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A flexible techno-economic model for the assessment of desalination plants driven by renewable energies

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ABSTRACT

One of the major difficulties in the assessment of costs of desalination projects is that key investment parameters and operation-related parameters are project-specific data. This information is commonly not in the public domain and is generally available only to the general contractor. In addition, the interpretation of published data is complicated by the fact that often plant boundaries are not clearly indicated (e.g. if the intake cost and the pipeline cost to and from the plant are included in the evaluation). Finally, the analysis involves an elevate number of design parameters, such as plant capacity and configuration, metal and other material prices, and very site-specific conditions (seawater quality, feed water intake, and brine discharge). In the end, these issues result in difficult comparability of data from different sources about the cost of the desalinated water. This paper deals with the implementation of a flexible techno-economic model for the assessment of desalination plants on system analysis level. Thereby, the focus is given to units driven by different technologies (conventional steam turbines and concentrating solar power). The model is applied in a case study in order to evaluate and compare the performance and the costs of different desalination technologies (multiple effect distillation and reverse osmosis). Finally, a sensitivity analysis of the results with respect to selected key design parameters is carried out.

Keywords: Techno-economic model; Renewable desalination; MED; MED-TVC; RO; Concentrating solar power (CSP); PV; Wind power; Technology comparison

1. Introduction

The calculation of levelized water cost (LWC) is a commonly used approach for comparing desalination plants, whereas the term “levelized” means that the sum of fixed and variable annual costs is divided by the total annual water production. The typical unit of LWC is (€/m^3) or ($/m^3). Nevertheless, before LWC is used as a mean for comparison, a number of specifications have to be given. In particular, following issues should be critically questioned:

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- Plant boundaries: are intake, brine discharge, drinking water supply pipelines and auxiliary infrastructure included in the economic calculation? Depending on the selected desalination technology, intake and brine discharge cost may account for approx. 10% up to 20% of the total capital expenditures (CAPEX).
- Plant capacity: specific investment cost depends on plant capacity. Effects of scale are particularly important for the economic evaluation of small and medium capacities (e.g. below 10,000 m^3/d), while they become negligible for large utility scale plants (e.g. above 30,000 m^3/d).
- Plant layout: the desalination plant configuration (e.g. number of stages in multiple effect distillation, MED plants or the number of passes in reverse osmosis, RO plants) impacts CAPEX and in turn LWC in a broad range. As an example, in hybrid MED-RO systems the RO unit is typically equipped with single pass instead of the two-pass conventional layout, which allows for significant reduction in the specific investment.
- Feed water quality: energy consumption and plant efficiency are affected by salinity and temperature of the raw water source. In addition, local feed water quality and its seasonal variations influence the selection of intake and pretreatment systems. Both units are strictly interdependent; thereby, a number of different choices are possible.
- Cost variations of basic components: in MED plants, metal price fluctuations significantly affect CAPEX for the evaporator. Also membrane price of RO vary over time.
- Power supply: desalination plants present elevated specific energy consumption (electricity and—within thermal units—heat). In recent years, the price of fossil fuels has been characterized by high volatility and generic upward trend. The price escalation of crude oil, coal and natural gas accounted more than 400% in the last 10 years [1]. Power plants typically have an operation life of ca. 25–30 years; therefore, the uncertainty about future fuel prices represents a critical economic risk factor. In the light of these considerations, the introduction of renewable energies can be seen not only as a climate change mitigation measure, but also as a cost-stabilizing factor. In fact, all renewable energy technologies are characterized by nearly fixed generation cost over time. In addition, it has to be specified which components are included in the calculation of the energy consumption (e.g. desalination unit, water intake, remineralization unit).
- Brine discharge type: investment cost and energy demand of seawater pumps also depends on environmental requirements and eventual regulatory constraints. If limitations are set to the maximal temperature and salinity level of the brine, it may be necessary to pump additional seawater and blend it with the reject flow.
- Financial boundary conditions and plant operation lifetime: last but not least, negotiated interest rate, loan payback time and assumed operation lifetime of the desalination units also play a decisive role in the determination of LWC.

Hence, it clearly appears that the definition of LWC is not that trivial and that LWC should not be used as a sole mean of comparison, if additional information is not provided.

2. General methodology

Based on the considerations exposed above, this paper mainly aims at the proposition of a general methodology for techno-economic evaluation of desalination plants. Particular focus is given to the analysis of the energy supply and to the comparison between conventional (fossil) and renewable power plants, with focus on concentrating solar power (CSP). The analysis of combined renewable systems (photovoltaic, wind power and CSP) is part of ongoing investigations and is not presented within this work. Two desalination technologies are taken into account, i.e. SWRO and MED. MSF is not considered, even if it still represents the dominant desalination technology in the Gulf Region. This choice is motivated by the high specific energy consumption of MSF plants, which reduces their economic competitiveness in comparison with RO and MED, all the more if energy cost is high.

The analysis consists of two main steps, i.e. technical model and economical model. After a brief description of the technical model, particular attention is given to the explanation of the proposed methodology used for economic analysis. Finally, the potentiality of both technical and economic models is shown in a case study.

3. Technical model

The technical analysis is performed within the tool INSEL [2]. INSEL is a software package to design, monitor and visualize renewable and conventional energy systems. The tool has been developed since more than 20 years and is a commercially distributed product. The graphical programming language is characterized by a user-friendly modular structure, which allows for flexible integration or adaptation of different plant components. Also, analysis series (e.g. parametric studies) can be easily performed without the utilization of the user interface by means of batch scripts (e.g. ruby or python). INSEL offers a wide range of commercial PV and wind turbine modules. In addition, the user has the possibility to implement its own models and integrate them to existing libraries. Different languages such as FORTRAN, C/C++ and Matlab can be used for programming new modules. In the last years, DLR has developed several CSP and desalination modules using this tool. An overview on these models is given in Fig. 1. A selection of these modules is described in the next Sections (3.1–3.3).

3.1. Concentrating solar power

In contrast to solar photovoltaic, which directly transforms solar irradiation into electricity, within a CSP plant the solar resource first is converted to high temperature heat. In a second step, the collected heat is used to drive a conventional steam turbine (Fig. 2). Basic requirement for the achievement of high temperatures and contemporary reduction of thermal losses is the concentration of direct normal irradiance (DNI) by means of optical devices. The key component of CSP plants is the solar field, which consists of a number of curved mirrors (in form of extruded parabola or paraboloid) that reflect DNI to a focus line or focus point, called receiver. Such plants are able to deliver dispatchable power (i.e. capacity on demand), due to the possibility to accumulate thermal energy into storage units (thermal energy storage or TES) at certain times of the day and deliver it to the steam turbine whenever required. TES is also used to compensate cloud transients or to avoid freezing of heat transfer fluid (HTF) in the solar field.

Base load operation has already been demonstrated in the Gemasolar plant [4]. The plant dispatchability is also guaranteed at times without DNI and empty thermal storage, as hybrid operation of the steam turbine with fossil fuel is possible. Typical capacity of CSP plants for electricity generation ranges from 5 MW to several hundreds of MW. The CSP modules implemented by DLR and integrated in INSEL include a wide range of options, as shown in Fig. 1. They consist of a series of collector types (line focusing such as Parabolic Trough and Linear Fresnel, and point focusing such as solar Tower), different thermal storage options (2-tank indirect molten salt and concrete) as well as a number of HTFs. The power block of CSP systems consists of a conventional steam cycle; different cooling system such as once-through, evaporative cooling or dry cooling can be selected. Such models have been implemented in close collaboration with other DLR groups such as the Institute of Solar Research and the Department of Thermal Process Technology. Due to brevity constrains, it is not possible to go into the detail of the thermodynamic modeling. However, exhaustive information can be found in [5]. Key design parameters of the CSP model —which can be set by the INSEL user—are summarized in Table 1.

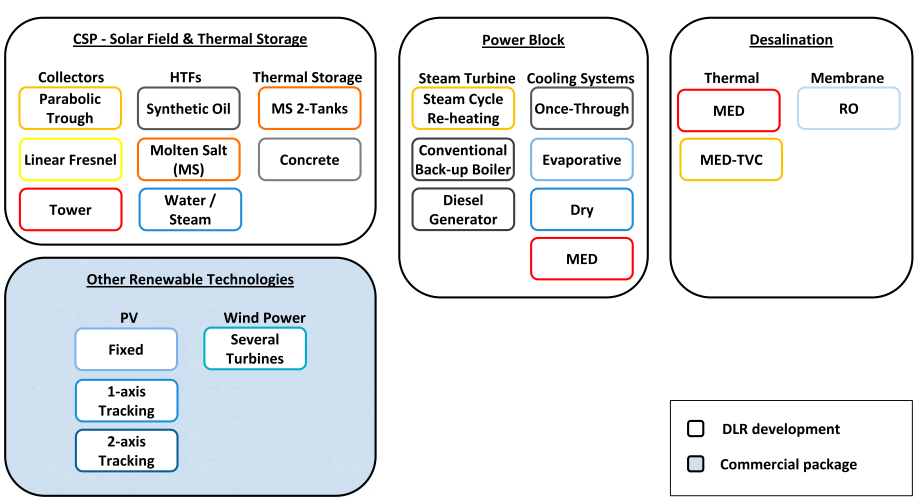

Fig. 1. Overview of currently available INSEL-components (existing libraries and DLR implementations).

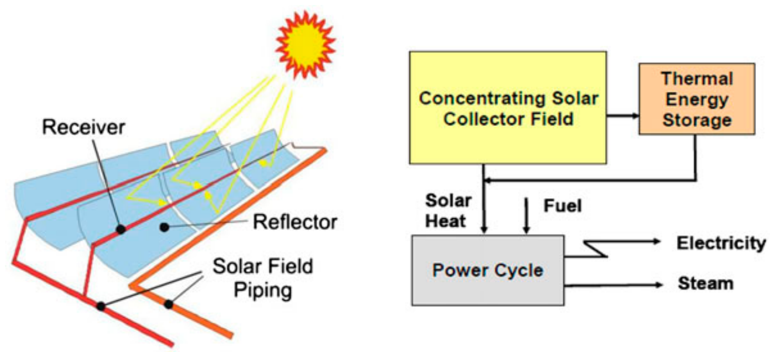

Fig. 2. Scheme of a parabolic trough field (left) and basic components of a CSP plant (right) [3].

Table 1
Summary of main design parameters of a CSP plant

Solar field	Thermal storage	Power block
Collector type and geometry	Full load capacity (hours)	Inlet nominal temperature
Distance between collector rows	Initial charge state	Inlet nominal pressure
Solar multiple	Thermal loss coefficient	Turbine gross capacity
Field layout (e.g. subfields)	Hot tank design temperature	Hybrid mode (fossil backup)
HTF type	Cold tank design temperature	Cooling type
Reflectivity and dirt factor		Start-up factor
HTF temperature in and out		

3.2. Multiple effect distillation

MED belongs to the family of thermal desalination processes. Such plants typically are constructed in cogeneration with thermal power plants, which allows for minimization of energy requirements. MED presents a number of advantages if compared with MSF, such as lower operation temperatures and lower electricity requirements. For these reasons MED is particularly attractive for desalination markets characterized by high energy cost and challenging seawater quality (e.g. high salinity, high turbidity). The working principle of an MED is shown in Fig. 3. The intake water is pre-heated while flowing along the condenser, which principally serves for the removal of excess heat from the desalination process (i.e. condensation of the steam generated by the last stage). A portion of the pre-heated water is routed to the MED process, where it is equally distributed on the heat exchangers of each stage by means of spraying nozzles. The sprayed droplets form thin water films on the external surface of the heat exchangers. Around 30% of the feed water evaporates and is used as heating steam in the successive stage. In the first stage, heat has to be supplied from an external source. The remaining water in the liquid phase (brine) is collected in the last stage and blended with the cooling water.

The INSEL user can set a number of design parameter of the MED unit. The most important of them are number of stages, the choice between plane MED and MED-TVC, nominal pressure and mass flow of heating steam, design seawater salinity and temperature, maximal salinity within the stages, intake type and layout, pre-heater design and maximal salinity, and temperature increases of the brine in comparison with the water source. The required inputs at each time step are current heating steam mass flow and pressure as well as actual seawater temperature and salinity. Key results are design parameters such as gain output ratio (GOR) and required heat transfer area of the evaporator (used later as input in the economic model), main mass flows (i.e. cooling water, feed water, distillate, and brine), and their temperature and salinity distributions. Finally, specific power consumption (heat and electricity) is calculated. A differentiation is made between power required for desalination process and water intake.

3.3. Reverse osmosis

In RO plants, water separation occurs by means of selective membranes. Selective means that the flow rate of water molecules through the membrane is

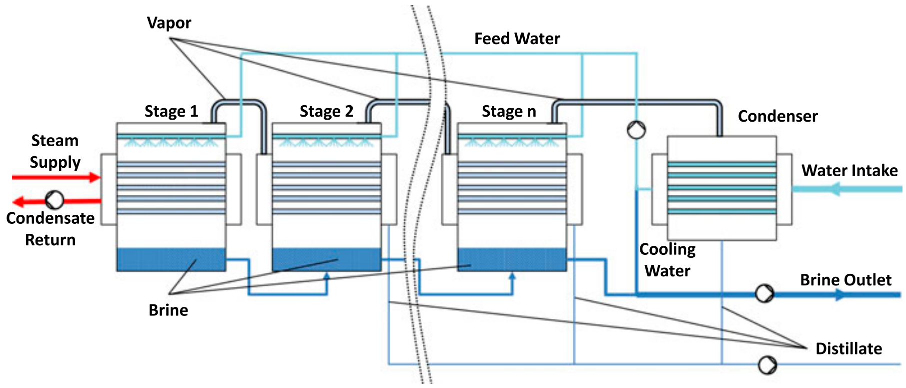

Fig. 3. Simplified scheme of a MED process (parallel-cross configuration)—Adapted from [6].

higher than the salt ion flow rate [7]. The driving force of RO processes is the pressure difference between the feed water side and product water side of the membrane. Commercial application of RO membranes for seawater desalination started during the early 1980s, driven to the development of composite aromatic polyamides membranes. Thereby, salt rejection could be enhanced. Currently used SWRO membranes are capable of rejecting approx. 99.5% of dissolved salts. RO systems mainly consist of pressure vessels, piping and manifolds, whereas each pressure vessel may contain up to eight membrane elements. A number of vessels connected in parallel are called stage. Feed water salinity and required permeate quality decisively impact the RO layout [8]. Fig. 4 presents the typical layout of SWRO plants, which goes under the name of concentrate staging. In such layout, the concentrate of the first stage serves as feed for the second stage.

Finally, Table 2 summarizes main design parameters of both considered desalination technologies.

3.4. Annual yield simulations

The yield calculation of conventional power generation systems typically bases on few steps. In the first step, a number of operating conditions are

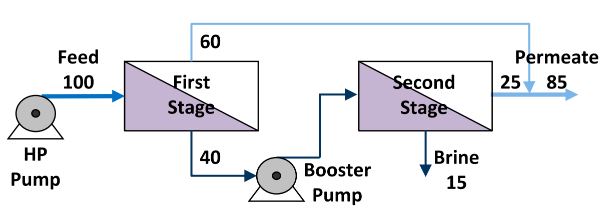

Fig. 4. Scheme of a SWRO plant with concentrate staging configuration.

determined, i.e. design case and a number of off-design conditions (partial load cases). Secondly, a probability of occurrence is assigned to each of the defined operating points, e.g. design conditions occurs 40% of the hours of the year and so on. Finally, the annual yield is calculated as sum of the multiplication of power output in the different cases with the correspondent probability of occurrence.

This simple approach cannot be applied for the analysis of renewable energy technologies, as renewable resources (solar irradiance and wind speed) are characterized by large daily and seasonal variations. A proven approach for annual yield calculation of such systems is hourly simulation. This means that the models are fed with new input values at each hour of the year, so that a total of 8,760 steps are required. Some of the models are set up as quasi-stationary models, i.e. the yield of a certain plant component at the time *t* is not influenced by its own status during the previous time step. However, transient effects have to be considered in the models in the case of storages and in the case of systems characterized by high thermal inertia (e.g. CSP solar field) [9].

Fig. 5 presents a general overview on the annual simulation procedure. On the left part of the figure main inputs are defined: site coordinates, meteorological inputs (DNI, global horizontal irradiance, diffuse irradiance, air temperature and relative humidity, wind speed with height measurement specification) and demand data (electricity and water). Longitude and latitude are very important data as they allow the determination of the position of the sun at each time step, which in turn has a relevant impact on the power yield of solar systems and CSP in particular [10]. In the second step, the INSEL user has to define a number of design parameters, which have been described previously (Tables 1 and 2).

Table 2
Key design parameters of photovoltaic, wind power and desalination plants (MED and RO)

MED	RO
Steam quality/mass flow	Capacity
TVC mode	Design product salinity
Number of stages	Recovery rate
Seawater quality	Number of passes
Intake type	Number of elements/pass
Pre-heating layout	Average membrane age
Max. salinity/temperature increase of discharge flow	Intake and pretreatment type

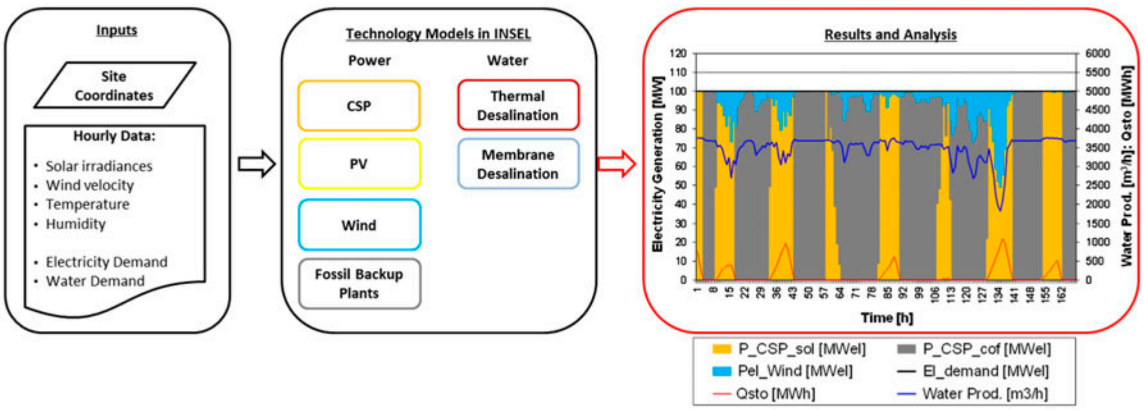

Fig. 5. General procedure of an annual yield simulation in INSEL (example).

Finally, the annual simulation is run and key results such as relevant design parameters and power and water yields are analyzed.

4. Economic model

4.1. LWC—definition

The calculation of the LWC bases on the assessment of investment cost and operating cost. As explained in the introduction, the estimation of the cost of desalination plants is a rather complex issue. LWC is calculated as:

$$\mathrm{LWC} = \frac{\sum_{t=1}^{t_{\mathrm{life}}} \frac{C(t)_{\mathrm{capital}} + C(t)_{\mathrm{operation}}}{(1+r_d)^t}}{\sum_{t=1}^{t_{\mathrm{life}}} \frac{M_{w\_y}}{(1+r_d)^t}} \tag{1}$$

with

$C(t)_{\mathrm{capital}}$ (Mio. €/y) capital cost in the year t (liquidation plus interest), $C(t)_{\mathrm{operation}}$ (Mio. €/y) operating cost in the year t, M_{w_y} (Mio. m^3/y) annual water production, t_{life} (y) economic plant life, r_d (%/y) discount rate.

The assessment of capital and operating expenditures is explained in detail in the following Sections 4.2 and 4.3.

4.2. Capital expenditures

4.2.1. Multiple effect distillation

The calculation of capital cost is performed breaking down the whole MED plant into functional groups. For each of the following groups a cost assessment is carried out: intake, pump station and brine discharge, feed water pre-treatment, steam supply, evaporator (incl. erection and commissioning), potabilization plant, drinking water storage, civil works and I&C and electrical works. The assessment of the specific evaporator costs is carried out in two steps. The first step consists in the selection of a reference plant, for which the price breakdown is known. In this case, the selected reference evaporator is a six-stage MED. The CAPEX for evaporator construction, insurance, and freight are 720 €/(m^3/d) [11]. After that, the reference costs need to be adapted to consider the case of a number of stages other than six. The major impacts of the number of stages are the cost of evaporator and the specific intake cost. These issues will be discussed in detail in the result section of the case study. The main assumptions of the evaporator model are as follows: the cost for production and transportation are proportional to the ratio of evaporator heat transfer area in the general case and in the reference case. In addition, equipment cost and EI&C cost are independent of the number of stages. Finance and insurance cost and added value tax are assumed to be 5% and 20% of CAPEX, respectively [11]. The CAPEX also considers the interests on capital during the construction period.

The costs of the remaining functional groups are assessed with a procedure similar to that used for the evaporator costs. For this proposition, the selected reference plant is a 14-stage plant [12]. The total specific investment cost is approx. 2,250 €/(m^3/d). The CAPEX breakdown of the reference plant is presented in Fig. 6. Evaporator cost accounts for approx. 58% of the total CAPEX, while other major contributions are the cost for intake and brine discharge (16%). The remaining functional groups, i.e. seawater pretreatment, steam supply, erection and commissioning, potabilization, civil and electrical works account to approx. 25%.

4.2.2. Reverse osmosis

Similar to the procedure used in the MED model, cost assessment of RO is performed dividing the plant into functional groups. Fig. 7 presents the CAPEX breakdown for the selected reference SWRO plant. This breakdown is assumed to be valid for a large SWRO plant with open intake and a DAF pre-treatment (dissolved air flotation) followed by gravity filters and pressure filters. The total CAPEX amounts to 1,730 €/(m^3/d). Investment costs have been adapted in order to take into account different design recovery ratios, case-specific intake costs and plant capacities. The selection of the recovery ratio as well as of the pre-treatment system is mainly affected by the feed water quality (i.e. salt content, turbidity, microbiological activity, presence of algae). Other than MED, whose cost is dominated by the evaporator cost, in the case of RO, the cost of the pressure vessels—which are the core of the plant—just accounts for 30% of the total CAPEX. Other three functional groups take a relevant portion of the cost, each of them representing between approx. 19% and 15% of the investment cost. These components are seawater pre-treatment, civil and electrical works, and intake.

4.3. OPEX

The operating cost of a desalination plant consists of fixed costs, i.e. costs which occur independently of the operation of the plant, and variable costs, which are related to the amount of produced water. Operating costs are summarized in Table 3 [6].

4.3.1. Fixed operating cost

The capital costs are calculated by means of the annuity method:

$$C(t)_{\text{capital}} = \text{CAPEX} \times \frac{r_i \times (1 + r_i)^{t_{\text{debt}}}}{(1 + r_i)^{t_{\text{debt}}} - 1} \quad (2)$$

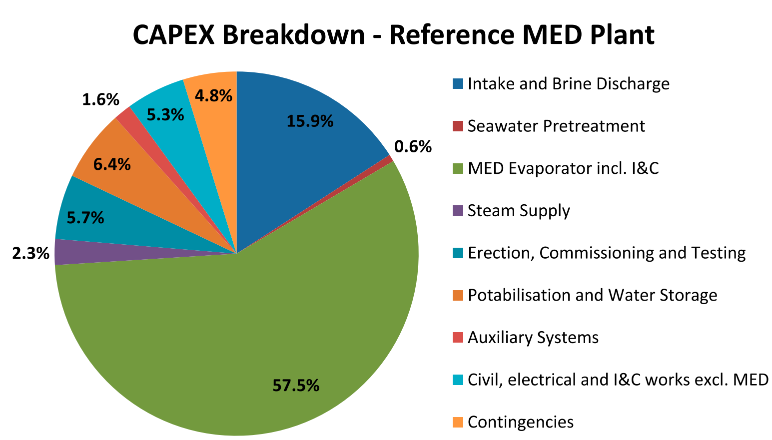

Fig. 6. CAPEX breakdown of an MED plant including auxiliary components [12].

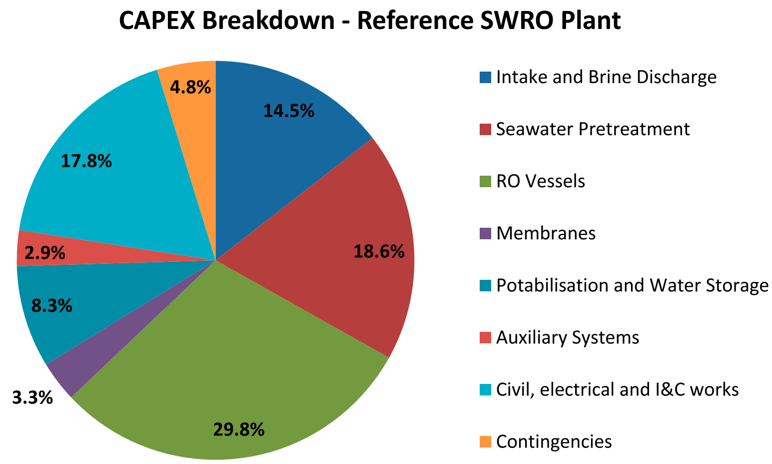

Fig. 7. CAPEX breakdown of the reference SWRO plant [12].

Table 3
Breakdown of operating costs for desalination plants

Fixed costs	Variable costs
Annual capital cost	Thermal energy
Personnel	Electrical energy
Maintenance and repair	Chemicals and additives
	Membrane replacement

with CAPEX (Mio. €) CAPEX at plant operation start, r_i (%/y) interest rate, t_{debt} (y) debt payback period.

Capital annual cost $C(t)_{\text{capital}}$ is equal to zero for $t_{\text{debt}} < t < t_{\text{life}}$. Personnel cost can be assessed as far as the number of employees and their qualification are known. Specific personnel cost for large desalination plants can be assumed to be approx. 0.027 €/m^3. Fixed annual costs for maintenance and repair can be expressed as percentage of the CAPEX. M&R cost depends on the plant layout; typical values are between 3.0 and 3.3% for MED units and approx. 2.7% for SWRO plants [12].

4.3.2. Variable operating cost

The evaluation of heat cost in MED plants is a complex issue. Different approaches have been proposed by authors such as [13,14]. This work applies the reference-cycle method as described in [15], which is a rather straightforward methodology. The approach bases on the comparison of steam turbine performances in two cases: MED case and reference case, whereas the reference cycle is defined as a power block with standard cooling such as once-through or evaporative tower. Under the assumption that both turbines are fed with the same steam quality and mass flow, the electrical efficiency of the reference turbine is higher than in the MED configuration. The higher are pressure and temperature of steam extraction, the higher are the specific electricity losses in comparison with the reference case (Fig. 8).

According to Fig. 8, heat cost is defined as the cost needed to compensate the missing income that would be generated in the reference case. In other words, if the steam which is extracted (e.g. at 0.3 bar) for MED application would be further expanded in the turbine (down to e.g. 0.1 bar), it would generate an additional amount of electricity. Therefore, annual heat cost can be expressed as:

$$C_{\text{heat}} = P_{\text{el}\_y\_\text{loss}} \times \text{LEC}_{\text{ref}} \quad (3)$$

C_{heat} (Mio. €/y) annual cost for heat supply, $P_{\text{el}\_y\_\text{loss}}$ (kWh/y) annual electricity losses, LEC_{ref} (€/kWh) LEC of the reference power plant.

The levelized electricity cost is calculated with a procedure similar to (Eq. 1), whereas investment and operation costs are adapted and the annual water production is substituted by the annual net electricity generation of the power plant. The difference in the investment cost between CSP and conventional fossil-fired power plants has a relevant impact on heat cost. This issue will be discussed later in the case study. The electricity cost is calculated as:

$$C_{\text{elec}} = P_{\text{el}\_y\_\text{loss}} \times \text{LEC} \quad (4)$$

C_{elec} (Mio. €/y) annual cost for electricity supply, $P_{\text{el}\_y\_\text{loss}}$ (kWh/y) annual electricity consumption for desalination.

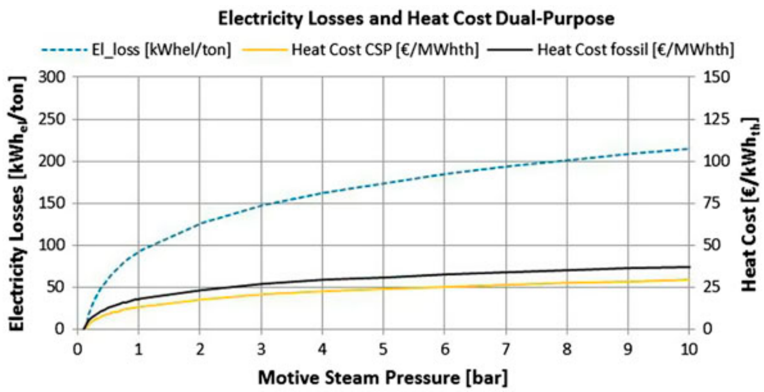

Fig. 8. Specific electricity losses and heat costs for a CSP plant and a fossil power plant (assumptions: state-of-the-art CSP investment costs; market crude oil prices in October 2013).

The annual electricity consumption of desalination plants is the sum of electricity requirements for the process itself and the energy needed for seawater intake and brine discharge. Typical specific electricity consumptions of MED and SWRO are approx. 1.5 kWh/m^3 and 4.0 kWh/m^3, respectively. The specific electricity consumption of thermal desalination plants is almost independent of seawater quality, while that of SWRO depends on seawater salinity. In addition, chemicals are used in different processes such as water pre-treatment, desalination, and post-treatment. Their cost assessment occurs on massflow base:

$$C_{chem} = \sum_{i=1}^{n} \dot{m}_i \times \frac{q_i}{x_i} \times h/y_i \times c_{\text{chem\_}i} \quad (5)$$

C_{chem} (Mio. €/y) annual chemical cost, $\dot{m}_i$ (kg/s) receiving mass flow, x_i (%) commercial chemical concentration, q_i (mg/l) chemical concentration to receiving flow, h/y_i (h/y) annual operation time of chemical dosing, $c_{\text{chem\_}i}$ (€/ton) specific chemical cost.

MED mainly makes use of antiscalant and remineralization agents. Specific chemical cost for MED is approx. 0.03 €/m^3. On the contrary, RO is characterized by higher specific chemical costs (approx. 0.08 €/m^3) due to coagulants used in the demanding pre-treatment section and antiscalants used in the RO process.

Membranes are prone to deterioration. Therefore they are substituted after a certain number of hours of operation. As large desalination units are characterized by relatively high membrane replacement costs, the depreciation method should be used for a correct cost assessment [6]. The membrane replacement rate depends on plant recovery rate and on the effectiveness of the pre-treatment process. In particular, different studies have proven that the selection of elevate recovery rates increases the risk of membrane fouling [8] and reduces in turn the membrane average lifetime.

4.4. Evaluation of cost uncertainties

The majority of cost assessments in the field of renewable energies and desalination use deterministic approaches. This means that each technical and economic parameter is a single fixed value. Nevertheless, the real value of most of such parameters is not known and is characterized by a certain uncertainty range. Thus, the questions should be answered, which the impact of eventual deviations of a certain input parameter on the results is and which the probability to reach a given LWC value is. The first question can be answered performing parametric studies on selected input parameters. The parametric studies are carried out under the assumption of “other things being equal.” This analysis makes possible to evaluate the influence of each parameter on the analyzed metrics. However, the probability of occurrence of LWC or LEC and their likelihoods being above or below a certain threshold cannot be evaluated with parametric studies. These questions could be best answered by means of probabilistic approaches as described in Ho et al. [16].

5. Case study

The results reported in the following analysis mainly aims at the exposition of the potentiality and flexibility of the developed tool, rather than at the indication of suggestions for the implementation of a particular technical solution. Perhaps, the data used for economic analysis are affected by a certain degree of uncertainty. The problem is that such data are commonly not in the public domain and are generally available only to the general contractor. The sensitivity analysis exposed in 6.3 gives some additional indication on this regard. Nevertheless, the analysis shows a number of interesting relationships and trends about the impact of plant layout of desalination plants and of prices (investment cost and operation cost) on the final cost of the produced water.

5.1. Input data

The used meteorological hourly data are gathered from [17,18]. The annual sum of direct normal and global horizontal irradiance amounts to 2,530 kWh/m^2/y and 2,386 kWh/m^2/y, respectively, while the annual average wind velocity at hub height is 7.92 m/s. The hourly wind data have been adapted from measurement height to hub height according to the logarithmic wind velocity profile. The ground roughness factor is assumed to be 0.05 m. The seawater salinity varies along the year in a narrow range around 40,150 ppm, while the seawater temperature oscillates between 22°C in January and 28°C in August. As renewable energy resources—DNI and wind speed- are characterized by relevant year-to-year differences, a comprehensive analysis should include the simulation of a series of years—at least 10–15 years—in order to capture the long term meteorological resource variability. This last part of the analysis will be presented soon in a separate work.

5.2. Selected configurations

This case study focuses on the comparison between conventional desalination and desalination based on CSP. The power required for the desalination plant is supplied by a 50 MW steam turbine. The water demand is set to 30,000 m^3/d. Two main desalination layouts are compared: in the first case a hybrid desalination system is analyzed, which consists of combined MED and SWRO units. In addition, the number of stages is varied from 4 to 14 in order to value the impact of such different layouts on the CAPEX and in turn on the water supply cost. The gap between MED water production and total water demand is covered by the SWRO plant. As the salinity of the distillate from the MED plant is almost salt free (approx. 20 ppm), RO can be equipped with single-pass configuration. On the contrary, stand-alone SWRO plant typically presents two-pass layout in order to comply with the local drinking water standards after remineralization. In addition, the combined impact of pressure level of heating steam on MED performance plant and on turbine efficiency is considered. In particular, two cases are analyzed: 0.2 and 0.4 bar. The power supply technology and the price of the used reference fossil fuel also significantly impact the economic metrics. The results presented in the following paragraph focuses on four cases: the first case assumes a conventional (fossil) steam turbine as power supply for the two desalination units, while the second case considers a Central Receiver CSP plant. The used heat transfer medium in the solar field as well as in the two-tank TES is a molten salt mixture (solar salt). The storage and the solar field are designed in order to supply approx. 14 h of full load turbine operation under design conditions. Whenever solar operation is not possible (i.e. absence of direct irradiance and completely discharged storage), continuous operation of the steam turbine is guaranteed by the fossil backup system, which is integrated in the CSP plant. Finally, the impact of the price of the reference fuel is taken into account in both cases (conventional steam turbine and CSP). Thereby, just two cases are considered: the first one is a very low price (8 $/barrel), which may approximate the current situation in some oil-exporting MENA countries. The second case assumed world market oil price. Table 4 summarizes the analyzed cases.

6. Results and discussion

6.1. Conventional power supply

The first part of the case study analyzes the economics of desalination plants supplied by conventional power technologies. The results are presented in Fig. 9, while a LWC breakdown for the different analyzed cases is reported in Table 5 (here only the case with low fuel price is reported). The two curves and the line near to the bottom of the diagram show the case of low fossil fuel price (8 $/barrel). The continuous line represents the SWRO-only case, while the curves describe the impact of the number of stages on LWC. One can observe that both curves have a minimum, which in the case of low-heating steam pressure corresponds to six stages. In the case of higher steam pressure, the minimum shifts toward the right part of the diagram (10 stages). After these minima, both curves rise and reach their maximum by 14 stages. The main reason for the convexity of the curves can be explained as a trade-off between efficiency of the MED plant and increasing cost for the achievement of that efficiency. Indeed, the higher is the number of stages, the higher is the efficiency, but the lower is the effective temperature difference between two

Table 4
List of analyzed combinations

Parameter	Unit	List of analyzed cases	
Water demand	m^3/d	30,000 (continuous operation)	
Desalination technology	–	SWRO only	Hybrid (MED and SWRO)
MED stages	–	–	4–14, step 2
MED steam pressure	bar	–	0.2/0.4
Power supply	–	Conventional steam turbine	CSP (SM3) and fossil backup
Reference fuel price	US$/barrel	8	100

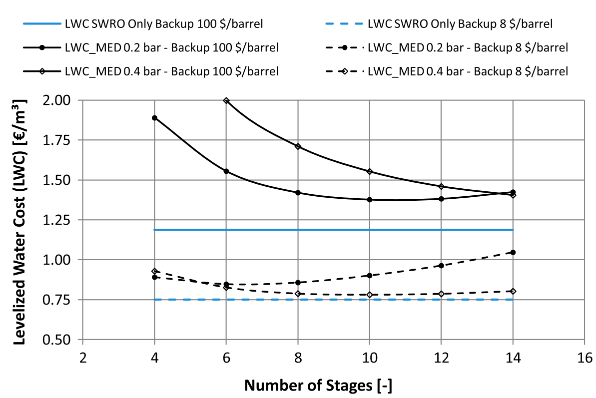

Fig. 9. Variation of number of stages in the MED plant and comparison with SWRO (power supplied by fossil steam turbine).

consecutive MED stages. In turn, this implicates higher specific heat transfer areas for the evaporator (the transferred heat has to be kept constant) and finally, higher material and construction cost. While the GOR increase is roughly proportional to the number of stages elevated at the 0.9th power [19], the cost for the evaporator increases hyperbolically, as the heat transfer area is proportional to the inverse of the temperature difference between stages. This explains the right part of the diagram.

However, it remains to consider why LWC increases as the number of stages is very low. This is mainly due to the increasing impact of the intake cost. The waste heat of MED plant needs to be cooled; this is performed in the final condenser, where cold seawater enters the condenser and condensates the steam flow produced in the last effect. After the condenser, only a portion of the pre-heated seawater is directed toward the MED (feed water), while the remaining part (cooling water) is mixed with the brine before it is discharged to the sea. Now, the higher is the steam flow which has to be cooled by the condenser, the higher is the required intake water flow and the higher is the investment for this auxiliary equipment (intake and water pre-treatment) and also the higher is the specific electricity consumption. On equal terms (e.g. constant drinking water production), the lower the number of stages, the higher the specific intake investments.

Intake costs are very sensitive to local conditions such as bathymetric profile of the shore, intake type (open intake, submerged intake, beach well), and required intake water flow, which in turn is a function of the seawater temperature rise in the condenser. Their evaluation cannot be, therefore, generalized and has to be carefully analyzed case-by-case. The results of the current case study were generated assuming a submerged intake with a pipe length of 500 m and an elevation difference of 20 m. The temperature difference in the final condenser is 8 K. The pressure of the heating steam also has a relevant impact on the results. Low steam pressure means that the temperature difference between top brine temperature and condenser temperature is lower. As a consequence, the increase of the heat transfer area and of the correspondent capital investment is appreciable also for a low number of stages. On the other side, lower heating steam pressure corresponds to lower heat cost (according to the reference cycle method exposed above) and higher gross electrical efficiency of the steam turbine. Comparing the results of the MED case with the RO case, for this particular case RO performs lower LWC.

In Table 5, it can be observed that the capital cost —which includes the MED evaporator and all auxiliary equipment such as intake as described before— reaches a minimum in the eight-stage case and after that slightly increases again. The maintenance and repair cost (M&R) are assumed to be independent of the number of stages. The higher the number of stages, the lower is the specific electricity cost. While the specific electricity consumption of the MED process is assumed to be constant (0.6 kWh/m^3), the specific power required for the intake pump is lower, the higher is the number of stages. Heat cost is relatively

Table 5
LWC breakdown in main functional plant components (conventional power supply, 8 $/barrel fuel price, MED 0.4 bar)

		Hybrid MED and RO			RO only
MED					
Number of stages	–	4	8	12	–
Capital cost	€/m^3	0.49	0.43	0.45	–
Personnel cost	€/m^3	0.02	0.01	0.01	–
M&R cost	€/m^3	0.22	0.22	0.22	–
Electricity cost	€/m^3	0.09	0.06	0.04	–
Heat cost	€/m^3	0.08	0.04	0.03	–
Chemical cost	€/m^3	0.03	0.03	0.03	–
Membrane replacement cost	€/m^3	0.00	0.00	0.00	–
Fix LWC	€/m^3	0.73	0.66	0.68	–
Variable LWC	€/m^3	0.20	0.13	0.11	–
LWC MED	€/m^3	0.93	0.79	0.79	–
SWRO					
Capital cost	€/m^3	0.34	0.36	0.47	0.41
Personnel cost	€/m^3	0.01	0.01	0.04	0.01
M&R cost	€/m^3	0.13	0.14	0.18	0.13
Electricity cost	€/m^3	0.08	0.08	0.09	0.11
Heat cost	€/m^3	0.00	0.00	0.00	0.00
Chemical cost	€/m^3	0.05	0.06	0.08	0.06
Membrane replacement cost	€/m^3	0.04	0.04	0.05	0.04
Fix LWC	€/m^3	0.48	0.51	0.69	0.54
Variable LWC	€/m^3	0.18	0.18	0.22	0.21
LWC SWRO	€/m^3	0.65	0.69	0.91	0.75
LWC hybrid	€/m^3	0.75	0.75	0.80	0.75

low, which may appear surprising. However, this can be explained by the reference cycle method: on annual basis the cost savings for the cooling unit (an investment which is required in the reference cycle but not in the MED case) partly balance the electricity losses according to the diagram of Fig. 8.

Finally, in the case of high fossil fuel price (100 $/barrel), the minimum of LWC rises from 0.75 to 0.80 €/m^3 to approx. 1.40 €/m^3 e. In addition, the optimal number of stages shifts toward a higher value, which applies for both considered steam pressure levels. This shift can be explained with the increase of the price of electricity and heat. As the cost for water production is higher, in this case it is convenient to invest in a more efficient MED layout (i.e. higher number of stages).

6.2. CSP power supply

The economic figures significantly change in the case the power supply is provided by a hybrid CSP plant. Despite most of the considerations exposed above remains true (i.e. minimal LWC occur in correspondence of the trade-off between MED efficiency and overall cost), the position of the minima as well as the impact of heating steam pressure and of fuel price differ from the previous case. In the current case, high-pressure MED performs better only if the number of stages is higher than 9 or 10. The CSP-MED case is characterized by higher capital investment (solar field, TES) which is also required to compensate lower turbine efficiency in comparison with the reference cycle. Therefore, heat cost is higher than in the conventional case, in particular, in the case of high heating steam pressure (see also Fig. 10) and low number of stages (as the supplied heat is not optimally used). Instead, heating steam (in particular at higher pressure) requires an elevate number of stages (i.e. 11–12 in the case of elevate fuel price) in order to be utilized in a cost-efficient way. If the fuel price is low, RO-only configuration has lowest LWC (0.95 €/m^3). If the fuel price achieves 100 $/barrel, the water costs are in a range between approx. 1.00 €/m^3 and 1.10 €/m^3 for SWRO and MED, respectively. Despite higher investment cost, LWC of CSP desalination is comparable with the cost of conventional desalination, in particular under the assumption of market fuel prices. In addition to the positive environmental impact, the introduction of renewable energies will allow for cost stabilization in the long run and for prevention of risks related to further cost escalation of limited fossil fuels.

Taking a look on Table 6, fixed costs, which mainly consist of capital and M&R costs, are higher for very low number of stages, reach a quite broad minimum between 8 and 12 stages (in the case of high fuel price) and then rise again. Concerning variable costs, they are dominated by electricity and heat cost.

6.3. Sensitivity analysis on metal price

A number of technical, economic and financial parameters impacts final LWC. A series of case studies could be performed for e.g. specific intake water cost, financial boundary conditions (loan period, interest rate) and many other parameters. The following example focuses on the sensitivity analysis of metal price. Different metals such as copper and nickel are commonly used in MED plants. Their price fluctuations over the last 30 years can be seen in Fig. 11 [1]; it is interesting to note that the metal price trends correlate with the oil price (right *y*-axis).

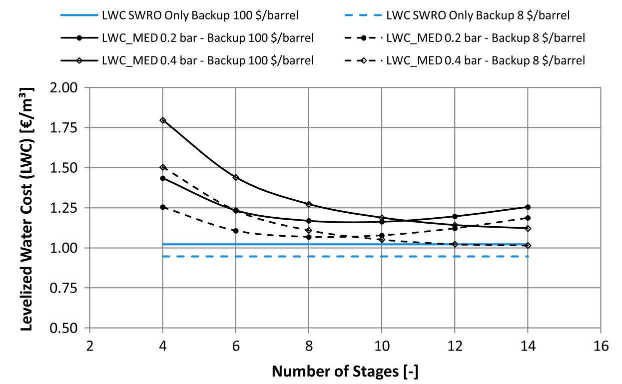

Fig. 10. Variation of number of stages in the MED plant and comparison with SWRO (power supplied by hybrid CSP, solar multiple 3.0).

The results represented in Fig. 12 show the impact of metal cost and number of stages on LWC. Three cases are taken into account. The base case assumes a metal price of 50 US$/ton (MED BASE). In addition, a price of 25 US$/ton and 100 US$/ton is considered in the two other cases MED 0.5× and MED 2×, respectively. All analyzed cases assume hybrid CSP as power supply

Table 6
LWC breakdown in main functional plant components (Central Receiver CSP power supply, solar multiple 3.0, 100 $/barrel fuel price, MED 0.4 bar)

		Hybrid MED and RO			RO only
MED					
Number of stages	–	4	8	12	–
Capital cost	€/m^3	0.49	0.43	0.45	–
Personnel cost	€/m^3	0.02	0.01	0.01	–
M&R cost	€/m^3	0.22	0.22	0.22	–
Electricity cost	€/m^3	0.31	0.19	0.15	–
Heat cost	€/m^3	0.73	0.39	0.28	–
Chemical cost	€/m^3	0.03	0.03	0.03	–
Membrane replacement cost	€/m^3	0.00	0.00	0.00	–
Fix LWC	€/m^3	0.73	0.66	0.68	–
Variable LWC	€/m^3	1.07	0.61	0.46	–
LWC MED	€/m^3	1.80	1.27	1.14	–
SWRO					
Capital cost	€/m^3	0.34	0.36	0.47	0.41
Personnel cost	€/m^3	0.01	0.01	0.04	0.01
M&R cost	€/m^3	0.13	0.14	0.18	0.13
Electricity cost	€/m^3	0.28	0.27	0.30	0.38
Heat cost	€/m^3	0.00	0.00	0.00	0.00
Chemical cost	€/m^3	0.05	0.06	0.08	0.06
Membrane replacement cost	€/m^3	0.04	0.04	0.05	0.04
Fix LWC	€/m^3	0.48	0.51	0.70	0.54
Variable LWC	€/m^3	0.38	0.37	0.43	0.48
LWC SWRO	€/m^3	0.85	0.88	1.13	1.02
LWC hybrid	€/m^3	1.19	1.14	1.14	1.02

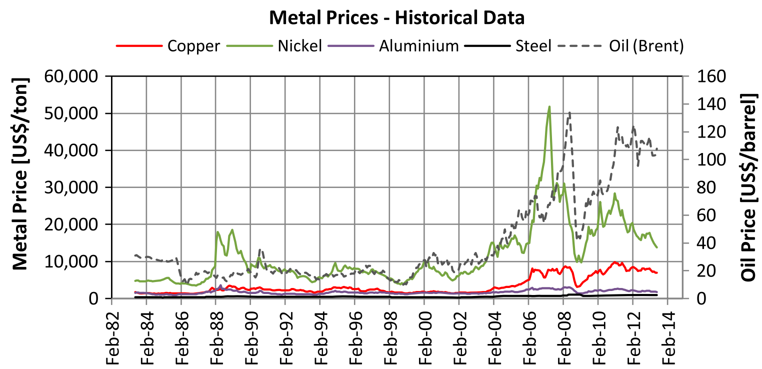

Fig. 11. Historical price trends of metals used for the construction of MED evaporators and comparison with oil price fluctuations.

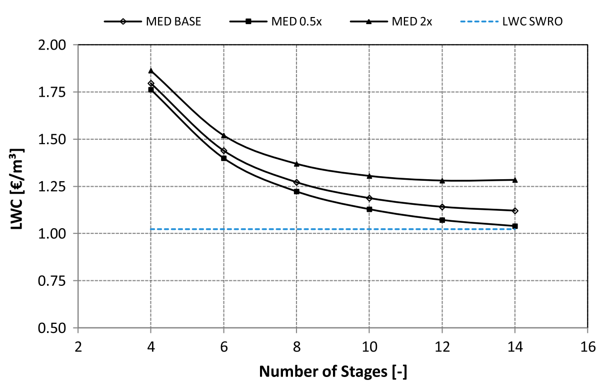

Fig. 12. Sensitivity of LWC on metal price for MED evaporator (base = 50 US$/ton; low = 25 US$/ton; high = 75 US$/ton); 100 $/barrel fuel price, hybrid Central Receiver CSP, solar multiple 3.0.

and high backup fuel cost (100 $/barrel). Fig. 12 shows the LWC of the MED plant, which allows highlighting the impact of metal price on the optimal number of stages in the different cases. Under these assumptions, in the base case minimal LWC is achieved for a number of stages equal to 14. A metal price increase causes an increase in CAPEX and in turn of LWC. In addition, the higher is the number of stages, the larger is the difference to the base case, which is due to the larger weighting of evaporator cost on total CAPEX. Finally, high metal price also result in a shift of the optimal number of stages toward the left part of the diagram. As one could expect, the opposite occurs in the case of low metal price, i.e. LWC is generally lower and the optimal number of stages is higher than in the previous cases.

7. Conclusions and outlook

Desalination is experiencing considerable market growth, which is driven by the combined impact of population increase and depleting water resources. However, desalination processes are energy intensive and cause negative impact on the environment. In addition, risk issues related to the on-going price escalation of fossil fuels will become even more challenging in the future. All this calls for the introduction of renewable energy in electricity systems and also in desalination processes. This paper represents the continuation of the research activities in the field of solar desalination at DLR which started in 2007 with the AQUA-CSP study. While previous works focused on water supply scenarios and pre-feasibility studies in selected locations, the contribution at hand presents a flexible techno-economic model for the detailed analysis of renewable desalination. The model has been developed in the last years within the PhD thesis of the author, based on DLR in-house know-how in the field of CSP and using the commercially available simulation tool INSEL. The first part of the paper presents the basics of the developed methodology for techno-economic analysis, while the second part shows the potentiality of the tool in an exemplary case study. Thereby, the combination of conventional power generation plants and CSP with MED, RO and hybrid MED-RO is analyzed. A number of critical issues which limits the comparability of commonly used economic metrics such as LWC are highlighted. In addition, the sensitivity of results on technical plant layout (number of MED stages, pressure of heating steam) and on selected economic parameters (fuel price, metal price) is shown.

The future work will concern further relevant aspects of renewable desalination such as consideration of other renewable energy technologies (photovoltaic and wind power), optimization of the configuration of renewable power plants and on the impact of long-term variability of renewable resources on technical and economical plant performance. Finally, impact of desalination plant capacity on specific investment cost will be considered.

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