Scientific and Technological Alliance for
Guaranteeing the European Excellence in
Concentrating Solar Thermal Energy

FP7 Grant Agreement number: **609837**
Start date of project: **01/02/2014**
Duration of project: **48 months**

Project Deliverable 10.5:

Final report on Concentrating Solar Thermal Energy and Desalination

WP10 – Task 10.3	**Deliverable 10.5**
Due date:	**January 2018**
Submitted	**January 2018**
Partner responsible	**CIEMAT**
Person responsible	**Diego-César Alarcón-Padilla**
Author(s):	**WP10 Project Partners**
Document version:	**1**
Reviewed/supervised by:	
Dissemination Level	**PU**

Table of contents

1. Introduction

This deliverable results from WP 10 "STE plus desalination", which is part of the Research and Technological Development activities of STAGE-STE project. The main objective of this WP aims to answer the basic question about under which conditions a solar thermal cogeneration scheme can be more feasible than the separate production of power by a STE plant and the use of such power to run a desalination process.

One of the tasks of this WP is the economic assessment of different STE+D configurations in different locations. This deliverable presents the results of such analysis which has been carried out for two specific geographical locations chosen as representative of different regions with widespread development of CSP plants and an increasing water deficit planned to be mitigated with desalination: Almería, in Spain, and Abu Dhabi, in United Arab Emirates. The analysis has been carried out for the following STE+D configurations:

- Low Temperature Multi-Effect Distillation (LT-MED) plant integrated into a Concentrating Solar Power plant using parabolic trough collector technology (PT-CSP): Configuration #1

- Multi-effect Distillation with Thermal Vapour Compression (MED-TVC) plant integrated into a PT-CSP plant: Configuration #2

- Reverse Osmosis (RO) plant connected to a PT-CSP plant: Configuration #3

In Configuration #1, the desalination plant is coupled to the PT-CSP plant by using the exhaust steam from the turbine as the thermal energy source for the desalination plant (the steam leaves the turbine at the temperature required by the desalination plant), which allows the replacement of the conventional power-cycle condenser. In Configuration #2, the steam expands completely in the turbine until it reaches the permitted value for the condenser conditions. The integration takes place through part of the steam extracted from the turbine that is used as high-pressure steam for the steam ejector of the MED-TVC plant. Finally, Configuration #3 is a basic combination of a RO plant with a PT-CSP plant, in which the electricity generated by the PT-CSP plant is used to feed the high-pressure pump that pumps the seawater through the RO plant membranes producing desalinated water. In Configurations #2 and #3, evaporative cooling method has been considered for the condensation of the exhaust steam.

2. Description of the configurations

2.1. Configuration #1

The integration of an LT-MED plant into a PT-CSP plant is an attractive prospect as it allows for the replacement of the CSP refrigeration system by utilising the exhaust steam from the turbine as a thermal energy source in the desalination process. In this way, energy that would otherwise be dissipated through the power-cycle refrigeration system is used for freshwater production, which converts into an added value for the combined system. However, in this case, the exhaust steam exits at a slightly higher pressure than in the other configurations analysed since it is used to feed the LT-MED plant at 70 °C. This means a drop in the power-cycle efficiency. A further shortcoming of this configuration is that the desalination plant needs to be situated as close to the turbine as possible since the exhaust steam has a high specific volume and, consequently, large diameter pipe is necessary to drive the steam to the desalination plant. This means situating the plant near the coast where there is generally less direct solar radiation.

Figure 1 shows a flow diagram of this configuration's process.

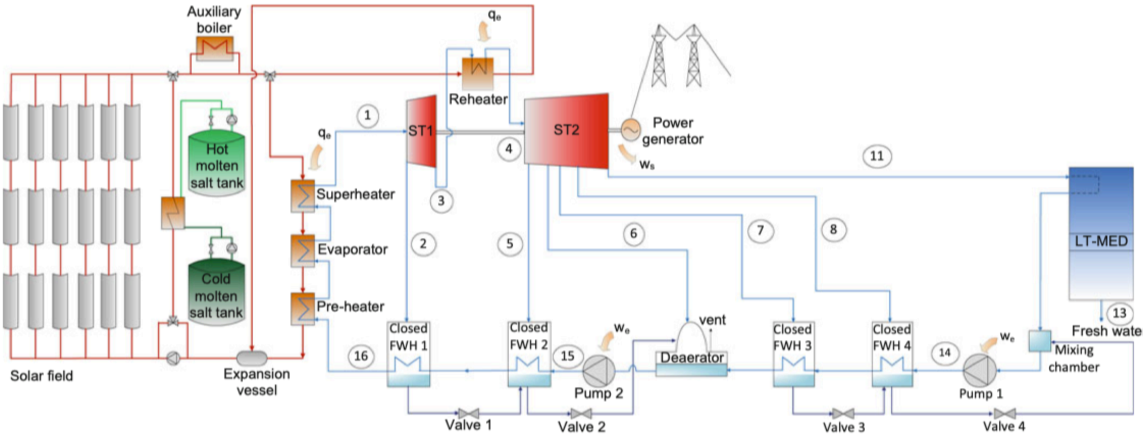


Figure 1. Flow diagram of an LT-MED plant integrated into a PT-CSP plant

2.2. Configuration #2

This configuration is of great interest because, unlike the previous case, the desalination process does not have to follow the load of the power cycle due to the presence of the PT-CSP plant condenser. Furthermore, an additional advantage is that the condensation of the exhaust steam does not depend on the desalination plant operation, which can be a problem in the case of a desalination plant failure.

Regarding the distillation unit, the MED-TVC plant has a higher Gained Output Ratio (GOR) than LT-MED plants since less thermal energy is required to produce the same amount of freshwater (part of the steam generated in one of the MED plant effects is recovered). Moreover, the need for refrigeration in these plants is less than in LT-MED plants given that part of the steam produced in the desalination process is extracted for use in the thermocompressor as entrained vapour and, therefore, less seawater volume is required to condense the steam produced in the final effect of the MED plant.

In Figure 2, a flow diagram of this configuration is shown.

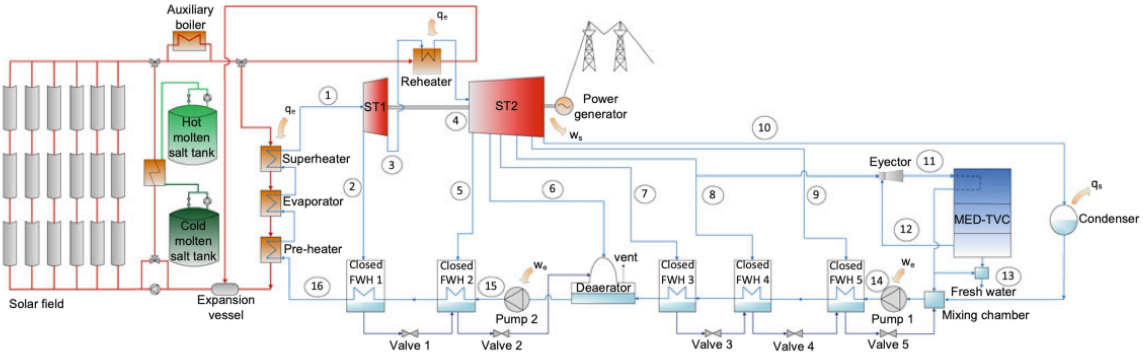


Figure 2. Flow diagram of a MED-TVC plant integrated into a PT-CSP plant using steam extracted from the low-pressure turbine (ST2) as motive steam.

2.3. Configuration #3

This configuration has the advantage over previous configurations of being able to completely separate the desalination process from the electricity-generation process, including geographically. In this case, there are no losses in electricity generation due to modifications in the power cycle, as there are in the previous cases. However, the refrigeration requirements are greater when compared to Configuration 1 (where the need for refrigeration is eliminated completely) and with respect to Configurations 2 (in which part of the cycle steam is used as motive steam in the thermocompressor) since all the steam that leaves the turbine is condensed through the power-plant condenser.

In Figure 3, the diagram of the process flow for this configuration is shown.

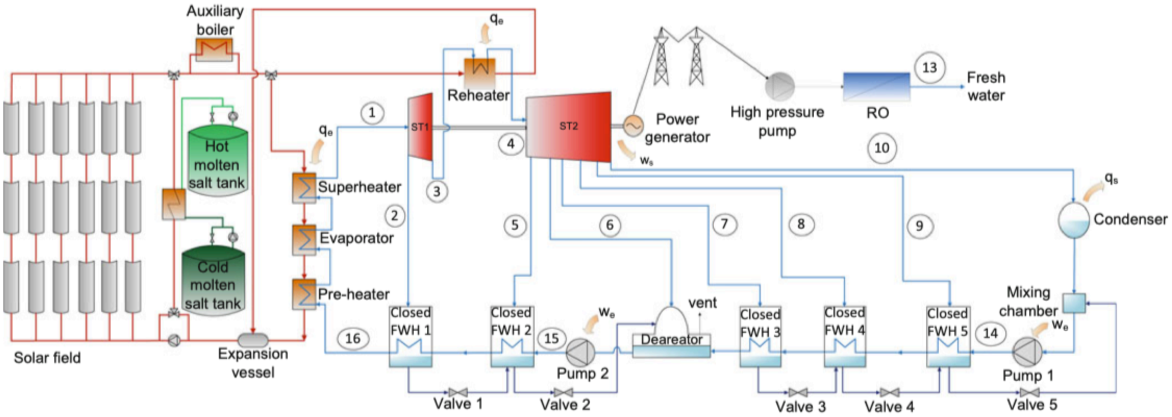


Figure 3. Flow diagram of an RO plant connected to a PT-CSP plant

3. Economic analysis

As already mentioned above, two specific geographical locations have been chosen as representative of different regions with widespread development of CSP plants and an increasing water deficit, planned to be mitigated with desalination: Almería, in Spain, and Abu Dhabi, in the United Arab Emirates. As already shown in Deliverable 10.4, Almería account with a direct normal irradiation (DNI) value around 1990 kWh/m^2·year and Abu Dhabi with a DNI of roughly 1925 kWh/m^2·year [1].

Firstly, the integrated cycle (composed by the power block and the integrated desalination plant), P&D cycle of each configuration is solved in order to find the total thermal power required to accordingly size the corresponding solar field. The solving of the P&D requires the selection of reference day or design point. This day is selected in order that avoids a large difference between summer and winter was chosen. If the design point was chosen in summer, the resulting solar field size would be too small to deliver the required thermal power for the power block during winter, when consequently it would work at partial load. On the contrary, if the design point was chosen in winter, the larger solar field resulting would be costlier and deliver more thermal power than needed in the summer. Taking these considerations into account, the design point chosen for the present study was the 21st of September at solar noon for both locations. For each location, radiation and ambient temperature data have been taken from a typical meteorological year using the software Meteonorm. In the particular case of Abu

Dhabi, Meteonorm DNI profiles have been used but normalized with the real measurement of the annual average of the DNI given above (1925 kWh/m^2·year). The input variables of solar irradiance and those corresponding to meteorological values of interest at this point are shown in Table 1.

Table 1. Ambient conditions at 21st September solar noon for Abu Dhabi and Almería

Location	Ambient Temperature (ºC)	Direct normal irradiance (W/m^2)	Relative Humidity (%)
Abu Dhabi	37.1	853	47
Almería	27.1	884	43

The solving of the P&D cycle is carried out by the iterative calculation showed in Figure 4. From the exhaust steam temperature and from the cooling system selected the procedure consists on an iterative calculation of the sizes of the steam turbine and the desalination plant. The former was calculated to meet the required net power generation at design conditions. The latter was determined to satisfy the net fresh water production as outlined by the computational simulation of Configuration #1, where all the steam from the turbine must be condensed in the desalination unit and this establishes the fresh water production according to the thermal efficiency of the distillation plant. The iteration was required since the internal electricity consumption of the various plant components and the fresh water consumed internally in the power plant are dependent on the gross capacities of the CSP and the desalination plant, which are still not known at the beginning of the calculation. Both, the power cycle and the desalination plants were modelled using the models shown in previous Deliverables and implemented in Engineering Equation Solver (EES) software environment.

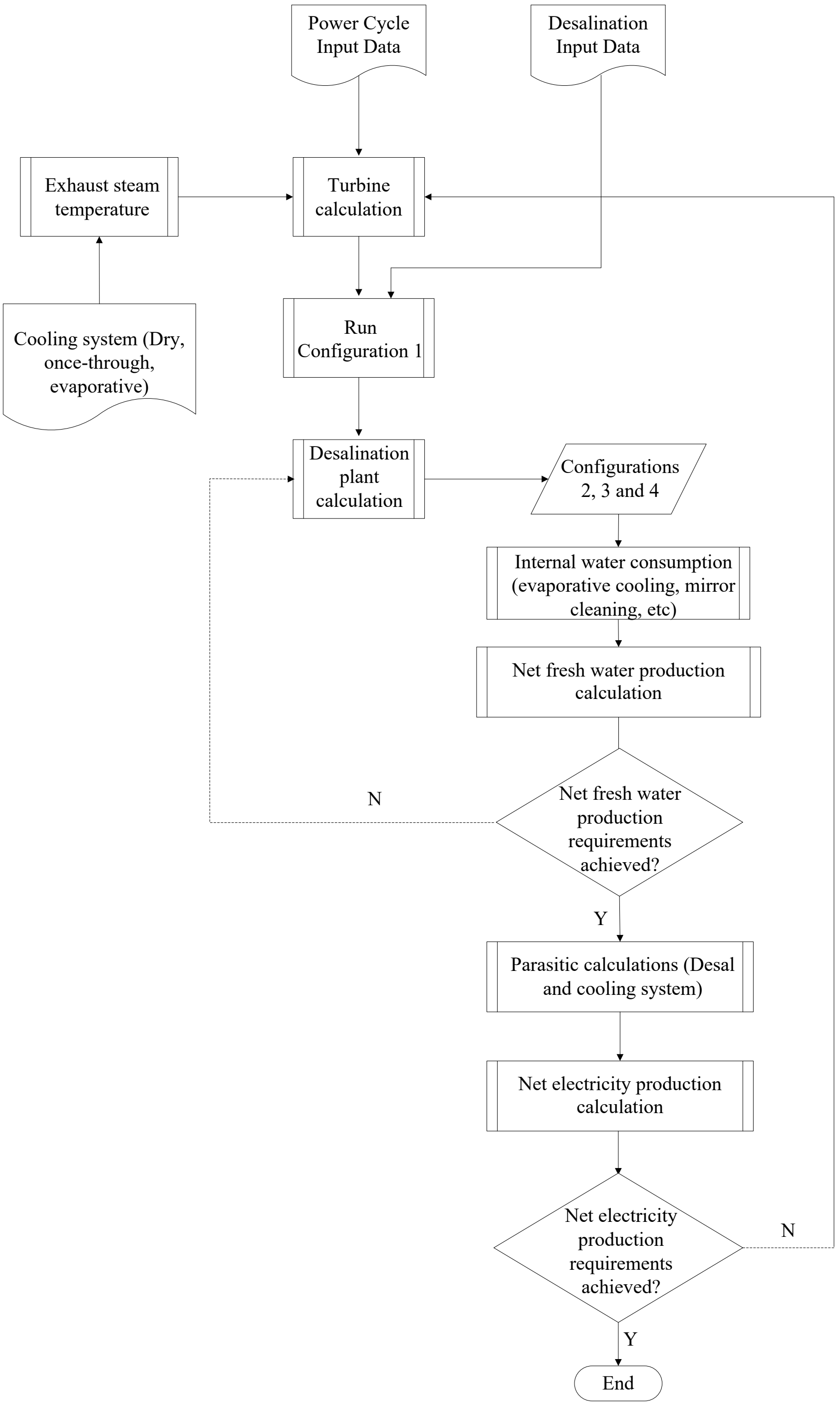


Figure 4. Flow diagram for P&D calculation procedure

As already mentioned, the cooling method selected for Configurations #2 and #3 was evaporative cooling. The cooling method together with the ambient conditions of the location establishes the steam condensation temperature (i.e. the steam temperature at the outlet of the turbine). In this one, the condensation temperature is determined by the sum of wet bulb temperature and three different factors: the tower approach (the difference between the cooling tower outlet and the wet bulb temperature), the cooling tower range (the difference between the cooling tower inlet and the cooling tower outlet) and the difference between the inlet and outlet temperature in the condenser. The data of these three factors were taken from Andasol-1 plant [2]: 7 °C, 8 °C and 3 °C respectively. As comparison, in dry cooling, the temperature differential in the aero-condenser would be around 22 ºC, based on the average values from a report disseminated by the U.S. Department of Energy [3]. The resulting condensation temperature at point 10 in Configurations #2 and #3 and #4 were 37 ºC for Almería and 45 ºC for Abu Dhabi.

The net power production of the PT-CSP plant was considered 50 MW_e in all configurations, which is the normal size of a commercial PT-CSP plant [4]. The rest of the input variables corresponding to the operating conditions used for the simulation of P&D cycle are shown in Table 2. As already explained, the calculation was firstly performed for Configuration #1. In addition to the fresh water production, the GOR associated to this production was obtained from the computational simulation of the first configuration. The number of effects of the MED plant was set according to the seawater temperature of each location. For the location of Almería, a 14-effect MED plant was selected whereas an 11-effect MED plant was considered in the case of Abu Dhabi. The resulting GOR of the 11-effect LT-MED and 14-effect LT-MED plants was 8.4 and 10, respectively, and 10 and 12 for the 11-effect TVC-MED and 14-effect TVC-MED plants, respectively. The net fresh water production obtained in Configuration #1 was 35607 m^3/day for the location of Abu Dhabi, and 42927 m^3/day for the location of Almería.

Table 2. Operation conditions set for the thermodynamic simulation of the systems shown in Figure 1-Figure 3

Point in the diagram	Parameters	Values
1	Temperature and Pressure	373 °C, 100 bar
2	Pressure	33.5 bar
3	Pressure	18.5 bar
4	Temperature and Pressure	373.4 °C, 16.5 bar
5	Pressure	14 bar
6	Pressure	6.18 bar
7	Pressure	3.04 bar
8	Pressure	1.17 bar[a]
9	Pressure	0.37 bar
11	Pressure	0.3121 bar
12	Pressure	0.1817 bar
14	Pressure	8.38 bar
15	Pressure	103 bar

[a] *Vapor for the fourth extraction is used since the lower the motive steam pressure is, the lower the penalty in the overall efficiency of the power cycle is. A lower value would be very close to that one that is used to feed the LT-MED unit.*

[c] *The entrained vapor is taken from an intermediate effect of the MED plant*

For calculating the power required by the desalination plant, a specific electric consumption of 1.5 kWh/m^3 of distillate production was assumed in the case of the MED plant for both locations [5]. For the RO, a value of 3 kWh/m^3 was chosen for Almería, and 4 kWh/m^3 for Abu Dhabi due to the different conditions of salinity and temperature of the raw seawater [5]. The power consumptions described above only refer to the internal consumptions of the desalinations processes, so they do not take into account the pumping of feedwater from the sea to the desalination plants neither the cooling seawater pumping for the condenser of the MED plant. These latter power consumptions were calculated assuming that the desalination plants are located close to the CSP plant at an altitude of 150 m above the sea level and a distance from the sea of about 60 km. This assumption is based on the commercial CSP located closest to the sea (Shams 1 in Abu Dhabi), and in order to avoid the problems of lower DNI and the conditions of saline environment that could damage the parabolic-trough mirrors.

Once the P&D cycle was solved, the solar field size was determined considering the total thermal power by the P&D cycle. The collectors are Eurotrough type with the following dimensions and characteristics: aperture area of 817.5 m^2, 150 m total gross length, and a peak optical efficiency of 80 %. The heat transfer fluid that circulates through the absorber tubes of the collectors is thermal oil, namely Monsanto VP-1, whose maximum operational temperature is 400 ºC.

With all these data (thermal power required by the P&D cycle, solar field size, GOR of the LT-MED and MED-TVC plants), the economic analysis is performed. For this purpose, an economic model has been developed and implemented in Excel tool. It consists in the calculation of the electricity and water costs of the proposed configurations. The following definition of Levelized Electricity Cost (LEC) was used [6]:

Equation 1

$$LEC = \frac{crf \times K_{invest} + K_{O\&M} + K_{fuel}}{E_{net}}$$

where K_{invest} is the total investment of the plant, $K_{O\&M}$ are the annual operation and maintenance costs, K_{fuel} is the annual fuel cost (which is only applicable in the case of solar energy with backup), E_{net} is the annual net electricity delivered to the grid and crf is the capital recovery factor, which is calculated from:

Equation 2

$$crf = \frac{k_d(1 + k_d)^n}{(1 + k_d)^n - 1} + K_{insurance}$$

being k_d (6.5%) the real debt interest rate, n is the depreciation period in years (20 years) and $K_{insurance}$ is the annual insurance rate (1%).

A similar procedure was used for the Levelized Water Cost (LWC) estimation.

Table 3 shows the values used for the input variables, which were based on published data by NREL [7] and personal communication from CSP experts [8]. As shown in the table, it was established a thermal energy storage size of 6.5 hours for all the configurations.

Table 3. Economic values for the calculation of *LEC* and *LWC*

	Values
Hours thermal energy storage	6.5 hours
Plant availability (power and desalination plants)	96%
Land preparation and infrastructure	$15\ \$/\mathrm{m}^2$
Solar collector	$150\ \$/\mathrm{m}^2$
Heat transfer fluid and hydraulic circuit	$90\ \$/\mathrm{m}^2$
Thermal storage system	$35\ \$/\mathrm{kW_{th}h}$
Power block	$1{,}000{,}000\ \$/\mathrm{MW_{gross}}$
Auxiliary gas burner	$60\ \$/\mathrm{kW_{th}}$
Reverse Osmosis plant	$1207\ \$/(\mathrm{m}^3/\mathrm{day})^*$
Multi-effect Distillation plant	$1230\ \$/(\mathrm{m}^3/\mathrm{day})^*$

*[9] IDA, 2013

3.1. Parametric analysis

Taking the results from the previous economic analysis as the base case, a parametric analysis changing the hours of thermal energy storage and the GOR of the MED plants (in the case of Configurations #1 and #2) has been performed to find the effect in the costs (LEC and LWC). The variation of the hours of thermal energy storage and GOR is as follows:

- Hours of thermal energy storage: 6.5 (base case), 8.5, 10.5, 12.5, 14.5, keeping a GOR of the LT-MED plant and MED-TVC as in the base case (8.4 and 10 for the LT-MED located in Abu Dhabi and Almería, respectively; and 10 and 12 for the MED-TVC plant located in Abu Dhabi and Almería, respectively).
- GOR LT-MED plant: 10 (base case), 12, 14, 16 and 18 in the location of Almería, and 8.4 (base case), 10.4, 12.4, 14.4 and 16.4 in the location of Abu Dhabi. In all cases, the hours of thermal energy storage were kept as in the base case (6.5 hours).
- GOR MED-TVC plant: 12 (base case), 14, 16, 18 and 20 in the location of Almería, and 10 (base case), 12, 14, 16 and 18 in the location of Abu Dhabi. In all cases, the hours of thermal energy storage were kept as in the base case (6.5 hours).

4. Results

4.1. Base case

The results of the simulations of the P&D cycle, the solar field and the economic analysis for the base case in each configuration are shown in Table 4 and Table 5. It shows the thermal power required by the P&D cycle (given by $\boldsymbol{P_{th}}$), the global efficiency of the P&D cycle ($\boldsymbol{\eta_{th}}$), the gross power ($\boldsymbol{P_{gross}}$) and fresh water production ($\boldsymbol{M_{d,gross}}$), the size of the solar field ($\boldsymbol{A_a}$) and the levelized electric and water costs ($\boldsymbol{LEC}$) and the levelized water cost ($\boldsymbol{LWC}$).

The results obtained for Abu Dhabi (Table 4) show that the integration of a LT-MED into a CSP plant was the most efficient option thermodynamically. The reduction in the power cycle efficiency resulting from preventing the expansion of the exhaust steam to a lower pressure (Configuration #1) was smaller than that due to using high pressure steam from the turbine to feed the steam ejector (Configurations #2). With respect to the economic results, Configuration #1 was also more favourable for all cases in terms of electricity costs (LEC) due mainly to the extra power that the CSP must generate for the cooling system in the rest of configurations. As seen in Table 4, a gross power of 62.95 MW_e must be produced in the case of Configuration #3 against 55.36 MW_e that should be produced in Configuration #1. This means an increase of about 5% in the LEC. In the case of water costs (LWC) the results obtained for Configuration #1 were very similar to those obtained for Configuration #3. Although the investment costs of RO are lower, the evaporative cooling method requires a higher gross fresh water production which makes the RO plant larger (11% larger). Although the good results obtained for Configuration #1, the CSP industry is reluctant to fully eliminate the condenser of the power cycle, so Configuration #2 could be the alternative option. This configuration offers the possibility of a better adaptation to the yearly electricity and water demand curves. As seen in Deliverable 10.4, the steam ejector can be connected to the steam extraction selected according to the power and fresh water demands. The difference in LEC and LWC between Configurations #2 and #3 is not that large (7% and 3%, respectively) and might not be a strong enough reason for choosing Configuration #3, especially considering the further challenges that RO desalination can have in the Arabian Gulf, such as red algae blooms and problems derived from the high seawater salinity.

Table 4. Results obtained from the techno-economic analysis in Abu Dhabi

	Units	Conf #1	Conf #2	Conf #3
η_{th}	[-]	30.41	26.33	29.65
P_{th}	MW_{th}	164	190	169
$M_{d,gross}$	m^3/day	35950	40016	40448
P_{gross}	MW_e	55.36	57.05	62.95
A_a	m^2	807690	935220	830580
LEC	c€/kWh	16.58	18.76	17.40
LWC	€/m^3	0.83	0.91	0.88

In the case of Almería (Table 5), the ambient conditions allow the exhaust steam to expand to lower pressures (37ºC in the steam condensation temperature against 47ºC). This improvement in the power generation efficiency compensates the extra power consumed by the condenser and the higher electricity consumption by the RO in Configuration #3 with respect to the LT-MED (the overall efficiency of the latter was 30.02% against 30.85% of the former). The difference with respect to electricity costs was negligible in this case (0.3%) and the $\boldsymbol{LWC}$ were slightly more favourable for the case of LT-MED (the RO plant was 9% larger to supply the additional fresh water needed in the evaporative tower). At these lower steam outlet pressures, Configurations #2 was also more strongly penalized with respect to Configuration #2. Therefore, it seems more realistic for the Mediterranean basin to opt for the combination of CSP with RO. However, for cooling systems other than the evaporative cooling, Configuration with MED could be contemplated as an option. Improvements in the investment cost or the efficiency of the LT-MED could help counterbalance this scenario.

Table 5. Results obtained from the techno-economic analysis in Almería

	Units	Conf #1	Conf #2	Conf #3
η_{th}	[-]	30.02	26.27	30.85
P_{th}	MW_{th}	167	190	162
$M_{d,gross}$	m^3/day	43,274	47,380	47,723
P_{gross}	MW_e	56.08	57.62	62.42
A_a	m^2	752,100	860,010	732,480
LEC	c€/kWh	18.73	20.95	18.79
LWC	€/m^3	0.96	1.05	1.01

4.2. Parametric analysis

4.2.1. Hours of thermal storage

4.2.1.1. Configuration #1

Table 6 and Table 7 show the variation of LEC and LWC against the variation of the number of hours of thermal energy storage (HTS) for Almería and Abu Dhabi, respectively. The deviation (in %) of these cost parameters with respect the base case is also shown. As can be seen, the water costs are not affected by the variation in the number of HTS since the freshwater production is not further modified. In the case of the electricity costs, the LEC slightly increases the higher the HTS in both locations, being larger in the case of Almería. Such increase is not that high in the case of a thermal storage with 6.5 and 8.5 hours but become significant for a higher HTS, achieving an increase of 12-13% if a storage system of 14.5 h is considered in the STE plant.

Table 6. Effect of the variation in the number of hours of thermal storage on the LEC and LWC. Location: Almería

Hours thermal storage (h)	LEC (c€/kWh)	LWC (c€/m^3)	Deviation_LEC (%)	Deviation_LWC (%)
6.5	18.73	0.96	0	0
8.5	19.33	0.96	-3.20	0
10.5	19.94	0.96	-6.46	0
12.5	20.54	0.96	-9.66	0
14.5	21.14	0.96	-12.87	0

Table 7. Effect of the variation in the number of hours of thermal storage on the LEC and LWC. Location: Abu Dhabi

Hours thermal storage (h)	LEC (c€/kWh)	LWC (c€/m^3)	Deviation_LEC (%)	Deviation_LWC (%)
6.5	16.58	0.83	0	0
8.5	17.08	0.83	-3.02	0
10.5	17.58	0.83	-6.03	0
12.5	18.08	0.83	-9.05	0
14.5	18.58	0.83	-12.06	0

4.2.1.2. Configuration #2

Table 8 and Table 9 show the variation of LEC and LWC against the variation of the number of hours of thermal energy storage for Almería and Abu Dhabi, respectively. The deviation (in %) of these cost parameters with respect the base case is also shown. The results are very similar to those of Configuration #1 for both locations, with a slight difference in the increase of the electricity costs that become a bit larger than those of Configuration #1.

Table 8. Effect of the variation in the number of hours of thermal storage on the LEC and LWC. Location: Almería

Hours thermal storage (h)	LEC (c€/kWh)	LWC (c€/m^3)	Deviation_LEC (%)	Deviation_LWC (%)
6.5	20.95	1.05	0	0
8.5	21.64	1.05	-3.29	0
10.5	22.33	1.05	-6.59	0
12.5	23.01	1.05	-9.83	0
14.5	23.7	1.05	-13.13	0

Table 9. Effect of the variation in the number of hours of thermal storage on the LEC and LWC. Location: Abu Dhabi

Hours thermal storage (h)	LEC (c€/kWh)	LWC (c€/m^3)	Deviation_LEC (%)	Deviation_LWC (%)
6.5	18.76	0.91	0	0
8.5	19.34	0.91	-3.09	0
10.5	19.92	0.91	-6.18	0
12.5	20.5	0.91	-9.28	0
14.5	21.08	0.91	-12.37	0

4.2.1.3. Configuration #3

Table 10 and Table 11 show the variation of LEC and LWC against the variation of the number of hours of thermal energy storage for Almería and Abu Dhabi, respectively. The deviation (in %) of these cost parameters with respect the base case is also shown. As in the previous case, the results obtained in terms of electricity costs were similar. Just to highlight that for this configuration, the increase obtained in the LEC for the location of Abu Dhabi was the lowest one between the three configurations.

Table 10. Effect of the variation in the number of hours of thermal storage on the LEC and LWC. Location: Almería

Hours thermal storage (h)	LEC (c€/kWh)	LWC (c€/m^3)	Deviation_LEC (%)	Deviation_LWC (%)
6.5	18.79	1.01	0	0
8.5	19.38	1.01	-3.14	0
10.5	19.96	1.01	-6.23	0
12.5	20.55	1.01	-9.37	0
14.5	21.13	1.01	-12.45	0

Table 11. Effect of the variation in the number of hours of thermal storage on the LEC and LWC. Location: Abu Dhabi

Hours thermal storage (h)	LEC (c€/kWh)	LWC (c€/m^3)	Deviation_LEC (%)	Deviation_LWC (%)
6.5	17.40	0.88	0	0
8.5	17.92	0.88	-2.99	0
10.5	18.43	0.88	-5.92	0
12.5	18.95	0.88	-8.91	0
14.5	19.46	0.88	-11.84	0

4.2.2. Gain Output Ratio

4.2.2.1. Configuration #1

Table 12 and Table 13 show the variation of LEC and LWC against the variation of the GOR of the LT-MED plant for Almería and Abu Dhabi, respectively. The deviation (in %) of these cost parameters with respect the base case is also shown. As can be seen, the electricity costs slightly increase the higher the GOR, from 2 to 7%, for both locations. The rise in the LEC is due to the increase in the fresh water production with the GOR, which makes the turbine to require more vapour to keep the fixed net electricity production of 50 MW$_e$. In the case of the water costs, they show a slight decrease, especially for high GOR when the LWC decreased up to 2-2.4%.

Table 12. Effect of the variation in the GOR of the LT-MED plant on the LEC and LWC. Location: Almería

GOR	LEC (c€/kWh)	LWC (c€/m^3)	Deviation_LEC (%)	Deviation_LWC (%)
10	18.73	0.96	0	0
12	19.04	0.96	-1.66	0
14	19.36	0.95	-3.36	1.04
16	19.63	0.95	-4.81	1.04
18	19.95	0.94	-6.51	2.08

Table 13. Effect of the variation in the GOR of the LT-MED plant on the LEC and LWC. Location: Abu Dhabi

GOR	LEC (c€/kWh)	LWC (c€/m^3)	Deviation_LEC (%)	Deviation_LWC (%)
8.4	16.58	0.83	0	0
10.4	16.89	0.82	-1.87	1.20
12.4	17.16	0.82	-3.50	1.20
14.4	17.43	0.81	-5.13	2.41
16.4	17.69	0.81	-6.69	2.41

4.2.2.2. Configuration #2

Table 14 and Table 15 show the variation of LEC and LWC against the variation of the GOR of the LT-MED plant for Almería and Abu Dhabi, respectively. The deviation (in %) of these cost parameters with respect the base case is also shown. In this case, the increase of the LEC was a bit higher (up to roughly 8%) but the decrease obtained in the LWC was quite more significant than in Configuration #1, up to 6%. Therefore, depending on water price of the location, the increase in GOR in STE+D configuration with MED-TVC could compensate the increase in LEC.

Table 14. Effect of the variation in the GOR of the MED-TVC plant on the LEC and LWC. Location: Almería

GOR	LEC (c€/kWh)	LWC (c€/m^3)	Deviation_LEC (%)	Deviation_LWC (%)
12	20.95	1.05	0	0
14	21.34	1.03	-1.86	1.90
16	21.74	1.01	-3.77	3.81
18	22.13	1.00	-5.63	4.76
20	22.57	0.99	-7.73	5.71

Table 15. Effect of the variation in the GOR of the MED-TVC plant on the LEC and LWC. Location: Abu Dhabi

GOR	LEC (c€/kWh)	LWC (c€/m^3)	Deviation_LEC (%)	Deviation_LWC (%)
10	18.76	0.91	0	0
12	19.14	0.89	-2.03	2.20
14	19.47	0.87	-3.78	4.40
16	19.85	0.86	-5.81	5.49
18	20.23	0.85	-7.84	6.59

5. How to increase competitiveness of solar thermal cogeneration processes

An evident conclusion of the analysis performed was that thermal distillation technologies need to increase their energy efficiency (thermal and electrical) and reduce also their specific investment costs. During STAGE-STE Project it has been reported the different research activities carried out by different WP10 partner with such target.

In order to increase the thermal efficiency of the MED processes there are two options: to increase the top brine temperature (TBT) of the process allowing to increase the number of effects and consequently the energy efficiency of the process. In this regard the coupling of membrane processes like nanofiltration or forward osmosis as pretreatment of the MED feedwater can allow to remove the bivalent salts and increase the current limitation of the TBT above the 70ºC. The other option in the coupling of a heat pump to the thermal distillation plant. Several WP10 have reported their works above the use of thermocompressors and absorption heat pumps for that purpose.

To reduce the specific investment cost of MED technology the use of cheaper materials for the heat exchange surfaces is another research line developed by WP10. CIEMAT and CEA have reported within STAGE-STE their works in the development and experimental assessment of polymeric heat exchangers for MED plants.

5.1. Development of polymer evapo-condensers for MED desalination (CEA)

5.1.1. Introduction

If the idea to use polymers to make heat exchangers is not new - the first developments date back to 1965 by DuPont - their use is not widespread because of their low thermal conductivity, their poor mechanical resistance and ageing under stressing conditions. However, their low cost, their excellent behaviour to corrosion and fouling and their easiness to be transformed into various shapes make them very attractive. The SolMED technology under development is based on multi-effect distillation (MED) to ensure an excellent thermal efficiency and flexibility to load variations. The use of very thin flexible tubes made of polymer make possible a good heat transfer rate and brings the advantages of this materials family. Coupling this technology with a solar heat source or a low temperature thermal waste allows to save fossil fuel and do not release additional CO_2. All these advantages make that SolMED is a sea water desalination technology with a low environmental impact. This meets recommendations of international organizations editing desalination roadmaps. The targeted market is related to rather small desalination units, from 500 to 1 000 m^3/d.

5.1.2. Technical challenge

Considering plastic processing, manufacturing long tubes having a thickness of only 50 microns and matching with very strict specifications requires to develop a process and tools experienced in blow extrusion. Parts dedicated to keep the tubes circular and in vertical position while many other functions must be ensured have to be designed. The impact of this disruptive technology on the techno-economic optimization of the full desalination process must be totally modeled. Beside the distillation process, this model must include economic data, as a minimized water cost is currently the main optimization criterion. Environmental balance considering CO_2 emission saving and blow-down content in terms of concentration and flux have also to be taken into account. To facilitate evaluations and comparisons, the same model is developed for metallic reference units. Finally, a significant scale prototype has been constructed. A five effects unit able to produce 9 m^3/d was retained, an electric boiler simulates a sunny day energy profile or an available thermal load, at variable temperature or power.

5.1.3. Main results

A techno-economic model has been finalized to size MED units using polymers and for the reference case of metallic tubes. In addition to distillation aspects, it includes an evaluation of environmental impact, an exergetic balance and a funding model. So, three independent criteria are available for the optimization: economic, environmental and exergetic. An industrial design study addressing different constraints - economic and integration in a landscape - completes the impact limitation of SolMED. Lastly, coupling this model with a solar heat source model including a heat storage option has been completed.

A first generation of tubes made of polymer and their fixing parts matching with the defined specifications have been realized and validated. These specifications are related to the dimensional characteristics, thermal and mechanical properties, life time, and surface properties governing the tube wettability. All the required functions of the fixing parts is ensured.

Thermal measurements using a single polymer tube have allowed to determine transfer laws during evapo-condensation process and refine the model.

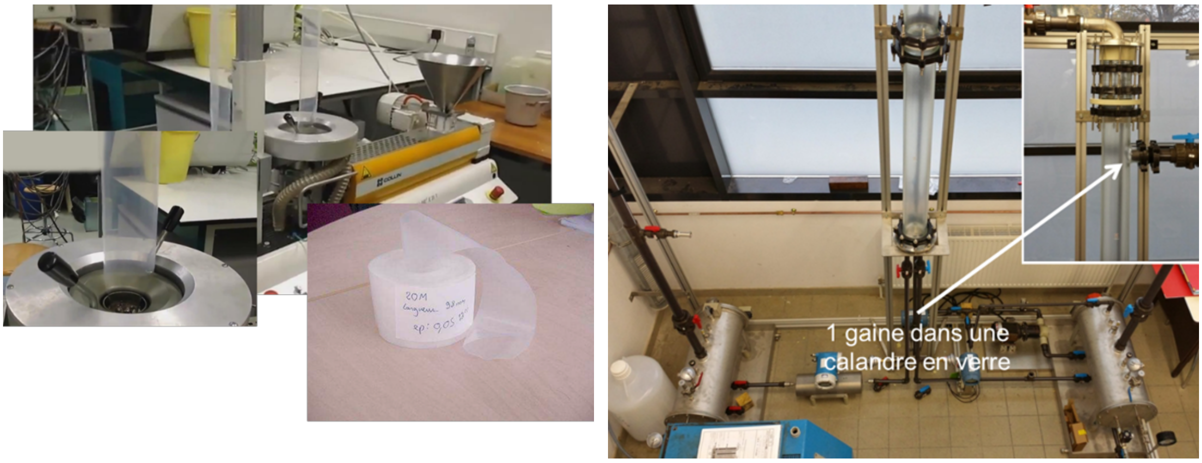
A prototype composed of five effects for a daily capacity of 9 m^3 has been constructed to materialize a proof of concept.

5.1.4. On-going activities and future works

Hydraulic design of the prototype is under modification to decrease pumping power and increase thermal efficiency. A second generation of tube would be developed to improve their lifetime and decrease maintenance cost. This can be achieved by the use of a filler in the polymer matrix or crosslinking the material.

Overview of SolMED prototype

Bottom view of the four plastic evaporators



Tube manufacturing by blow extrusion

Set-up for heat transfer characterization

Figure 5. Different views of SolMED prototype

5.2. Assessment of high performance heat conducting polymer tubes (CIEMAT)

5.2.1. Introduction

It is well known that thermal desalination puts high demands on corrosion resistant materials and requires expensive metals or alloys. Furthermore, the price of these materials is highly volatile, leading to risks in calculation. Polymers are a real alternative that bring a lot of advantages especially in highly corrosive environments like high salt concentration as they do not show corrosion at all. However, standard polymers have poor heat conducting properties that would lead to a huge increase of the required heat exchange surface making this option unprofitable.

Technoform Kunststoffprofile, specialist in the extrusion of reinforced technical plastics, dealt with this problem and developed a thermally conductive compound. This is based on polymers with a high amount of thermal conductive filler. This compound is processed by extrusion to form heat exchanger profiles in any shape that can deliver the required properties in terms of corrosion resistance and heat transfer. Additionally, previous tests conducted on tubes in a Multiple Effect Desalination (MED) simulation test rig at the University of Bremen showed an exceptionally lower scale formation rate of up to 89% less than metal. It is therefore apparent that polymer tubes offer totally new opportunities in terms of scale resistance resulting in lower operating and maintenance costs as well as the ability to use elevated evaporation temperatures meaning an increase in performance. Furthermore, the compound withstands even highest salt concentrations with ease allowing it to be used for higher concentrated brine. These points can to lead to a breakthrough in thermal desalination.

5.2.2. Development

The focus of research was concentrated on the two most promising polymer grades for most heat exchanger applications. The first was Polypropylene (PP) which has a very good chemical resistance and a confirmed long term operating temperature of 80°C. The second was the high-performance polymer Polyphenylene Sulfide (PPS) which also has also outstanding chemical resistance and is predestinated for a higher temperature level of up to 200°C. For the use in MED seawater desalination the PP based material meets all requirements at an attractive price.

These polymers are used in many standard applications, but still miss the thermal conductivity. To change this, these materials have to be blended with a heat conducting filler material. As the most suitable material for this task, graphite was identified because of its high thermal conductivity, lightweight, price, food save/nontoxic, low wear on processing equipment and most of all its chemically inert character making it indifferent to corrosion. But graphite, due to its plate like structure, brings along a high degree of anisotropy of its thermally conducting properties. It has conductivity values of about 10-15 W/m K across the plane direction and values of up to 400 W/m K in plane direction. Therefore, a special extrusion technology is advantageous in order to align the graphite particles in the polymer melt not only in flow direction, as usual in standard extrusion, but to align a high degree of particles in transversal direction enabling to form a heat conducting path through the polymer compound tube wall. Additionally, the high degree of filler with 50% in volume (=73%weigth for PP) can only be processed in the special Technoform extrusion technology.

5.2.3. Concept of a full polymer stage

For field testing an existing pilot 14 stage MED Plant (SOL-14 at CIEMAT-Plataforma Solar Almería) was selected by Technoform to exchange one metallic tube bundle by a polymer based. The tube bundle is replaced by new combination of material. In order to evaluate the concept for a full plastic stage, tube sheets, support plate, tie rods and header made of polymer are used in in this field test. In order to test elevated temperatures and to reduce thermal expansion as well as creep phenomena a robust polymer was selected. Polyoxymethylene (POM) is a robust thermoplastic with low creep tendency and low water absorption. Polyphenylene sulphide with 40% short glass fiber reinforcement (PPS-GF40) has very good mechanical properties at 100°C and even above. For this prototype, the components are manufactured out of combination of available plate material in POM and extruded tension rods of PPSGF40 to reduce thermal elongation. For a possible future series production of small to medium sized parts the injection molding process is a feasible and economical way of production. This allows to form ready to use tube sheets, baffles or support plates out of the injection molding machine. This brings along a lot of cost saving potential since there is no need for expensive machining like milling and drilling to the required shape as long as the amount of produced parts justifies the invest for an injection molding tool.

Figure 6. Assembled full polymer tube bundle manufactured by Technoform

5.2.4. Main results

An experimental campaign in undergoing and it is expected to publish the first results by the third quarter of 2018.

References

[1] Goebel, O., 2010. Shams one 100 MW CSP plant in Abu Dhabi. Update on projects status. Proc. Expanding CSP research frontier: Challenges to be addressed by Combined Solar Power and Desalination plants. Perpignan, France, Proc. of the 16th SolarPaces Symposium, September, 21-24.

[2] Blanco-Marigorta, A.M. et al., 2011. Exergetic comparison of two different cooling technologies for the power cycle of a thermal power plant. Energy 36, 1966-1972.

[3] US DoE, 2009. Concentrating solar power commercial application study: reducing water consumption of concentrating solar power electricity generation.

[4] Geyer M. et al., 2006. Dispatchable solar electricity for summerly peak loads from the solar thermal projects Andasol-1 & Andasol-2. In: Proc. of 13th SolarPACES Symposium, Sevilla, Spain.

[5] Trieb F., 2007. Concentrating solar power for seawater desalination, Aqua-CSP Study report, German Aerospace Center.

[6] Short, W., Packey, D.J., Holt, T., 1995. A manual for the economic evaluation of energy efficiency and renewable energy technologies. NREL/TP-462-5173.

[7] NREL, 2010. https://sam.nrel.gov/cost.

[8] Zarza. Personal communication.

[9] IDA, 2013. Global Water Intelligence and International Desalination Association. IDA Desalination Yearbook 2012-2013. Water Desalination Report.