) [103] algorithms.

We minimise the system based on the lowest total lifetime cost, where both the initial equipment investment costs and the ongoing cost of grid electricity are considered. We provide other target variable for optimisation, such as the LCOE, grid-electricity fraction and auxiliary- and renewable-heating fractions, in our open-source code depending on the needs of various stakeholders [53].

2.6.1 Sensitivity analysis

Despite the potential for Li-ion batteries in renewable-energy contexts [104] and recent attempts to improve degradation modelling [105], there remain uncertainties around the impact of environmental conditions, deep discharging and overcharging on both their cycle lifetime and lifetime capacity loss [75, 76, 106, 107]. Uncertainties also exist around the lifetime of solar inverters, where climatic conditions can result in a five-fold variation in lifetime [84].

To account for this uncertainty, we carried out a sensitivity analysis in which we varied the cycle lifetime of the Li-ion batteries and solar inverters

modelled. Sensitivity to other parameters, such as the costs of various components and electricity sourced from the grid, is partially accounted for by the different case-study components and locations considered respectively. Results of the sensitivity analyses, and the impact of technology choice amongst different commercially-available collectors, are contained within the S.I.

2.7 Lifetime-emissions analysis

To determine the desalination system best able to provide clean water in line with the United Nations SDGs [20], it is necessary to quantify, not only the costs, but also the environmental impact of these systems. For their climate-change impact, we quantify this in terms of their embedded carbon dioxide equivalent (CO₂eq) emissions. Detailed information on the methodologies and inputs used to determine the associated emissions of the systems are given in the S.I.

2.8 Reverse-osmosis benchmark

As RO is the most commonly deployed desalination technology globally [21, 22], we calculated the specific emissions and costs of using RO to meet an equivalent clean-water demand to the plants modelled, the specifics of which are given in Table 6. The specific energy consumption of RO is taken as a range from 2 to 7 kWh_{el}/m³ [108]. In keeping with our approach for modelling MED desalination, we do not account for costs associated with the RO system, including, e.g., the capital investment costs associated with installing the RO plant and operational costs associated with the replacement of membranes.

For the costs and emissions of grid-powered RO, we compute the associated lifetime electricity consumption for powering an RO unit through grid electricity. The embedded emissions associated with grid electricity, given in the S.I., are used to calculate an upper-bound estimate for the lifetime emissions as the carbon intensity of grid-sourced electricity is likely to decrease over time as countries decarbonise. For the emissions arising from the CAPEX and non-energy RO components, such as membrane replacement and chemical pre-treatment, we take a range of values from 0.299 to 0.320 kgCO₂eq based on the breakdown produced by Shahabi et al. [109].

As 43% of renewably-powered desalination was performed using PV-RO as of 2020 [29], we used PV-RO as a further benchmark for the lifetime costs and emissions. To calculate the size of PV-and-battery system needed to carry out desalination independent of a grid connection, we used the open-source modelling tool CLOVER which is capable of sizing renewable electricity systems over the lifetime of our plant [49?]. We used the m-Si PV collector, the specifics of which are given in Table 4, and the Li-ion battery considered here, the specifics of which are given in Table 5.

We considered upper and lower bounds for the energy consumption of the RO units based on uncertainties in the literature. We assumed that the RO

units operated for 12 hours from 6 a.m. to 6 p.m. as a crude load-shifting optimisation to maximise solar-resource consumption whilst minimising the need for electrical storage. For the CAPEX and non-energy OPEX costs associated with RO desalination, we take a fixed value of 0.602 USD/m³ based on 2022 data calculated by Ghaithan et al. [110].

3 Results

We undertook optimisations of the number of PV, PV-T and ST collectors, as well as the number of batteries, mass-flow rate through the collectors, and the size of the hot-water buffer tank installed. The optimisation process described in Section 2.6 resulted in no optimisation of the buffer-tank capacity, potentially due to the slow-varying dependence of the total lifetime cost of the system on the tank capacity. The hot-water buffer tanks were hence fixed by the volume of water required per hour by each of the three plants respectively to reduce computation time when performing the multi-variable optimisation.

Results are given in this section for the various case-study locations and plant capacities. Results for the lowest-cost systems are presented first, with the reliance of the systems on solar technologies vs grid-sourced power presented given in Section 3.1. Results for the largest-scale plant are detailed in Section 3.1.1, with specific costs for all three plants considered detailed in Section 3.1.2. The sensitivity of the specific cost of desalinated water to a choice of collector is outlined in Section 3.1.3, whilst the sensitivity analyses outlined in Section 2.6.1 are given in the S.I. The analysis of embedded carbon is given in 3.3, with more results outlined in the S.I.

3.1 Plant performance optimisation

The storage-, solar- and grid-electricity fractions correspond to the fraction of the MED plant's electricity demands that were met using energy supplied from battery storage, sourced directly from solar PV or PV-T collectors, or taken from the grid respectively. These three fractions sum to one for any given optimisation run. The auxiliary-heating fraction is the fraction of the plant's thermal requirements that were met using the auxiliary electrically-driven heat pump. Any demand that wasn't met this way was supplied in the form of hot water from the PV-T and/or ST collectors. This fraction can be negative, implying an excess of solar energy, and range up to one, where a fraction of one implies that all heating demand was met using the auxiliary heat pump. These fractions, for each location, are shown in Figure 2.

The results of 211 optimisations are shown in a vertical scatter along with a kernel-density estimate (KDE) of the distribution of the points shown as a violin plot. The number of optimisations is a result of switching between different component types that best represent the space of commercially-available collectors, and across three different plant sizes (see Section 2). The results are aggregated over the various plant capacities, the specifics of which are detailed

in Table 6, and over the various technologies, which are detailed in Tables 1, 3 and 4 for the ST, PV-T and PV collectors respectively.

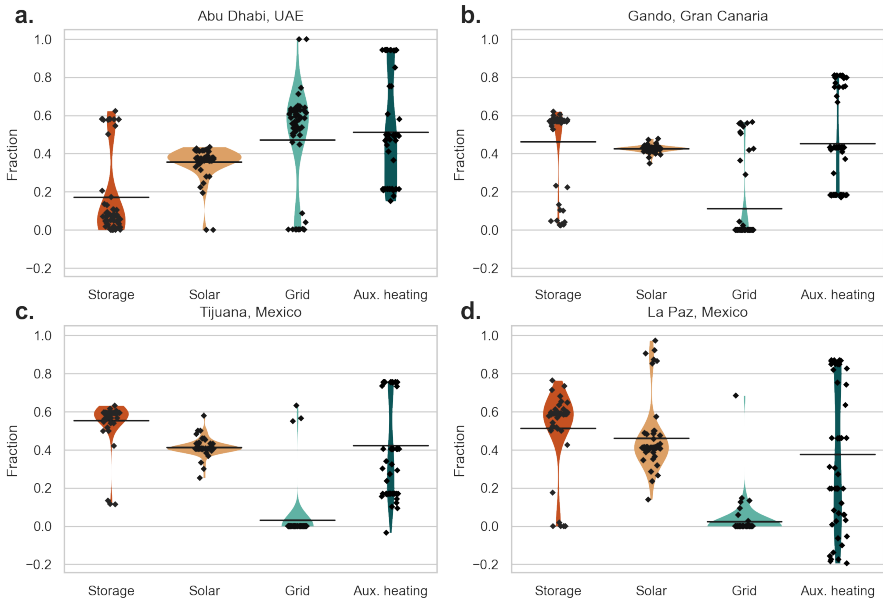


Fig. 2: Storage, solar and grid fractions. Scatter plot with an overlaid kernel-density estimate (KDE) in the form of a violin plot showing the storage, solar and grid electricity, and auxiliary-heating, fractions of the optimum system for 211 optimisations (resulting from different component types and plant sizes) for the lowest lifetime cost. The mean value is marked with a horizontal line. The results are aggregated over the three MED plant sizes considered, as well as the various collector technologies, across the four case-study locations considered: a. Abu Dhabi, UAE, b. Gando, Gran Canaria, c. Tijuana, Mexico and d. La Paz, Mexico. The locations are listed in order of increasing mean grid electricity cost.

The data show a high sensitivity of the lowest-cost system on location which is likely due to the varying grid price. Abu Dhabi in the UAE has a grid cost of 0.078 USD/kWh_{el} [100] and relies, on average, on the grid to meet 47% of the MED plant's electricity demands, both base-load electricity demands of the plant as well as auxiliary heating utilising heat pump, with electricity storage meeting only 11% of the demand. Gando in Gran Canaria has a reduced reliance on the grid for night-time electricity in comparison. This is potentially due to the price of grid electricity of 0.146 USD/kWh_{el} [101] being more comparable to investing in electrical storage over the lifetime of the plant.

La Paz has a specific grid cost over 35 times that of Abu Dhabi, with additional usage-based, fixed-monthly and capacity-based costs, the specifics of which are given in Table 10. The mean optimum system in La Paz uses electricity from the grid to meet 2.5% of the electricity demands of the plant and relies on electricity storage for 51% of its demand. We attribute this shift from grid-reliant towards self-reliant, solar-and-storage powered systems to the comparatively expensive cost of grid electricity in Mexico resulting in electricity which is sourced from the grid being considerably more expensive than investing in electrical (battery) storage to meet the night-time demands of the plant. In Abu Dhabi, the price of grid electricity of 0.078 USD/kWh_{el} [100] likely results in grid-sourced electricity being a cheaper method for powering the desalination plant during night hours than investing in batteries.

We also attribute the increasing solar-electricity fraction across the four case-study locations to the rising mean cost of grid electricity. Solar electricity, sourced from either PV or PV-T collectors, meets 36%, 43%, 41% and 46% of the electrical demands of the plants in Abu Dhabi, Gran Carnaia, Tijuana and La Paz in Mexico respectively.

The increasing mean cost of grid electricity across the four case-study locations is also correlated with lower auxiliary-heating fractions, suggesting a shift towards systems which are more reliant on PV-T and ST collectors for hot-water heating than auxiliary electrically-driven heat-pump heating, powered through either the grid and PV panels. This trend can also be seen in Figure 3 for the largest-sized MED plant considered, specifics of which are given in Table 6. The mean number of collectors and batteries installed in each of the locations is given in Table 11.

3.1.1 Large-scale desalination

The optimum number of components installed for the largest-scale desalination plant considered are shown in Figure 3. The results show the number of batteries and PV, PV-T and ST collectors installed which resulted in the lowest overall lifetime cost of the energy-generation system. The results show an overall trend that, with an increasing mean cost of grid electricity, the total mean number of components installed increases across the four case-study locations.

We identify two thresholds in the configuration of the systems as the price of grid-sourced electricity increases. Abu Dhabi, with the lowest cost of grid electricity of 0.078 USD/kWh_{el}, shows the lowest number of batteries installed on average, visible in Figure 3. As the cost of grid-sourced power increases, PV collectors, in conjunction with electrical-battery storage, become a cheaper way to provide power for auxiliary heating than relying on the grid. Overall, the system still relies on auxiliary heating to meet most of its hot-water demand. This threshold is passed for Gando, with a cost of 0.146 USD/kWh_{el} for grid-sourced electricity, compared with Abu Dhabi.

As the cost of grid-sourced electricity is increased further, the second threshold is passed. For Tijuana and La Paz, the tiered pricing structures for grid-sourced power are given in Table 10. For these locations, a drop in the

Table 11: Mean number of PV, PV-T and ST collectors installed, aggregated over technology, for each of the case-study plants and locations considered determined by an optimisation to reduce the total lifetime cost of the system.

Plant	$\dot{m}_{\text{prod}}$, m ³ /day	Location	Batteries	PV collectors	PV-T collectors	ST collectors
Small	3 [78]	Abu Dhabi	26	112	1	5
		Gran Canaria	117	207	0	2
		Tijuana	231	536	54	115
		La Paz	129	588	303	173
Medium	120 [79]	Abu Dhabi	1460	1790	15	176
		Gran Canaria	4340	3340	152	93
		Tijuana	4960	4260	25	14
		La Paz	4260	2830	287	173
Large	1694 [80]	Abu Dhabi	23100	27300	1600	1180
		Gran Canaria	62400	56500	1350	1570
		Tijuana	62000	73500	18000	4860
		La Paz	43000	24800	26600	54700

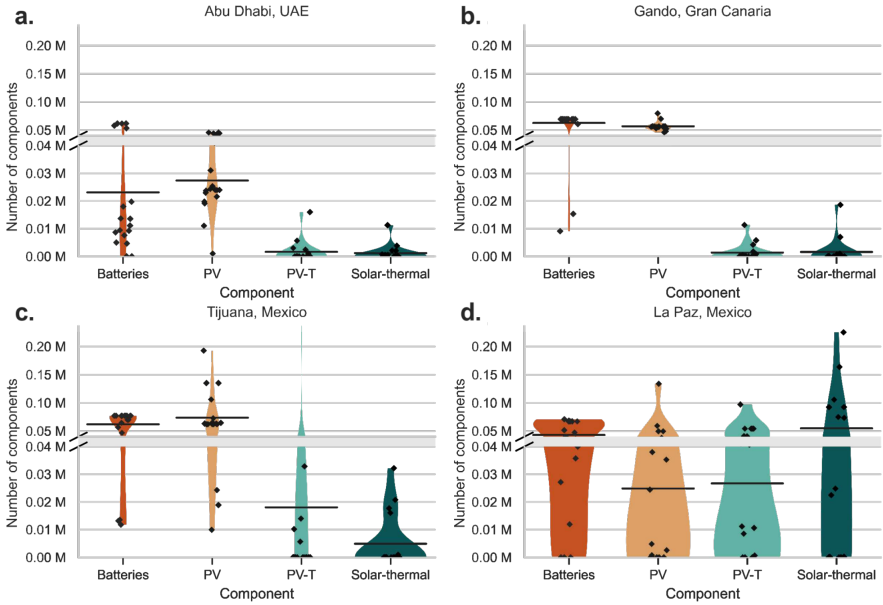


Fig. 3: Installed components for the largest-scale MED plant. Scatter plot, along with an overlaid KDE in the form of a violin plot, of the number of batteries and PV, PV-T and ST collectors installed for 70 results (resulting from different component types and plant sizes) for the lowest total lifetime cost system for the largest-scale MED desalination plant considered. The mean value is marked by a black line. The plant considered is capable of outputting up to $1694 \text{ m}^3/\text{day}$ of fresh water, the specifics of which are detailed in Table 6. Results are shown for the four case-study locations considered: a. Abu Dhabi, UAE, b. Gando, Gran Canaria, c. Tijuana, Mexico and d. La Paz, Mexico. The results show an increase in system size across the four case-study locations considered correlated with an increase in the cost of grid-sourced electricity.

number of PV modules and batteries installed, compared to Gando, is visible in the spread of the KDE in Figure 3. This coincides with an increase in both the number, and vertical spread, of PV-T and ST collectors installed. We attribute this shift to the price of grid-sourced electricity passing a threshold between Gando and Tijuana such that self-reliant thermally-driven systems become more cost-effective over the lifetime of the MED plants compared with electrically-driven heat-pump-based systems. This increase in the number of installed ST and PV-T collectors is visible also in Table 11. The spread in the KDEs for the number of batteries and PV collectors installed in both Tijuana and La Paz suggests that there is a trade off between using electrically- or thermally-driven systems depending on the choice of collector.

3.1.2 Specific costs

The specific costs of the lowest-cost energy-supply system are shown in Figure 4. The reference cost of a grid-powered RO system is shown as a hatched grey area, where the costs of grid electricity are taken from Tables 9 and 10 and the specific energy consumption of RO is taken as a range from 2 to 7 kWh_{el}/m³ [108]. The reference cost of a PV-and-battery RO system is shown using a yellow hatched area. The specific cost of the energy-generation system includes the solar collectors, electrical and hot-water storage tanks, auxiliary heat pumps, water pumps and inverters.

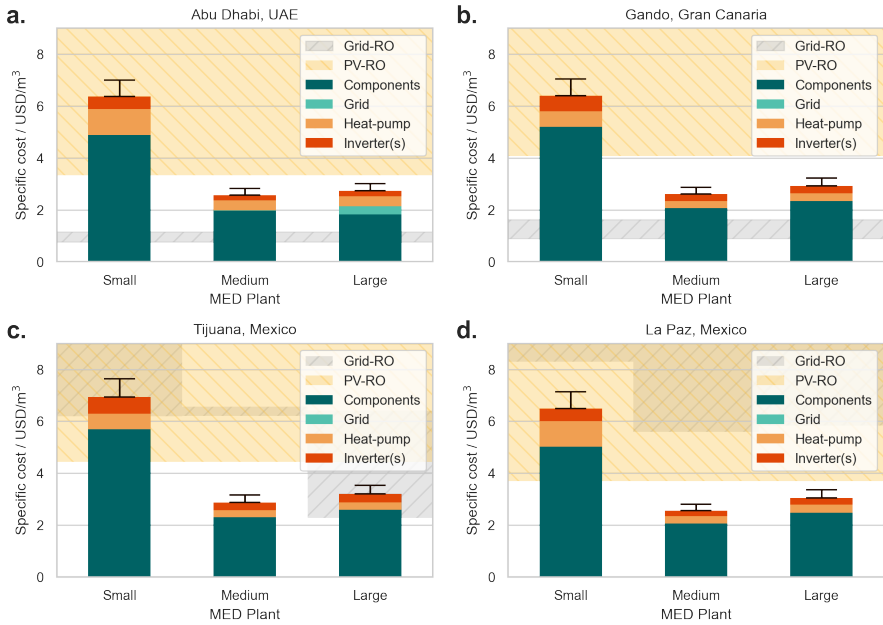


Fig. 4: Specific cost of MED-desalinated water. Stacked-bar plot showing the specific costs of the energy-supply system for the lowest-cost configuration of components for the three MED plants considered. The bars are broken down vertically into component costs, the costs of grid-sourced energy, costs associated with the auxiliary heat pump and with the solar inverters, for each of the four case-study locations considered: a. Abu Dhabi, UAE, b. Gando, Gran Canaria, c. Tijuana, Mexico and d. La Paz, Mexico. The specific costs associated with grid-driven and standalone PV-and-battery-driven RO desalination are shown with grey- and yellow-hatched areas respectively. The estimate for the embedded costs in the construction of the MED plant is shown with the black error bar.

The data show that, across the four case-study locations, the medium-scale desalination plant considered [79] afforded the lowest specific cost of clean-water generation, with values of 2.57, 2.61, 2.87 and 2.55 USD/m³ for Abu Dhabi, Gando, Tijuana and La Paz respectively. This was followed by the largest-scale plant [80], with values of 2.73, 2.93, 3.20 and 3.05 USD/m³ respectively across the four locations, and by the smallest-scale plant considered [78], with values of 6.37, 6.40, 6.94 and 6.49 USD/m³ across the four locations respectively. We attribute the fact that the medium-scale plant produces clean water with the lowest specific cost of the MED plants considered as being due to it having the lowest specific heat consumption of the three plants considered: 142.8 kW_{th}/m³ as opposed to 153.0 kW_{th}/m³ and 307.7 kW_{th}/m³ for the largest- and smallest-scale plants considered respectively.

The cost of grid-driven RO, shown as a grey-hatched area in Figure 4, is entirely driven by the cost of grid-sourced electricity. In Abu Dhabi and Gando, where grid-sourced power is relatively cheap (0.078 and 0.146 USD/kWh_{el} respectively), grid-driven RO is cheaper than both PV-and-storage-driven RO and MED desalination. In Tijuana and La Paz, however, the higher costs associated with the grid result in both MED and PV-driven-RO desalination producing clean water with a lower specific cost. This aligns with the shift, visible in Figures 2 and 3, from grid-supplemented auxiliary heating for meeting the demands of the MED plants modelled towards self-reliant PV-T- and ST-driven power generation.

The lowest specific costs of energy generation which could be achieved across all technology combinations, i.e., the choice of ST, PV-T and PV collectors, the details of which are given in Tables 1, 3 and 4 respectively, are shown by the stacked bars in Figure 4. The low grid-electricity fractions across all four case-study locations for the lowest-cost systems shown demonstrate that an optimal choice of technology results in self-reliant systems with a low reliance on the grid. (Ten of the twelve plant-location combinations shown in Figure 4, namely, all results other than the medium- and largest-scale plants in Abu Dhabi, have no associated grid costs and hence a grid-electricity fraction of zero. Only one of these, the largest-scale plant, has a grid-electricity fraction which is large enough to be clearly visible in Figure 4.) For those technology combinations for which the lowest-cost system configuration had a higher grid electricity fraction than those shown in Figure 4, the overall total cost of the system, and hence the specific cost of clean-water production, was higher than a system which utilised a different, either a cheaper or more-efficient, choice of collector and which had a lower grid electricity fraction.

We attribute the variations in the costs associated with the auxiliary heat pumps installed across the four-case study locations for any given plant, visible in Figure 4, as being due to variations between the reliance on ST- as opposed to PV-driven hot-water heating, with installations which are more reliant on PV collectors and grid connections having larger heat-pump than those which are reliant on ST and PV-T collectors. Similarly, we attribute variations in the

costs associated with inverters as being due to variations in the capacities of PV and PV-T collectors as opposed to ST or grid-driven systems.

3.1.3 Component selection

The effect of changing which specific collector was included in the model on the total cost of the smallest plant size [78] is shown in Figure 5, with the choice of collectors which resulted in the lowest overall system cost for each plant size and location given in the S.I. Altering which collector was selected had an impact across all three plant sizes. Results were disaggregated by plant size due to the three plants considered having specific costs which differed due to efficiency factors and which could not easily be represented. The dependence of the total cost of the system on which collector model was used in the optimisations was most pronounced for the smallest plant, capable of producing 3 m³/day of fresh water, the specifics of which are given in Table 6. The results for this plant are shown here in Figure 5.

The grey lines and extrema points in Figure 5 across all case-study locations, with the exception of Abu Dhabi, show that systems which utilised the p-Si panel modelled were associated with lower costs over the lifetime of the MED plants compared with those utilising m-Si collectors. Recent reductions in the cost of m-Si PV modules may lead to the lowest costs over the lifetime of the plant for systems involving m-Si collectors compared with p-Si collectors [69]. By making our modelling open-source, we enable these analyses to be re-calculated as necessary as markets shift [53].

The data in Figure 5 show a difference between grid-reliant systems, identified in Figures 2 and 4 as Abu Dhabi in the UAE and Gando in Gran Canaria, as opposed to independently-operating systems in Mexico, namely Tijuana and La Paz. The effect of changing technology choice on the total lifetime cost of the system is most pronounced for Tijuana and La Paz, with clear differences in the median and spread of the results for each technology visible.

For the smallest-scale plant shown here, the red lines, indicating the lowest specific cost which was achieved when fixing a single technology, demonstrate that systems which utilise the relatively high-cost and high-thermal-efficiency Augusta ETC, the specifics of which are given in Table 1, are cheaper across all four case-study locations for the smallest plant, shown in Figure 5. We attribute this to the relatively low auxiliary-heating fraction of the smallest-scale plant of 15% (compared with 80% and 37% for the medium- and largest-scale plants respectively) resulting in there being a benefit in employing higher-thermal-efficiency ST and PV-T collectors when compared with, e.g., the largest-scale plant, where the relatively low-thermal-efficiency and lower-cost collectors are employed.

3.2 Sensitivity analysis

Due to the uncertainties in the lifetime of Li-ion batteries [75, 76, 106, 107] and solar inverters [84], we carried out sensitivity analyses where the inverter

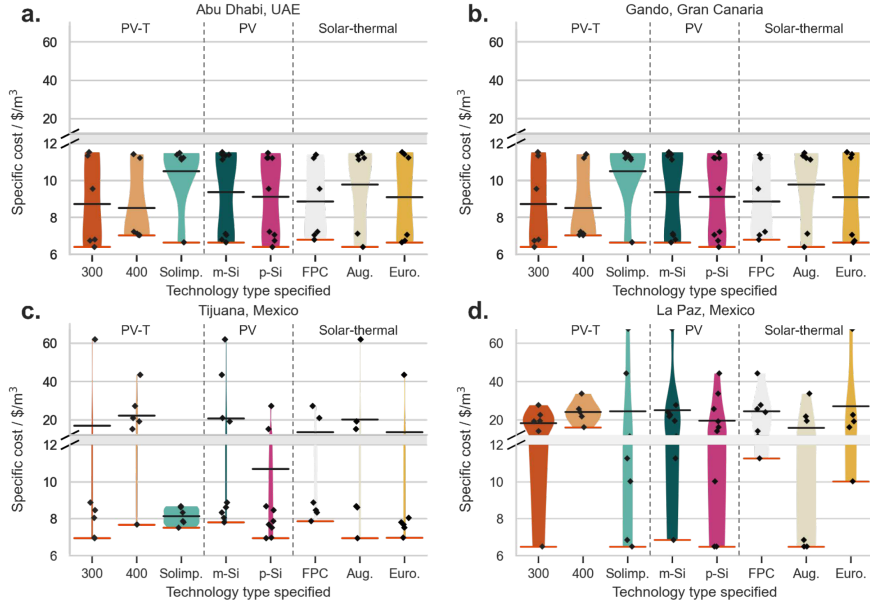


Fig. 5: Effect of component choice. Scatter plot, along with an overlaid KDE in the form of a violin plot, of the total cost of the installed system over the lifetime of the smallest MED plant simulated [78]. The mean and minimum values for each technology type are marked by horizontal black and red lines respectively. Vertical dashed grey lines demarcate the technologies into three groups: PV-T, PV and ST collectors. For each result, a particular solar-collector technology was specified and results for the lowest lifetime cost aggregated over all other possible combinations. Results for all four case-study locations are shown: a. Abu Dhabi, UAE, b. Gando, Gran Canaria, c. Tijuana, Mexico, and d. La Paz, Mexico.

lifetime was varied between 1 and 29 years at 2-year intervals and the battery cycle lifetime was varied between 100 and 3000 cycles at 100-cycle intervals. Results of these analyses are presented in the S.I.

3.3 Emissions analysis

We carried out optimisations for the lowest total lifetime cost of the energy-generation system. The specific emissions, broken down into component-, heat-pump- and inverter-based emissions, as well as the emissions arising from grid-sourced electricity, for all three case-study plants across all four case-study locations are shown in Figure 6.

The data show that, similar to the specific-cost data plotted in Figure 4, the specific emissions associated with each of the plants scale with their specific heat consumption: $142.8 \text{ kW}_{\text{th}}/\text{m}^3$, $153.0 \text{ kW}_{\text{th}}/\text{m}^3$ and $307.7 \text{ kW}_{\text{th}}/\text{m}^3$

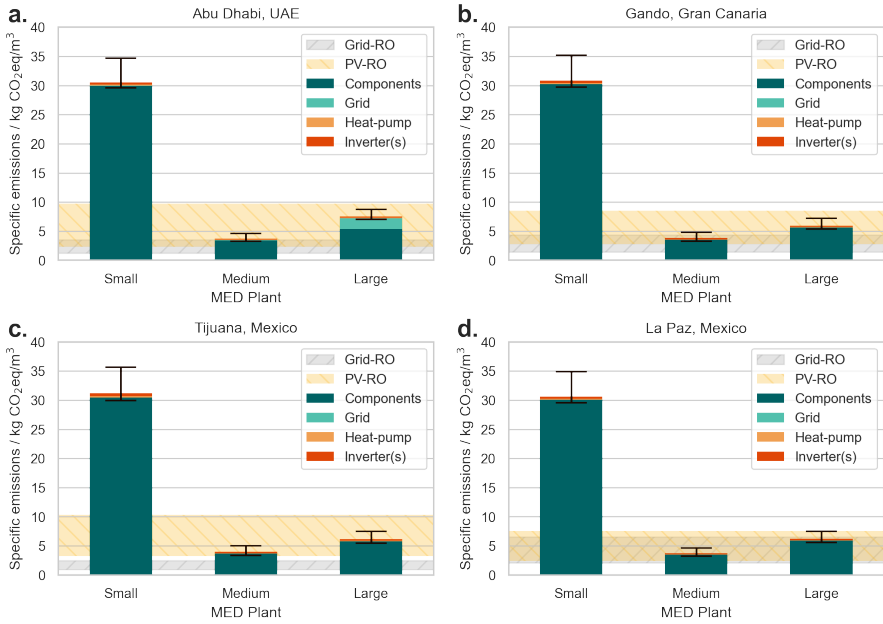


Fig. 6: Specific emissions of MED-desalinated water. Stacked-bar plot of the specific emissions resulting from energy generation for each of the three plant capacities when optimised for the lowest lifetime cost in each of the four case-study locations: a. Abu Dhabi, UAE b. Gando, Gran Canaria, c. Tijuana, Mexico and d. La Paz, Mexico. The specific emissions resulting from grid-driven and PV-and-battery-driven RO desalination are shown with grey- and yellow-hatched areas respectively. Uncertainty in the emissions resulting from grid-powered RO arises from the range of specific energy-consumption values for RO used: 2 to 7 kWh_{el} [108]. Uncertainty in the emissions associated with the batteries and inverters, detailed in the S.I., along with a 10% margin for emissions resulting from the MED plant infrastructure [19], result in the error bars visible. The embedded emissions in the construction of the MED plant are accounted for in the black error bar also.

for the medium-, largest- and smallest-scale MED plants considered respectively. We attribute this to plants which require a greater energy per unit of desalinated water also thus requiring a greater number of components and a larger amount of grid-sourced electricity per unit of clean water produced.

The data in Figure 6 also show that, when optimised for the lowest-cost system across all available technology combinations for the lifetime of the plant, only the medium-scale MED plant in Abu Dhabi and Gando, and the medium- and largest-scale plants in La Paz, had specific emissions lower or comparable within error than grid-powered RO. For Tijuana, the relatively low carbon intensity of electricity sourced from the grid of 310 gCO₂eq/kWh_{el} results in the energy-generation systems, when optimised for the lowest total

lifetime cost, having a higher specific carbon intensity than grid-powered RO. However, as shown in Figure 4, grid-powered RO in Tijuana is more expensive than these solar-based systems for all three case-study MED plants considered.

For La Paz, the relatively high carbon intensity of electricity sourced from the grid of 890 gCO₂eq/kWh_{el}, as well as the highest grid cost of the four case-study locations considered, means that the lowest-lifetime-cost systems for the medium- and largest-scale MED plants considered are lower in both specific costs and emissions than grid-powered RO. Where this is the case, optimising for the lowest total lifetime cost of the energy-generation system also results in an emissions saving when compared to grid-powered RO, suggesting that PV-, PV-T- and solar-thermal-driven MED desalination can provide both costs and emissions savings when compared with grid-powered RO where either the emissions intensity of grid-sourced electricity is relatively high or the specific heat consumption of the specific MED plant is relatively low.

The results in Figure 6 also show that, when compared with PV-and-battery-driven RO, the medium- and large-scale MED plants considered were able to produce clean water with a comparable emissions intensity. We attribute the relatively high emissions intensity associated with the smallest-scale system as being due to a combination of the higher specific energy consumption of the smaller-scale plant considered as well as the embedded emissions in the non-scalable system components. A comparison of the embedded costs and emissions associated with each of the case-study locations and technology combinations is given in the S.I.

The relatively low emissions intensity across all four case-study locations of grid-powered RO can be partly attributed to the embedded emissions in grid-connected infrastructure, as well as the new grid connection required, which were neglected here. Due to uncertainties around the transmission losses, we estimate this value to range from anywhere between 0.0357 kgCO₂eq/kWh_{el}, for the lowest available estimate for the smallest-scale plant considered, to 1.2308 kgCO₂eq/kWh_{el}, using an upper-bound estimate combined with the largest-scale plant considered; a potentially significant alteration to the emissions intensity [111]. However, as the carbon intensity of grid-sourced electricity in all four of the case-study locations considered is likely to change significantly over time, we neglected these estimates here.

4 Discussion

There are several implications of the results shown in Section 3. These are discussed in Section 4.1. Limitations of the methodology are discussed briefly in Section 4.2.

4.1 Implications

The cost of grid-sourced electricity greatly affects both the specific cost and emissions of the clean water generated and the capacity of the optimum system installed. In Abu Dhabi in the UAE and Gando in Gran Canaria, grid-powered

RO is a more cost-effective means of supplying clean-water than solar-driven MED desalination. In Tijuana and La Paz, both in Mexico, grid-powered RO is higher in cost than solar-driven MED, meaning that the MED plants considered here are cheaper than grid-powered RO. These results are also reflected in Figure 4 where the specific costs of the MED plants are only cost-competitive within error or cheaper in Tijuana and La Paz.

The price of grid-sourced electricity hence has a great impact on which desalination technology, whether electrically-driven RO or thermally-driven MED, is able to produce clean drinking water at the lowest specific cost. As grid prices vary, both geographically and over time, it is hence necessary to carefully consider the performance of any desalination technology over the system lifetime in order to ensure the most optimal system is selected.

The choice of specific collectors used had a significant impact on the specific cost of clean water achieved. This is especially in La Paz where the cost of grid-sourced electricity was highest amongst the four case-study locations considered and, as shown in Figure 2, where the systems were primarily self-reliant. In Figure 5, the impact of collector choice had a clear impact on the costs associated with the energy-generation system with the relatively lower-efficiency Augusta ETC, p-Si PV and D.S. 300 PV-T collectors being associated with systems with a lower cost of clean water.

The lifetimes of the batteries and solar charge inverters installed, which are directly correlated with the number of replacements which are needed over the lifetime of the system, affect the balance between self-generated and grid-sourced electricity used to power the plant, and, hence, the capacity of collectors which need to be installed. It is hence necessary to carefully consider the available collectors, not only the most-efficient designs, as well as the various batteries and solar inverters available when commissioning an MED plant as these can have a significant impact on the system capacity needed.

The results in Figure 6 show that optimising for the lowest lifetime cost results in systems that are higher in emissions than grid-powered RO in all case-study locations excepting La Paz, where the emissions intensity of grid-sourced electricity is the highest of the case-study locations considered, with only medium-scale desalination comparable within error due to its relatively lower specific energy requirements. Utilising self-reliant solar technologies to drive MED desalination, whilst it may produce a lower cost than grid-powered RO, thus doesn't result in lower greenhouse-gas emissions necessarily despite renewable solar collectors being installed and despite the relatively high specific emissions associated with grid-sourced electricity.

The results in Figure 6 also demonstrate that the emissions associated with solar-powered MED desalination when optimised for the lowest-cost system are generally lower than, or overlapping within error with, those associated with PV-powered RO systems. I.E., that efficient MED desalination can have emissions which are comparable with those arising from PV-driven RO desalination within error. Similar to the approach used for modelling the case-study MED plants considered, the PV-RO benchmark was generated by optimising

for the lowest total lifetime cost. Optimising, either solely for, or simultaneously with the GHG emissions attributed to the systems, it may be possible for lower emissions intensities than grid-powered RO to be achieved whilst not sacrificing considerably on cost.

4.2 Limitations

There are a few limitations in the modelling approach used, primarily in terms of how discount rates and costs are treated, as well as the nature of the simulation and optimisation approaches undertaken. These limitations, and their impact on the study, are outlined here.

4.2.1 Component and grid costs

The price of the grid electricity used for the case-study locations considered, detailed in Tables 9 and 10, will change over time, both on a daily basis, as the hourly renewable energy resource available and real-time demand placed on the grid affect the cost of purchasing electricity from the grid, and on a longer-term scale as countries introduce legislation and aim to decarbonise their grids. In this work, we assumed that the cost of grid-sourced electricity was unchanging over the lifetime of our plant. Ignoring the longer-term effects may result in an outcome which favours self-reliant systems due to current high prices of grid electricity making these systems unattractive. On a shorter time scale, we selected case-study locations with a fixed tariff, i.e., one which does not vary depending on the environmental conditions. As such, the model developed is limited in its current scope to a static price of grid electricity but is not limited in this regard.

The costs of components will also change over time and, if historic trends continue, are likely to decrease for solar PV panels [112] and Li-ion batteries [113]. In-keeping with the approach taken for the cost of grid electricity, we considered only static costs for the various components installed. This is likely to result in battery storage being a less favourable means of providing night-time electricity than grid-sourced power as, when batteries are replaced, they will be replaced at the original price used at the start of the simulation period, rather than the discounted price. This effect will be in competition to the impact of considering a static non-decreasing grid-electricity price.

4.2.2 Optimisation algorithms

The nature of the optimisation algorithms employed means that local, rather than global, optima are found [102, 103]. These approaches thus reduce the computation time for generating results at the cost of determining the global lowest-cost system. Further, N-M and L-BFGS-B algorithms result in non-integer solutions due to the continuous nature of the optimisation variables. To mitigate this, after the optimisation process has been completed, we considered all permitted integer results surrounding the optimum point and selected that

with the most optimum value depending on the optimisation criterion being minimised or maximised.

5 Conclusion

We present an open-source integrated model for the lifetime optimisation of the configuration of photovoltaic (PV), hybrid photovoltaic-thermal (PV-T) and solar-thermal (ST) systems, as well as battery storage, the mass flow rate of heat-transfer fluid, and the capacity of thermal storage installed, for a multi-effect distillation (MED) plant. We consider a selection of PV, PV-T and ST technologies representative of the space of commercially-available technologies [60], as well as three MED plant capacities ranging from community-scale (3 m³/day [78] and 30 to 60 people per day [36]) to municipal-scale (1964 m³/day [80], up to 33,000 people per day [36]).

We make our model open-source so that other stakeholders, manufacturers, and industry experts can utilise our methodology to consider components particular to their needs for optimising and simulating the performance of such systems over the lifetime of plants of various capacities [53]. Further, by doing so, we provide scope for investigating novel technologies such as smaller-scale membrane distillation [22] within the framework developed. We optimised the configuration of the systems based on the lowest total lifetime cost incurred.

We find a strong dependence of the grid-reliance of the systems on the cost of grid-sourced electricity. Case-study locations with a cost of grid electricity of 0.078 USD/kWh_{el} relied on grid-sourced power to meet 47% of the demands of the plant, compared with locations with a cost of grid electricity upwards of 2.91 USD/kWh_{el} which relied on grid-sourced power to meet 2.5% of their demands. Between these two locations there was also an observable shift in the reliance on battery storage for night-time power supply and ST and PV-T collectors for thermally-driven heating.

We find that off-grid systems powered wholly through solar collectors with electrical and thermal storage are more affordable across all three case-study plants considered in three of our case-study locations, with grid-reliant systems only cheaper for the medium- [79] and largest-scale [80] plants in Abu Dhabi, UAE, where the price of grid electricity was the cheapest considered at 0.078 USD/kWh_{el}. However, due to the high emissions associated with electricity in the UAE, we conclude that this is not in line with the United Nations Sustainable Development Goal 6, “clean water and sanitation for all” [20].

We find that the technical specifications associated with the lowest-cost system depend on the reliance of the system on PV-T- and solar-thermal-driven heating as opposed to electricity-driven heat-pump heating with these trends being most pronounced for the smallest-capacity plant considered. The more-expensive and higher-efficiency evacuated-tube collectors generally resulted in lower specific costs than the cheaper and lower-efficiency flat-plate collectors considered. Poly-crystalline silicon PV modules were associated with systems with lower costs compared with mono-crystalline silicon (m-Si) collectors,

though this may change as a result of recent reductions in the cost of m-Si panels which are not captured in the case-study panels considered here [69]. We conclude that, when planning for and sizing energy-generation systems for MED desalination, the choice of technology can have a significant impact on the lifetime costs and performance of the system which is not correlated purely with the costs or emissions of the collectors.

We find that, by optimising for the lowest total lifetime cost of the plants' energy-generation systems, embedded emissions were lower than grid-driven reverse osmosis (RO) for the medium-scale plant [79], with the lowest specific heat demand of $142.8 \text{ kWh}_{\text{th}}/\text{m}^3$, in three of the four case-study locations considered, namely Abu Dhabi, Gando and La Paz, and that they were lower for the largest-scale plant [80], with a specific heat demand of $153 \text{ kWh}_{\text{th}}/\text{m}^3$, in La Paz, the case-study location considered with the highest grid emissions intensity. We conclude that, when compared with grid-powered RO, a high grid emissions intensity or a low specific energy consumption can make MED desalination lower in both specific costs and emissions, thus suggesting that PV-, PV-T- and ST-driven MED desalination can produce clean water with both lower costs and emissions than grid-driven RO. Had we optimised for the lowest lifetime carbon emissions, the results would have produced systems of comparable or greater specific costs of clean water.

Optimising for the lowest total lifetime carbon emissions resulting from the energy-generation system, rather than the total lifetime cost of the system as has been done here, may result in a greater number of systems that have a lower specific emissions associated than grid-powered RO though the costs associated will increase. We make our model available online and open-source, and provide the embedded emissions as a target criterion for optimisations within our model, so that future work can consider desalination systems optimised for the lowest lifetime carbon emissions [53].

Supplementary Information. Supplementary information concerning detailed aspects of the methodology surrounding component degradation is attached.

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Author contributions

The manuscript was written with the contributions of all authors. All authors have given approval for the final version of the manuscript. B.W., G.H., P.S., J.C., J.N. and C.N.M. conceived of the presented study. B.W., G.H. and P.S. contributed to the design of the software used in the study. B.W. wrote the software used in, and carried out, the computations. J.N. and C.N.M. supervised the project and motivated the selection of case-study technologies and locations considered. B.W. and H.B. planned the investigations surrounding sensitivity to component degradation and the associated emissions. B.W. carried out the emissions analysis, and B.W., H.B., and J.N. analysed the outputs. All authors discussed the results and contributed to the final manuscript.

Competing interests

The authors declare no competing interests.

Data availability

The datasets generated and analysed during the current study are available on Zenodo and can be accessed via this link: <https://doi.org/10.5281/zenodo.7801893>.

Code availability

The underlying code for this study is available on GitHub in BenWinchester/HEATDesalination and can be accessed via this link: <https://doi.org/10.5281/zenodo.7612965>.

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