Integrating concentrated solar power with seawater desalination technologies: a multi-regional environmental assessment

Mohamed Alhaj, Sami G Al-Ghamdi

Supporting Information

Integrating Concentrated Solar Power with Seawater Desalination Technologies: A Multi-Regional Environmental Assessment

Mohamed Alhaj[1] and Sami G. Al Ghamdi[1*]

[1]Division of Sustainable Development, College of Science and Engineering, Hamad Bin Khalifa University, Doha, Qatar

Solar-Driven Desalination and the Sustainable Development Goals (SDGs):

Table 1. Relation of the SDGs to solar-driven desalination technology (United Nations 2017)

Sustainable Development Goal	Targets Relevant to Solar-driven Desalination
SDG 6: Ensure availability and sustainable managements of water and sanitation for all	6.1: By 2030, achieve universal and equitable access to safe and affordable drinking water for all. 6.4: By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity. 6.A: By 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programs, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies.
SDG 7: Ensure access to affordable, reliable, sustainable, and modern energy for all	7.1: By 2030, ensure universal access to affordable, reliable and modern energy services. 7.2: By 2030, increase substantially the share of renewable energy in the global energy mix. 7.A: By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology. 7.B: By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States, and land-locked developing countries, in accordance with their respective programs of support.

Description of the LCA System Boundary, Reference Flows, and Data Sources

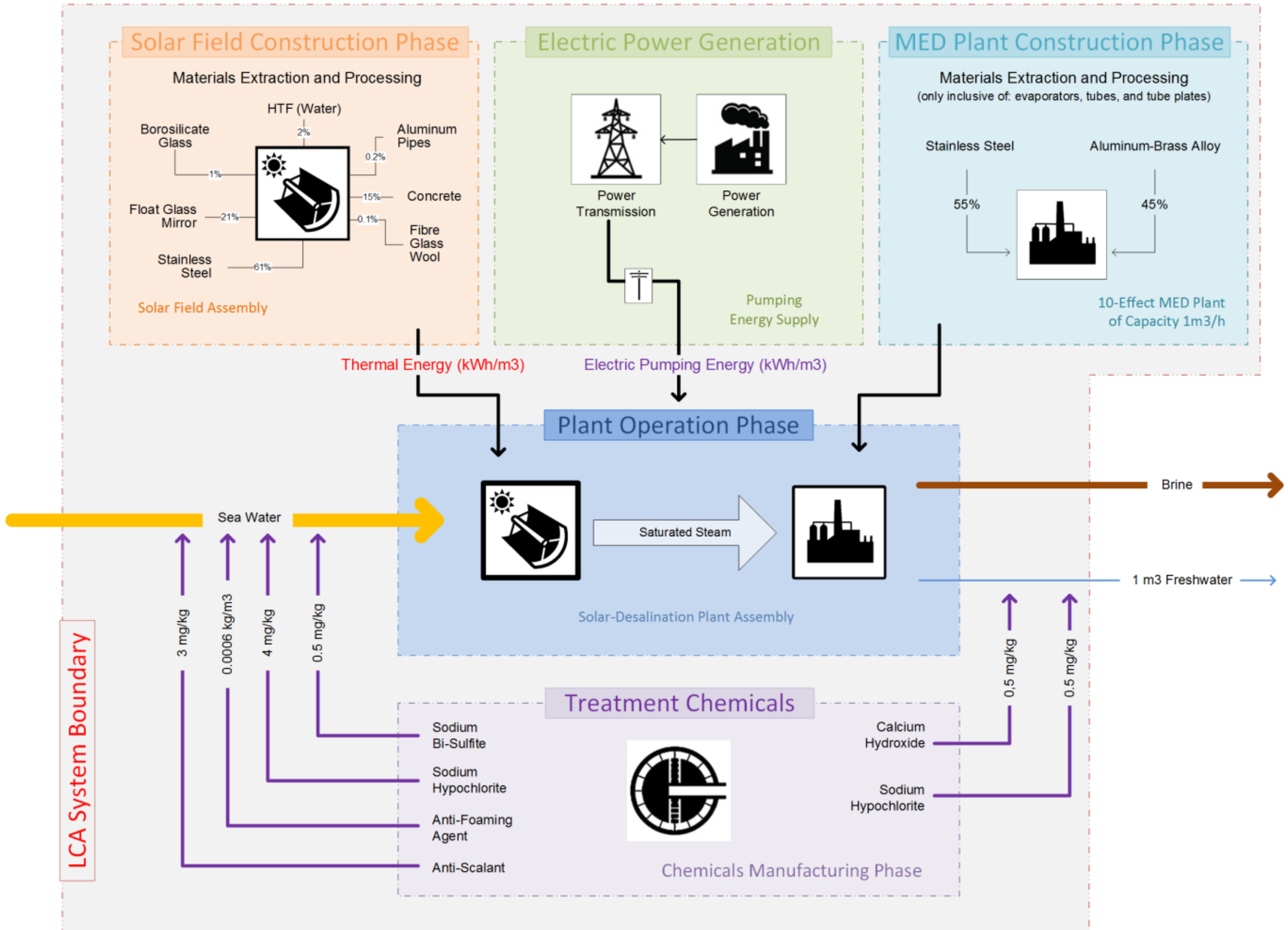

Figure 1. LCA system boundary for the solar-driven MED plant showing the construction phase, the operation phase, and the main reference flows.

The system boundary includes only the solar-MED plant's construction and operation phases. The end of life phase was neglected because previous studies on the end of life phase's impact of concentrated solar power plants and thermal desalination plants indicated the minimal impact of this phase (Raluy *et al* 2005, Heath *et al* 2011).

The construction phase consists of two parts: the solar field and MED plant. The construction phase of the solar field includes the bill of materials required to construct a linear Fresnel collector (LFC) solar field which consists of: mirrors, steel structures, materials of the receiver, concrete foundations, and materials of the air-cooled condenser. The bill of materials for the LFC solar field (shown in **Table 2**) was taken from a real plant's data (PE2 plant in Spain) (Aurélie *et al* 2013). The water required for cleaning the mirrors was taken from the estimation given by (Palenzuela *et al* 2015). The total water consumed for mirror washing is deducted from the lifetime distillate production of the plant (assuming 30-years life span). The data in **Table 2** was calculated by dividing the materials data for the PE2 plant by its aperture area (302,000 m^2). Given the data in **Table 2**, it is possible to estimate the bill of materials for any solar field's aperture area which is a necessary step for the multi-regional analysis.

Table 2. Bill of materials for the solar field (derived from the data given in (Aurélie *et al* 2013) and (Palenzuela *et al* 2015)).

Bill of materials	Quantity (all values are expressed per m^2 of aperture area)
Solar Field	
Mirrors	7.52 kg/m^2
Steel	22.12 kg/m^2
Receiver	
Steel	0.02 kg/m^2
Steel pipes	0.74 kg/m^2
Borosilicate glass	0.61 kg/m^2
Anti-reflex coating	0.03 m^2/m^2
Fibre glass wool	0.11 kg/m^2
Concrete	0.00046 m^3/m^2
Aluminum pipes	0.06 kg/m^2
Steel fan (air condenser)	0.16 kg/m^2
HTF (Water)	1.58 kg/m^2
Cleaning water	0.027 m^3/m^2/year

The construction phase of the MED plant should ideally cover all the plant's components such as: the evaporators materials (walls, evaporator tube plates, tubes), the piping system, the pumping devices etc. However, due to data unavailability, the only system components that were considered are: the evaporator's walls, the tube plates, and the tubes. Data from a commercial MED plant in the Gulf region was used to estimate the bill of materials for these components (shown in **Table 3**) which, similar to **Table 2**, can be used to estimate a partial construction materials inventory for any plant size (given the lifetime distillate production). The data in **Table 3** was calculated by dividing the materials mass by the estimated lifetime distillate production of the plant (assuming a 30 years lifetime and 100% plant availability). It should be noted here that since the multi-regional LCA conducted assumes the same MED plant size in all locations, the MED plant bill of materials for all the seven cities is the same.

Table 3. Bill of materials for the MED plant.

Bill of materials	Quantity (all values are expressed per m^3 of distillate)
Evaporator walls (stainless steel)	0.0179 kg/m^3
Tube plates (stainless steel)	0.00127 kg/m^3
Tubes (Aluminum-Brass alloy)	0.0158 kg/m^3

The plant's operation phase consists of two parts: the energy consumed (thermal and electric) and the pre and post treatment chemicals. The energy consumed (specific thermal energy and specific electric energy) for each location is calculated from the validated Engineering Equation Solver (EES) model (Alhaj *et al* 2018). These two values are primarily functions of the feed water's temperature, feed water's salinity, and ambient air conditions. The chemicals considered for pre and post treatment and their specific dosages are given in **Table 4**. It was assumed that the same dosage is used in all cities; however, due to the fact that the plant's recovery ratio will be different in each city, the absolute chemical dose will vary.

Table 4. Pre and post treatment chemicals considered in the LCA boundary (Darwish *et al* 2013).

Chemical name	Specific dose
Pre-treatment	
Cleaning acid (HCl 30%)	0.19 mg/m^3 of feed
Anti-foaming agent	0.20 mg/m^3 of feed
Sodium Hypochlorite solution	4 mg/m^3 of feed
Sodium Bi-sulfite	0.5 mg/m^3 of feed
Anti-scalants (H_2SO_4)	3 mg/m^3 of feed
Post-treatment	
Remineralization (CaOH)	0.5 mg/m^3 of distillate
Disinfection (Sodium hypochlorite)	0.5 mg/m^3 of distillate

Input Data for the Selected Locations

The input data for each location is shown in **Table 5**. For all locations, the DNI is taken from Global Solar Atlas (The World Bank 2018), the average seawater temperature and salinity from NASA's Scientific Visualization Studio webpage (NASA 2009), and the meteorology data (ambient air temperature and relative humidity) from each location's meteorological department website for July 23rd, 2018 (individual references are given in **Table 5**).

Table 5. Direct normal irradiation, average seawater temperature and salinity, and ambient air temperature and relative humidity for the selected locations.

Location	DNI (kWh/m^2 /year)	Seawater temp. (^oC)	Seawater salinity (g/kg)	Ambient air temp.	Relative humidity	Meteorology data source
1. Kuwait	1822.00	35	45	41.5	0.26	(Kuwait Meterological Department 2018)
2. Abu Dhabi	1891.00	35	45	34.9	0.65	(UAE National Center for Meterology 2018)
3. Escandida	2416.00	20	25	16	0.34	(The Weather Channel 2018a)
4. Algeria	2312.00	25	35	37	0.46	(Office National de la Metérorologie 2018)
5. Torrevieja	1779.00	35	35	29	0.43	(Spanish State Meterological Agency 2018)
6. Sydney	1684.00	20	25	19	0.29	(The Weather Channel 2018b)
7. Carlsbad	1961.00	20	25	22	0.84	(National Weather Service Forecast Office 2018)

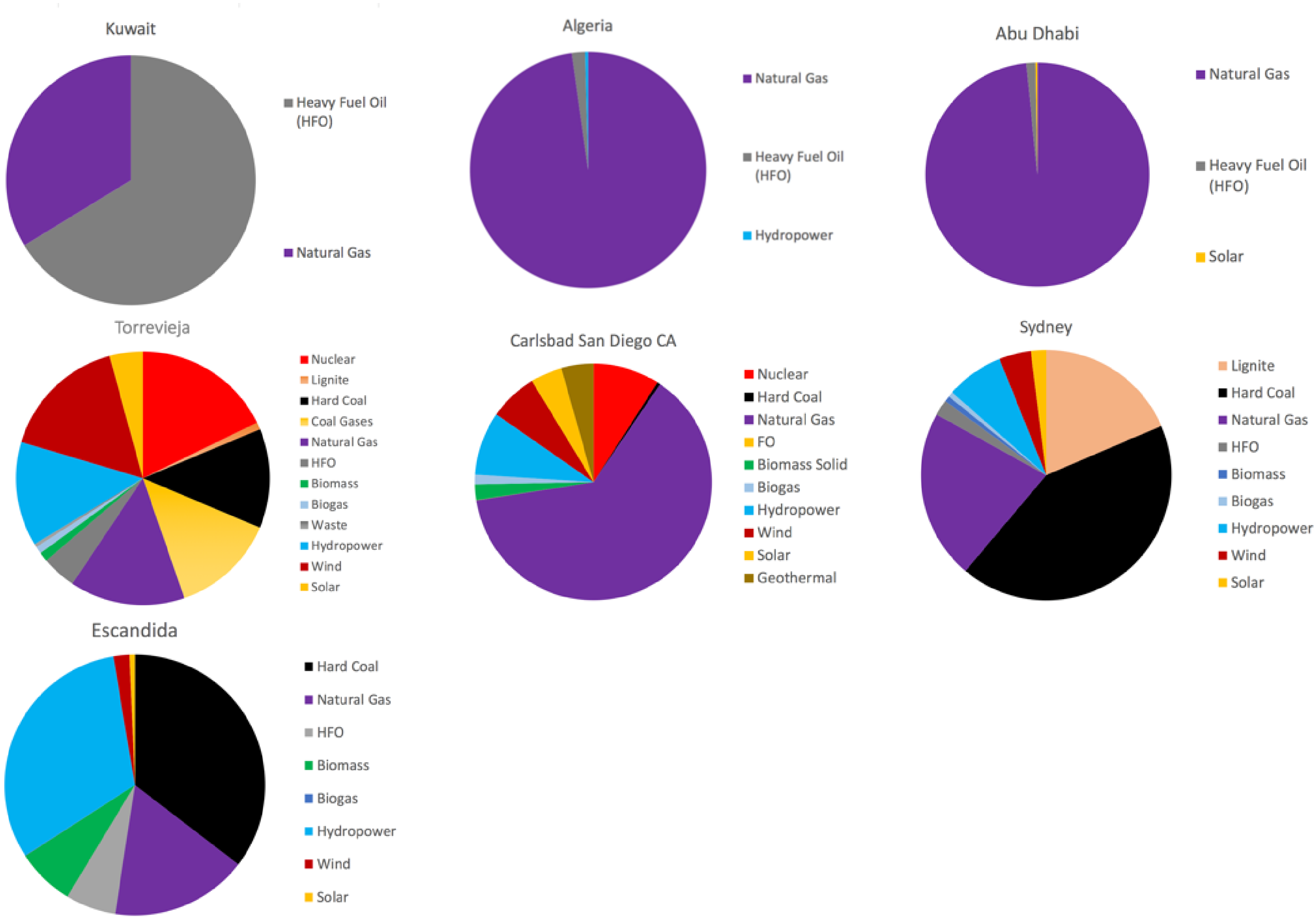

Figure 2. Regional electricity grid mix for the selected cities (Thinkstep 2018).

The EES Model

The validated EES model developed by the authors (Alhaj *et al* 2018) was used to estimate the following reference flows in the LCA boundary:

a) LFC aperture area in each location required to produce distillate at a rate of 1 m^3/h. This value will determine the bill of materials and hence affects the construction phase.

The aperture area for each location was calculated using this equation:

$$Q_{steam} \times h_{solar} = DNI \times A_{aperture} \times \eta_{optical} \times \eta_{thermal} \quad (1)$$

In the above equation, Q_{steam} is the power transferred to the saturated steam entering the evaporator in kW, h_{solar} is the solar hours per year, DNI is the annual average solar direct normal irradiation in kWh/m^2/year, $A_{aperture}$ is the LFC aperture area in m^2, $\eta_{optical}$ is the LFC's optical efficiency, and $\eta_{thermal}$ is the LFC's thermal efficiency. The following assumptions were made:

- h_{solar} = 1884 hours per year (or 21%), which is typical for concentrated solar power plants without energy storage (International Renewable Energy Agency (IRENA) 2012)
- $\eta_{optical}$ = 0.66 (this is the peak optical efficiency of the LFC as given by the manufacturer)
- $\eta_{thermal}$ = 0.9
- The LFC has a north-south orientation

b) Specific thermal energy and specific electric pumping in kWh/m^3. Both of these values will affect the operation phase. Both of these quantities are found by dividing the energy consumed (thermal or electric) by the distillate production in a given time frame.

c) Distillate recovery ratio (distillate/feed) for each location. This value will affect the chemicals consumption in the plant.

The EES program used for the calculations is given below, with the input values for Kuwait City as a sample (to run the program, the professional version of EES is required and the seawater properties library; seawater.lib):

```
PROCEDURE ACC(omega,T_in, m_dot_air, Q_cond : W_dot_fan)
Eta_fan = 0.9
Rho_air=Density(AirH2O,T=T_in,r=omega,P=1 [bar])
V_dot_air = m_dot_air/Rho_air
Rho_ref = 1.2 [kg/m^3]

DELTAP = (Rho_air/Rho_ref) * 320.0451719 - 0.2975215484* V_dot_air + 6.351486 *(10^(-4)) *
(V_dot_air^2) - 8.14*(10^(-7))* (V_dot_air^3)

W_dot_fan = ((V_dot_air * DELTAP)/ Eta_fan)/1000
```

```
end


$arrays ON
n=10;    T_sw= 35 [C]; X_sw= 45 [g/kg]
T_b[n] = 47.5 [C];  Distillate = 1 [m^3/h] ; F_total = Feed§/1000 {F_total is in m3/h}; B_total = F_total - Distillate
Feed§ = Feed * convert(kg/s,kg/h) ; Productivity = D_total * convert(kg/s,kg/h) ;

BPE = 0.7 [C]

TBT = T_b[1] ; X_max = X_bt[1]

T_f[n] = T_sw + DELTAT_ph
DELTAT_ph = 10 [C]
DELTAT_Plant= (T_steam - T_sw)/(n-1)

Delta_brine = (T_b[1] - T_b[n])/(n-1)

duplicate i=2,n-1
T_b[i] = T_b[i-1] - Delta_brine
end

duplicate i=1,n-1
T_f[i] = T_v[i] - 3
end

duplicate j=1,n
T_v[j]= T_b[j] - BPE
end


duplicate i=1,n
P_v[i] = P_sat(Steam,T=T_v[i])
h_v[i]= Enthalpy_vaporization(Water,P=P_v[i])
end

{Feed mass flow rates}
{Assumed equal feed distribution in reference case}
duplicate i=1,n
F_[i]= Feed/n
RR_[i]=D_[i]/F_[i]
end

duplicate i=1,n-1
F_ph[i]=F_[i] + F_ph[i-1]
end
F_ph[0] = 0

{Calculation of C_p for seawater}
duplicate i=1,n
Effect_[i]=i
C_p[i] = SW_SpcHeat(T_f[i],X_sw)/1000
C_px[i] = SW_SpcHeat(T_b[i],X_bt[i])/1000        {Used in the calculation of flashing brine in each effect}
```

```
end
C_p_sw= SW_SpcHeat(T_sw,X_sw)/1000

{LFC SOLAR FIELD INPUTS AND EQUATIONS}
//A_ap= 226 [m^2]                    {8 x 22 = 176 m^2 -- from LFC datasheet-- Base aperture area}
T_abs= T_avg + 10
T_avg=((T_1+T_2)/2)
L_r= 64.96 [m]
T_1 = 175 [C]
T_2 = 165 [C]
P_htf= 6 [bar]


HTF$='Water'                         {Pressurized water is the HTF. Single phase flow}

eta_pump=0.8                         {For evaluation of pumping energy}
m_htf= Q_req/(Cp_htf * DELTAT)
DELTAT = T_1 - T_2
Cp_htf=SpecHeat(HTF$,T=T_avg,P=P_htf)
Rho_htf=Density(HTF$,T=T_avg,P=P_htf)
W_dot_HTF = (P_x * m_htf)/(Rho_sw*eta_pump)


Q_steam = (DNI_x * A_ap * 0.66 * 0.9)/1884
DNI_x = 1822 [kWh/m^2]

{Seam Generator SG}
A = (T_1 - T_steam) - (T_2 - T_steam)
B =  (T_1 - T_steam)/(T_2 - T_steam)
LMTD_sg= A / ln(B)                   {LMTD in HX}
Q_req = U_sg * A_sg * LMTD_sg
U_sg= h_sg/1000
v_sg= m_htf/(1000*A_cs)
A_cs=pi*(0.0254^2)/4
Call External_Flow_Cylinder('water', T_1, T_cond,  P_htf*convert(bar,kPa), v_sg, 0.0254[m]: F_d\L, h_sg,
C_d, Nusselt, Re)
A_sg= ntsg * A_t                     {ntsg is the number of tubes in SG before rounding up}
n_sg= ceil(ntsg)                     {Rounds up the number of tubes to an integer}


T_steam = 70 [C]
TBT = T_steam - 5
Q_req = m_steam * h_steamx
P_steam= 0.3 [bar]
h_steam = Enthalpy(Water, x=1, P=P_steam)
T_cond=T_steam

{EFFECT 1 ENERGY AND MASS BALANCE}
F_[1]= D_[1] + B_[1]

Q_steam = Q_req
h_steamx = enthalpy_vaporization(water,P=P_steam)     {Latent heat transferred in first effect}
h_steam0= enthalpy(water,x=0,P=P_steam)
```

```
E_thermal = h_steamx                    {thermal energy consumption in kJ/kg. for PR calculations}

Q_steam = F_[1]*C_p[1]*(T_b[1] - T_f[1]) + D_[1]*h_v[1]    {D_[1] is total distillate from E1 : formed only
by boiling!}
m_v[1] = D_[1]

{Salt Balance for E 1}
F_[1]*X_sw = B_[1]*X_bt[1]
X_bt[1] = 70 [g/kg]                                {Constraint for the first effect max salinity}

X_bt[1]=X_b[1]; m_b[1]=B_[1]

{Total heating source from each effect}
duplicate j=1,n
D_h[j]= D_[j] + m_f[j]
end

{Preheaters from 1 n-1}
duplicate k=1,n-1
F_ph[k] * C_p[k]*(T_f[k] - T_f[k+1])= Y_[k]*D_h[k]*h_v[k]          {Y_[k] is the fraction of latent heat used
in preheating. Found in the areas calculation}
(1 - Y_[k]) * h_v[k] = h_eh[k]
end

{Effects 2 to n energy, mass and salt balance}
duplicate i=2,n
F_[i] + B_[i-1]= D_[i] + B_[i]
F_[i]=m_v[i] + m_b[i]
D_[i]=m_v[i] + m_vb[i]
B_[i]=m_br[i] + m_b[i]

D_h[i-1]*h_eh[i-1]=F_[i]*C_p[i]*(T_b[i] - T_f[i]) + m_v[i]*h_v[i]

m_vb[i]= Beta_[i] * B_[i-1]                 {m_vb[i] is the fraction of B_[i-1] that flashes in effect i}
m_vb[i]= B_[i-1]*C_px[i-1]*(T_b[i-1] - T_b[i])/h_v[i]

F_[i]*X_sw + B_[i-1]*X_bt[i-1] = m_br[i]*X_br[i] + m_b[i]*X_b[i]     {X_bt is the salinity of the total Brine
leaving the effect, X_br is salinty for m_br which is the non-flashed brine}
F_[i]*X_sw = m_b[i]*X_b[i]
B_[i]*X_bt[i] = m_br[i]*X_br[i] + m_b[i]*X_b[i]
end

{FLASH BOX #2}
D_[1] = m_c[2] + m_f[2]
m_f[2]= ((D_[1])* C_p[1] * (T_v[1] - T_v[2]))/h_v[2]

{FLASH BOX 3 to n}
duplicate i=3,n
D_h[i-1] + m_c[i-1] = m_c[i] + m_f[i]
m_f[i]= ((D_h[i-1]+m_c[i-1])* C_p[i-1] * (T_v[i-1] - T_v[i]))/h_v[i]
end
m_f[1] = 0 [kg/s]

{MAIN RESULTS}
```

```
D_total = sum(D_[i],i=1,n)
D_total = Distillate/3.6
GOR = D_total/m_steam
RR = D_total/Feed
h_ref = 2330 [kJ/kg]                                    {Specific enthalpy of steam at 71.2 C}
PR= GOR*h_ref/(E_thermal)
Th_specific = Q_req/Distillate                          {Units kWh/m3}
B_reject= B_[n]
B_reject§= B_[n]*3.6                                    {Brine reject in m3/h}

{Effects and Preheaters Areas}
{EFFECT 1}
F_[1]*C_p[1]*(T_b[1] - T_f[1]) + D_[1]*h_v[1]    = U_e_[1] * A_[1] * (T_steam - TBT)
U_e_[1] = 1.9695 + (1.2057*10^(-2))*TBT - (8.5989*10^(-5))*(TBT^2) + (2.5651*10^(-7))*(TBT^3)
A_[1]= nt_[1] * A_t
n_[1]=ceil(nt_[1])

{EFFECT 2-n Areas}
duplicate i=2,n
F_[i]*C_p[i]*(T_b[i] - T_f[i]) + m_v[i]*h_v[i] = U_e_[i] * A_[i] * LMTD_[i]
LMTD_[i] = T_v[i-1] - T_b[i]
U_e_[i]= 1.9695 + (1.2057*10^(-2))*T_b[i] - (8.5989*10^(-5))*(T_b[i])^2 + (2.5651*10^(-7))*(T_b[i])^3
A_[i]= nt_[i] * A_t
n_[i]=ceil(nt_[i])
end

{Preheaters 1-n-1}
duplicate i=1,n-1
Y_[i] * D_h[i] * h_v[i] = U_ph_[i] * AP_[i] * LMTD§_[i]
LMTD§_[i] = ((T_v[i]-T_f[i]) - (T_v[i]-T_f[i+1]))/ln((T_v[i]-T_f[i])/(T_v[i]-T_f[i+1]))
U_ph_[i] = 1.7194 + (3.2063*10^(-3))*T_v[i] + (1.5971*10^(-5))*(T_v[i]^2) - (1.9918*10^(-7))*(T_v[i]^3)
Ap_[i]= ntp_[i] * A_t
np_[i]=ceil(ntp_[i])
end

A_t= pi*d_t*L_t
d_t = 0.0254/3 [m]
L_t = 0.5 [m]


{Pumping Power}
W_dot_sw=(P_x * Feed)/(Rho_sw*eta_pump)                                {Seawater/Feed pump}
P_x = 400 [kPa]
W_dot_br=(P_x * B_[n])/(Rho_sw*eta_pump)                               {Brine disposal pump}
W_dot_p=(P_x * D_total)/(Rho_p*eta_pump)                               {Product}
Rho_p=Density(Water,T=T_v[n],P=P_x)
W_dot_c=(P_steam*convert(bar,kPa) * m_steam)/(Rho_steam§*eta_pump)     {Condensate pump}
Rho_steam§ = Density(Steam,T=T_cond,x=0)
Rho_sw = SW_Density(T_sw,X_sw)

W_dot_MED = (W_dot_sw + W_dot_br + W_dot_p + W_dot_c + W_dot_fan)

SPC = (W_dot_sw + W_dot_br + W_dot_p+W_dot_c+W_dot_fan)/Distillate     {MED only SPC}
```

```
{Air-cooled condensor}
DELTAH= Enthalpy_vaporization(Water,T=T_v[n])
Q_cond = D_[n] * DELTAH
T_o = T_v[n] - 2
T_in = 41.5 [C]
omega = 0.26
Q_cond = m_dot_air * Cp_air * (T_o - T_in)
Cp_air=Cp(AirH2O,T=T_in,r=omega,P=1[bar])

CALL ACC (omega,T_in, m_dot_air,Q_cond : W_dot_fan)

Q_cond = U_cond * A_cond * LMTD_cond
U_cond = 0.71 [kW/m^2-C]
LMTD_cond = ((T_v[n] - T_in) - (T_v[n] - T_o) )/ (ln((T_v[n] - T_in)/(T_v[n] - T_o)))
```

LCA Model: Flow diagram and GaBi data used

The following figure shows the calculation process in the LCA model; starting with input data (from the literature sources and the EES model) to the life-cycle inventory and ending with the environmental impact results and their interpretation.

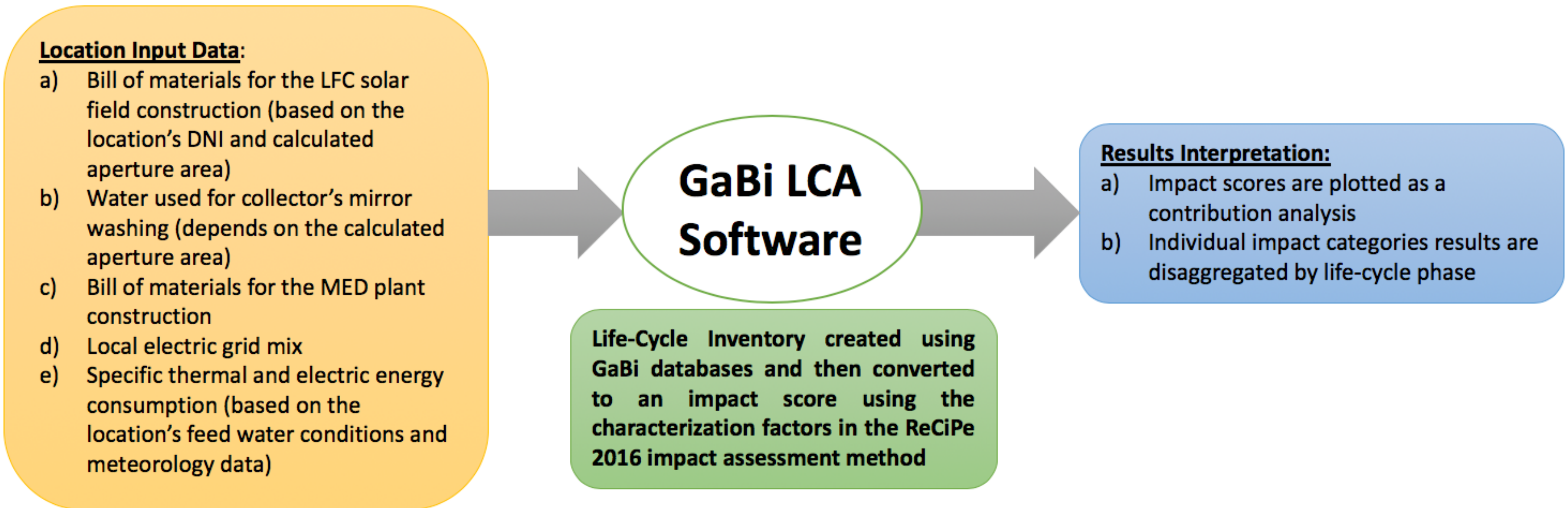

Figure 3. LCA process flow diagram.

The life-cycle inventory (LCI) is created in GaBi using its local databases for various materials and products (which includes extraction, processing, and manufacturing) and also for several energy processes. GaBi then converts the LCI into a specific impact score through two steps:

a) Classification: The LCI data is assigned into the life-cycle impact categories.
b) Characterization: The classified LCI is converted into a mid-point impact category score using the ReCiPe 2016 characterization factors (Huijbregts *et al* 2016).

Table 6 shows the materials and energy processes used in GaBi for this LCA study to model the construction and operation phases of the solar MED plant.

Table 6. Materials and processes used in the LCA study and their equivalent in the LCA tool GaBi.

Material/Process	GaBi Equivalent	Description
	Solar Field Construction	
Mirrors	Process: Float flat glass EU	Cradle-to-gate inventory
Steel	Process: Stainless steel slab DE	Cradle-to-gate inventory
Steel pipes	Process: Stainless steel drinking water pipe DE	Cradle-to-gate inventory
Borosilicate glass	Process: Borosilicate glass production EU	Cradle-to-gate inventory
Fibre glass wool	Process: Glass wool EU	Cradle-to-gate inventory
Concrete	Process: Concrete C12/15 (Ready-mix concrete) EU	Cradle-to-gate inventory
Aluminum pipes	Process: PEXc-Al-PEXc pipe production DE	Cradle-to-gate inventory
	Solar Field Operation	
Solar thermal energy	Process: Credit Thermal Energy GLO	Cradle-to-gate inventory
Electric pumping energy	City dependent	Cradle-to-gate inventory
	MED Plant Construction	
Steel	Process: Stainless steel slab DE	Cradle-to-gate inventory
	MED Plant Operation	
Electric pumping energy	City dependent	Cradle-to-gate inventory
Cleaning acid (HCl 30%)	Process: Hydrochloric acid (32%) DE	Cradle-to-gate inventory
Anti-foaming agent	Process: Antifoaming agent (ethoxylate fatty alcohols) GLO	Cradle-to-gate inventory
Sodium Hypochlorite solution	Process: Sodium hypochlorite solution U.S	Cradle-to-gate inventory
Sodium Bi-sulfite	Process: Sodium hydrogen sulfite (from NaOH and SO2) U.S	Cradle-to-gate inventory
Anti-scalants (H2SO4)	Process: Sulphuric acid EU	Cradle-to-gate inventory
Remineralization (CaOH)	Process: Calcium hydroxide DE	Cradle-to-gate inventory

Disinfection (Sodium hypochlorite)	Process: Sodium hypochlorite solution U.S	Cradle-to-gate inventory

For most process, the GaBi equivalent was based on data for the European Union, and in cases where EU data in not available, data from Germany (DE), United States (U.S), or the global average (GLO) was used. Most of the data required for the LCA were located in GaBi's local databases with the exception of some components in the construction phase; namely the anti-reflex coating. It is expected that this will not significantly affect the final results due to the small amount of this coating. Most of the data in Gabi's local databases is derived from literature sources for the respective region that are cited in each dataset's description which can be accessed here: http://www.gabi-software.com/international/databases/gabi-data-search/. Furthermore, GaBi's databases provides detailed notes on the data quality indicators, data validity, and data review process.

Calculation Steps

Given the above data, the calculation steps in this study are show in **Figure 4**.

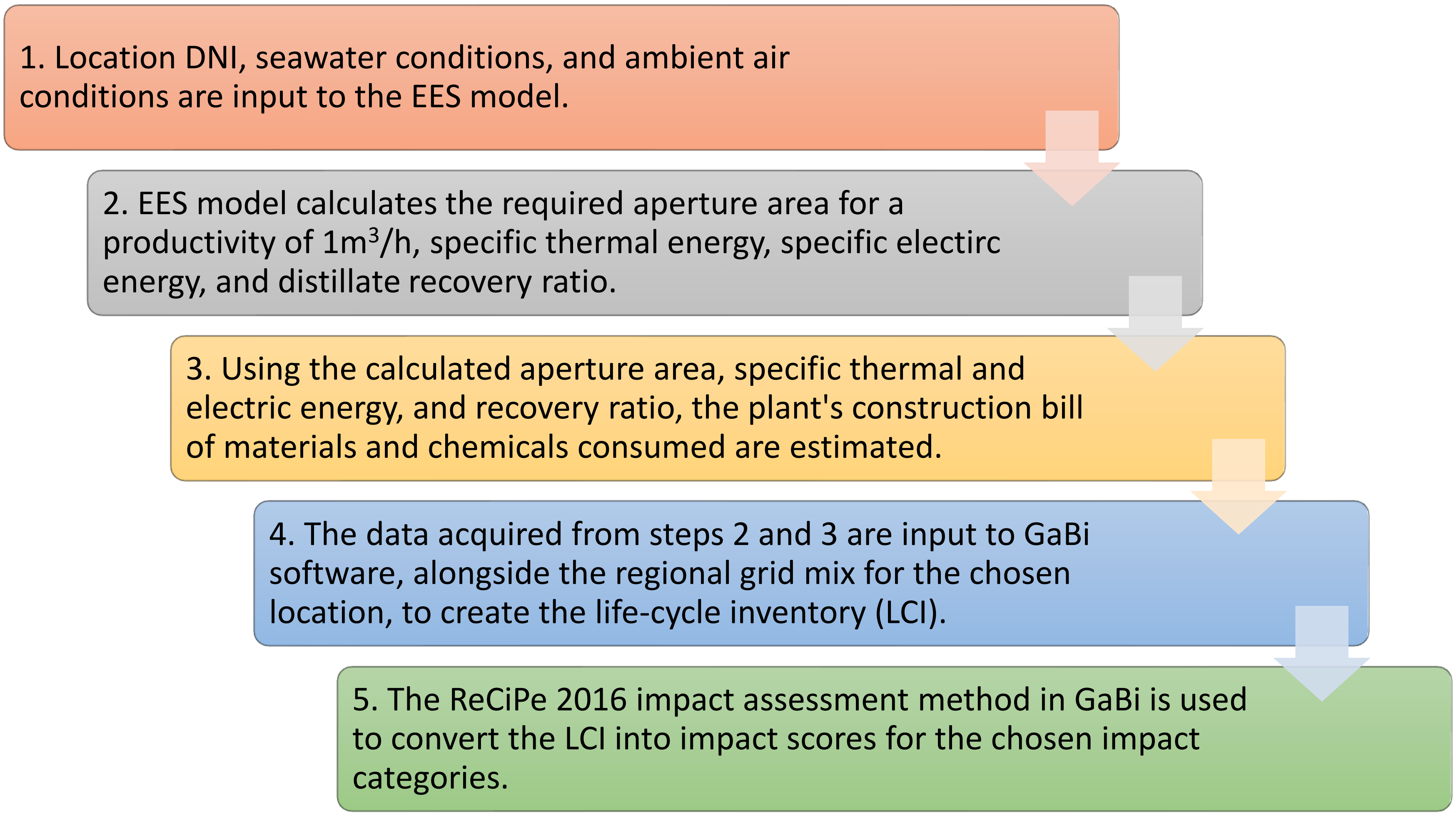

Figure 4. Calculation steps in this study.

The specific input data for all locations are given in **Table 7**.

Table 7. Specific material, energy, and chemicals used for each city in the LCA model.

	Kuwait, Kuwait	Algeria, Algeria	Abu Dhabi, UAE	Torrevieja, Spain	Carlsbad, US	Sydney, Australia	Escandida, Chile
Solar Field							
Mirrors (kg)	961.4	761.4	918.5	953.9	891.5	1038.0	723.8
Total steel in solar field (kg)	2946.7	2333.9	2815.4	2923.7	2732.4	3181.7	2218.7
Borosilicate glass (kg)	77.9	61.7	74.5	77.3	72.3	84.1	58.7
Fibre glass wool (kg)	13.5	10.7	12.9	13.4	12.5	14.5	10.1
Concrete (m^3)	0.1	0.047	0.1	0.1	0.1	0.1	0.04
Aluminum Pipes (kg)	7.7	6.1	7.3	7.6	7.1	8.3	5.8
HTF (Water) (kg)	202.0	160.0	193.0	200.4	187.3	218.1	152.1
Cleaning Water (m^3)	103.60	82.05	98.98	102.79	96.07	111.86	78.00
Chemicals							
Cleaning acid (HCl 30%) consumed (kg)	32.76	23.25	32.76	23.25	17.96	17.96	17.96
Anti-foaming (substance unknown)(kg)	35.87	25.45	35.87	25.45	19.67	19.67	19.67
Sodium Hypochlorite solution (kg)	700.85	497.38	700.85	497.38	384.34	384.34	384.34
Sodium Bi-sulfite (kg)	87.61	62.17	87.61	62.17	48.04	48.04	48.04
Anti-scalants (H2SO4) (kg)	525.64	373.03	525.64	373.03	288.25	288.25	288.25
Remineralization (CaOH) (kg/m^3 distillate)	28.26	28.26	28.26	28.26	28.26	28.26	28.26
Disinfection (Sodium hypochlorite) (kg)	28.26	28.26	28.26	28.26	28.26	28.26	28.26
Parameters calculated in EES model							
Aperture area (m^2)	127.9	101.3	122.2	126.9	118.6	138.1	96.3

Feed (m^3/h)	3.1	2.2	3.1	2.2	1.7	1.7	1.7
Brine (m^3/h)	2.1	1.2	2.1	1.2	0.7	0.7	0.7
Distillate (m^3/h)	1	1	1	1	1	1	1
Specific electric energy (kWh/m^3)	7.9	7.8	6.8	4	2.8	2.7	1.5
Specific thermal energy (kWh/m^3)	73.5	73.8	72.8	71.1	73.3	73.3	73.3
Distillate recovery ratio	0.32	0.45	0.33	0.46	0.58	0.58	0.58

LCA Results Tables

Table 8. LCA Results for Kuwait City, Kuwait.

Climate Change	Impact	Impact per m^3	Units	Contribution (%)
Solar Field Construction	1.30E+04	0.23	kg CO_2 eq./m^3	2.61
Solar Field Operation	9.67E+04	1.71	kg CO_2 eq./m^3	19.45
MED Construction	4.10E+03	0.07	kg CO_2 eq./m^3	0.82
MED Operation	3.81E+05	6.74	kg CO_2 eq./m^3	76.62
Pretreatment	2.33E+03	0.04	kg CO_2 eq./m^3	0.47
Post treatment	9.89E+01	0.00	kg CO_2 eq./m^3	0.02
Total	4.97E+05	8.80	kg CO_2 eq./m^3	

Water Depletion	Impact	Impact per m^3	Units	Contribution (%)
Solar Field Construction	2.64E+02	0.00	m^3/m^3	0.62
Solar Field Operation	9.40E+03	0.17	m^3/m^3	22.09
MED Construction	5.45E+01	0.00	m^3/m^3	0.13
MED Operation	3.24E+04	0.57	m^3/m^3	76.13
Pretreatment	4.41E+02	0.01	m^3/m^3	1.04
Post treatment	2.00E+00	0.00	m^3/m^3	0.00
Total	4.26E+04	0.75	m^3/m^3	

Fossil Depletion	Impact	Impact per m^3	Units	Contribution (%)
Solar Field Construction	3.60E+03	0.06	kg oil eq./m^3	2.14
Solar Field Operation	3.65E+04	0.65	kg oil eq./m^3	21.72
MED Construction	1.12E+03	0.02	kg oil eq./m^3	0.67
MED Operation	1.26E+05	2.23	kg oil eq./m^3	74.97
Pretreatment	825	0.01	kg oil eq./m^3	0.49
Post treatment	27.9	0.00	kg oil eq./m^3	0.02
Total	1.68E+05	2.97	kg oil eq./m^3	

Table 9. LCA Results for Algeria, Algeria.

Climate Change	Impact	Impact per m^3	Units	Contribution (%)
Solar Field Construction	1.07E+04	0.19	kg CO_2 eq./m^3	2.77
Solar Field Operation	7.55E+04	1.34	kg CO_2 eq./m^3	19.57
MED Construction	4.10E+03	0.07	kg CO_2 eq./m^3	1.06
MED Operation	2.93E+05	5.18	kg CO_2 eq./m^3	75.95
Pretreatment	2.33E+03	0.04	kg CO_2 eq./m^3	0.60
Post treatment	1.64E+02	0.00	kg CO_2 eq./m^3	0.04
Total	3.86E+05	6.83	kg CO_2 eq./m^3	

Water Depletion	Impact	Impact per m^3	Units	Contribution (%)
Solar Field Construction	2.15E+02	0.00	m^3/m^3	0.37
Solar Field Operation	8.66E+03	0.15	m^3/m^3	14.91
MED Construction	5.45E+01	0.00	m^3/m^3	0.09
MED Operation	4.86E+04	0.86	m^3/m^3	83.65
Pretreatment	5.67E+02	0.01	m^3/m^3	0.98
Post treatment	3.37E+00	0.00	m^3/m^3	0.01
Total	5.81E+04	1.03	m^3/m^3	

Fossil Depletion	Impact	Impact per m^3	Units	Contribution (%)
Solar Field Construction	2.97E+03	0.05	kg oil eq./m^3	1.44
Solar Field Operation	3.04E+04	0.54	kg oil eq./m^3	14.73
MED Construction	1.12E+03	0.02	kg oil eq./m^3	0.54
MED Operation	1.71E+05	3.03	kg oil eq./m^3	82.86
Pretreatment	825	0.01	kg oil eq./m^3	0.40
Post treatment	46.1	0.00	kg oil eq./m^3	0.02
Total	2.06E+05	3.65	kg oil eq./m^3	

Table 10. LCA Results for Abu Dhabi, UAE.

Climate Change	**Impact**	**Impact per m^3**	**Units**	**Contribution (%)**
Solar Field Construction	1.25E+04	0.22	kg CO_2 eq./m^3	4.64
Solar Field Operation	6.31E+04	1.12	kg CO_2 eq./m^3	23.45
MED Construction	4.10E+03	0.07	kg CO_2 eq./m^3	1.52
MED Operation	1.87E+05	3.31	kg CO_2 eq./m^3	69.48
Pretreatment	2.33E+03	0.04	kg CO_2 eq./m^3	0.87
Post treatment	9.56E+01	0.00	kg CO_2 eq./m^3	0.04
Total	2.69E+05	4.76	kg CO_2 eq./m^3	

Water Depletion	**Impact**	**Impact per m^3**	**Units**	**Contribution (%)**
Solar Field Construction	2.53E+02	0.00	m^3/m^3	0.49
Solar Field Operation	1.27E+04	0.22	m^3/m^3	24.83
MED Construction	5.45E+01	0.00	m^3/m^3	0.11
MED Operation	3.77E+04	0.67	m^3/m^3	73.70
Pretreatment	4.41E+02	0.01	m^3/m^3	0.86
Post treatment	1.97E+00	0.00	m^3/m^3	0.00
Total	5.12E+04	0.90	m^3/m^3	

Fossil Depletion	**Impact**	**Impact per m^3**	**Units**	**Contribution (%)**
Solar Field Construction	3.46E+03	0.06	kg oil eq./m^3	2.90
Solar Field Operation	2.86E+04	0.51	kg oil eq./m^3	24.01
MED Construction	1.12E+03	0.02	kg oil eq./m^3	0.94
MED Operation	8.51E+04	1.51	kg oil eq./m^3	71.43
Pretreatment	825	0.01	kg oil eq./m^3	0.69
Post treatment	27	0.00	kg oil eq./m^3	0.02
Total	119132	2.11	kg oil eq./m^3	

Table 11. LCA Results for Torrevieja, Spain.

Climate Change	Impact	Impact per m^3	Units	Contribution (%)
Solar Field Construction	1.29E+04	0.23	kg CO_2 eq./m^3	10.92
Solar Field Operation	2.93E+04	0.52	kg CO_2 eq./m^3	24.81
MED Construction	4.10E+03	0.07	kg CO_2 eq./m^3	3.47
MED Operation	6.93E+04	1.23	kg CO_2 eq./m^3	58.68
Pretreatment	2.33E+03	0.04	kg CO_2 eq./m^3	1.97
Post treatment	1.63E+02	0.00	kg CO_2 eq./m^3	0.14
Total	1.18E+05	2.09	kg CO_2 eq./m^3	

Water Depletion	Impact	Impact per m^3	Units	Contribution (%)
Solar Field Construction	2.62E+02	0.00	m^3/m^3	7.29
Solar Field Operation	8.85E+02	0.02	m^3/m^3	24.64
MED Construction	5.45E+01	0.00	m^3/m^3	1.52
MED Operation	1.82E+03	0.03	m^3/m^3	50.67
Pretreatment	5.67E+02	0.01	m^3/m^3	15.79
Post treatment	3.35E+00	0.00	m^3/m^3	0.09
Total	3.59E+03	0.06	m^3/m^3	

Fossil Depletion	Impact	Impact per m^3	Units	Contribution (%)
Solar Field Construction	3.57E+03	0.06	kg oil eq./m^3	10.28
Solar Field Operation	8.68E+03	0.15	kg oil eq./m^3	24.98
MED Construction	1.12E+03	0.02	kg oil eq./m^3	3.22
MED Operation	2.05E+04	0.36	kg oil eq./m^3	59.01
Pretreatment	825	0.01	kg oil eq./m^3	2.37
Post treatment	45.9	0.00	kg oil eq./m^3	0.13
Total	34740.9	0.61	kg oil eq./m^3	

Table 12. LCA Results for Carlsbad San Diego CA, U.S.

Climate Change	**Impact**	**Impact per m^3**	**Units**	**Contribution (%)**
Solar Field Construction	1.22E+04	0.22	kg CO_2 eq./m^3	11.50
Solar Field Operation	3.20E+04	0.57	kg CO_2 eq./m^3	30.18
MED Construction	4.10E+03	0.07	kg CO_2 eq./m^3	3.87
MED Operation	5.52E+04	0.98	kg CO_2 eq./m^3	52.06
Pretreatment	2.33E+03	0.04	kg CO_2 eq./m^3	2.20
Post treatment	2.11E+02	0.00	kg CO_2 eq./m^3	0.20
Total	1.06E+05	1.88	kg CO_2 eq./m^3	

Water Depletion	**Impact**	**Impact per m^3**	**Units**	**Contribution (%)**
Solar Field Construction	2.47E+02	0.00	m^3/m^3	7.71
Solar Field Operation	8.15E+02	0.01	m^3/m^3	25.43
MED Construction	5.45E+01	0.00	m^3/m^3	1.70
MED Operation	1.39E+03	0.02	m^3/m^3	43.37
Pretreatment	6.94E+02	0.01	m^3/m^3	21.65
Post treatment	4.35E+00	0.00	m^3/m^3	0.14
Total	3.20E+03	0.06	m^3/m^3	

Fossil Depletion	**Impact**	**Impact per m^3**	**Units**	**Contribution (%)**
Solar Field Construction	3.38E+03	0.06	kg oil eq./m^3	11.10
Solar Field Operation	3.87E+03	0.07	kg oil eq./m^3	12.71
MED Construction	1.12E+03	0.02	kg oil eq./m^3	3.68
MED Operation	2.12E+04	0.38	kg oil eq./m^3	69.61
Pretreatment	825	0.01	kg oil eq./m^3	2.71
Post treatment	59.6	0.00	kg oil eq./m^3	0.20
Total	30454.6	0.54	kg oil eq./m^3	

Table 13 .LCA Results for Sydney, Australia.

Climate Change	Impact	Impact per m^3	Units	Contribution (%)
Solar Field Construction	1.38E+04	0.24	kg CO_2 eq./m^3	6.00
Solar Field Operation	9.17E+04	1.62	kg CO_2 eq./m^3	39.84
MED Construction	4.10E+03	0.07	kg CO_2 eq./m^3	1.78
MED Operation	1.18E+05	2.09	kg CO_2 eq./m^3	51.27
Pretreatment	2.33E+03	0.04	kg CO_2 eq./m^3	1.01
Post treatment	2.12E+02	0.00	kg CO_2 eq./m^3	0.09
Total	2.30E+05	4.07	kg CO_2 eq./m^3	

Water Depletion	Impact	Impact per m^3	Units	Contribution (%)
Solar Field Construction	2.83E+02	0.01	m^3/m^3	10.84
Solar Field Operation	6.88E+02	0.01	m^3/m^3	26.36
MED Construction	5.45E+01	0.00	m^3/m^3	2.09
MED Operation	8.86E+02	0.02	m^3/m^3	33.95
Pretreatment	6.94E+02	0.01	m^3/m^3	26.59
Post treatment	4.36E+00	0.00	m^3/m^3	0.17
Total	2.61E+03	0.05	m^3/m^3	

Fossil Depletion	Impact	Impact per m^3	Units	Contribution (%)
Solar Field Construction	3.84E+03	0.07	kg oil eq./m^3	6.12
Solar Field Operation	2.49E+04	0.44	kg oil eq./m^3	39.68
MED Construction	1.12E+03	0.02	kg oil eq./m^3	1.79
MED Operation	3.20E+04	0.57	kg oil eq./m^3	51.00
Pretreatment	825	0.01	kg oil eq./m^3	1.31
Post treatment	59.7	0.00	kg oil eq./m^3	0.10
Total	62744.7	1.11	kg oil eq./m^3	

Table 14. LCA Results for Escandida, Chile.

Climate Change	Impact	Impact per m^3	Units	Contribution (%)
Solar Field Construction	1.02E+04	0.18	kg CO_2 eq./m^3	9.99
Solar Field Operation	1.83E+04	0.32	kg CO_2 eq./m^3	17.92
MED Construction	4.10E+03	0.07	kg CO_2 eq./m^3	4.01
MED Operation	6.70E+04	1.19	kg CO_2 eq./m^3	65.59
Pretreatment	2.33E+03	0.04	kg CO_2 eq./m^3	2.28
Post treatment	2.12E+02	0.00	kg CO_2 eq./m^3	0.21
Total	1.02E+05	1.81	kg CO_2 eq./m^3	

Water Depletion	Impact	Impact per m^3	Units	Contribution (%)
Solar Field Construction	2.05E+02	0.00	m^3/m^3	7.81
Solar Field Operation	4.26E+02	0.01	m^3/m^3	16.24
MED Construction	5.45E+01	0.00	m^3/m^3	2.08
MED Operation	1.24E+03	0.02	m^3/m^3	47.26
Pretreatment	6.94E+02	0.01	m^3/m^3	26.45
Post treatment	4.36E+00	0.00	m^3/m^3	0.17
Total	2.62E+03	0.05	m^3/m^3	

Fossil Depletion	Impact	Impact per m^3	Units	Contribution (%)
Solar Field Construction	2.85E+03	0.05	kg oil eq./m^3	9.78
Solar Field Operation	5.20E+03	0.09	kg oil eq./m^3	17.84
MED Construction	1.12E+03	0.02	kg oil eq./m^3	3.84
MED Operation	1.91E+04	0.34	kg oil eq./m^3	65.51
Pretreatment	825	0.01	kg oil eq./m^3	2.83
Post treatment	59.8	0.00	kg oil eq./m^3	0.21
Total	29154.8	0.52	kg oil eq./m^3	

Data quality index and estimation of basic uncertainty

The data quality index shown in Table 4 in the manuscript is based on the pedigree matrix method proposed by (Weidema and Wesnæs 1996) which is given in **Table 15**. The basic uncertainty refers to the standard deviation of the measured data or the deviation of the modelled data from the physical system. This value was only found for the annual average DNI and the energy flows from the EES model.

Table 15. Pedigree matrix for estimating the data quality indices.

Indicator score	1	2	3	4	5
Reliability	Verified[a] data based on measurements[b]	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on assumptions	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate
Completeness	Representative data from a sufficient sample of sites over an adequate period to even out normal fluctuations	Representative data from a smaller number of sites but for adequate periods	Representative data from an adequate number of sites but from shorter periods	Representative data but from a smaller number of sites and shorter periods or incomplete data from an adequate number of sites and periods	Representativeness unknown or incomplete data from a smaller number of sites and/or from shorter periods
Temporal correlation	Less than three years of difference to year of study	Less than six years difference	Less than 10 years difference	Less than 15 years difference	Age of data unknown or more than 15 years of difference
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown area or area with very different production conditions
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials but same technology	Data on related processes or materials but different technology

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