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Renewable desalination: a methodology for cost comparison

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ABSTRACT

The increasing water demand and the impacts of climate change call for the construction of a large number of new desalination capacities, causing—besides environmental impacts—a relevant amount of additional power consumption. Consequently, new power plants need to be installed and operated as base load plants in order to supply power continuously to the desalination units. As fossil fuel prices are characterized by high volatility and a clear trend upwards, the use of renewable energies allows for saving fossil fuels and therewith reducing risks related to energy price escalation along the whole desalination life cycle. However, the fluctuant nature of renewable energies conflicts with the—ideally—continuous operation of desalination plants. In contrast to technologies such as photovoltaic (PV) and wind power, which are prone to fluctuating and intermittent power generation, concentrating solar power (CSP) is able to supply firm capacity on demand and can be fully integrated into conventional power utilities. On the other hand, CSP is currently considered to be more expensive than other renewable energy technologies. This work highlights the key importance of comparing technology options with equal quality of supply in order to obtain resilient results. Within this work, a representative site in the Middle East and North Africa Region has been analyzed by two different methodologies in order to demonstrate the potential large difference of results. The first method assumes that any variations of renewable energy supply can be compensated by the electricity grid, while the second method assumes that the addition of load to the electricity grid will require the addition of an equivalent firm power supply capacity. Hourly solar and wind data of a typical meteorological year have been used as inputs for a techno-economic simulation. Different options for CSP solar field layout, thermal energy storage, PV, and wind installed capacity, are analyzed and compared in terms of power and water cost for reverse osmosis and multieffect distillation plants.

Keywords: Renewable energy; Concentrating solar power; MENA; Water supply; Sustainable desalination

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1. Introduction

Water scarcity represents a severe problem in many regions of the world, which affects a lot of sectors such as agriculture and industry, and is a serious constraint to the quality of human life and environment.

For a variety of reasons, in particular the Middle East and North Africa (MENA) countries are suffering

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an increasing water scarcity, as it has been exposed in several recent studies [1,2]. Fig. 1 shows a water supply scenario for the MENA Region between the years 2000 and 2050. Considering the MENA region as a whole, the major part of water supply consists of sustainable surface and groundwater extractions, a relatively small share of wastewater reuse and conventional desalination, and a quite relevant share of nonsustainable over extractions of groundwater. The differentiation between sustainable and nonsustainable groundwater extraction depends on annual precipitation and natural replenishment of the aquifers. Conventional desalination means that the desalination process is driven by burning fossil fuels. The origin of the practice of nonsustainable water extraction is to be found in the 60s of the last century, when drilling technology became available at affordable prices and an increasing number of people started pumping water from the aquifers [1]. Regulators were not able to control or set a limit to the extractions, so that detrimental effects such as falling groundwater levels and salty water intrusions into the aquifers near shore lines occurred. Nonsustainable extractions still are a common practice in MENA that could lead to critical situations in the near term. A look into future trends (Fig. 1) gives an idea of the tremendous efforts which will be required in the upcoming years in order to satisfy the water demand, which will increase due to population growth and economic development; while on the other hand—according to most climate change models—precipitations will be likely to fall by up to 20% with respect to the current situation. The Maghreb region, Syria, and Iran will probably be particularly affected by the precipitation reductions [3]. As a result, a severe water supply gap is opening. Different countermeasures should be implemented as soon as possible in order to mitigate this problem and to reduce the overexploitation of groundwater resources.

These countermeasures mainly fall under three categories:

- Productivity increases (improved agricultural practices such as enhanced irrigation systems, utilization of optimized crop varieties, and wastewater reuse).
- Demand reduction (reduction of irrigated area for agriculture, enhanced domestic and/or industrial efficiency of supply).
- Supply expansion by nonconventional sources (reservoirs and desalination).

Any of the implemented solutions will not be for free; different options will have different marginal cost and will be limited by their application and by their potential (e.g. maximal potential for installation of water reservoirs). Furthermore, the realization of new measures—for example, the substitution of unsustainable extractions with new sources of water supply—will take time, so that each measure is also limited by a maximum introduction speed. Recently, FutureWater proposed an innovative approach in order to characterize different measures. The analysis presented in Fig. 1 is based on a study by FutureWater, Fichtner, and DLR [3,4].

The main findings of this study were that in the MENA region the adaptation cost will be—depending on several factors such as assumed economic growth rate and applied climate change model—between 0.5 and 1.6% of the total GDP of the MENA region. However, significant differences can be observed among the analyzed countries. According to this analysis, countries like Egypt, Jordan, Iraq, Morocco, and in particular Yemen have to be prepared to spend a relevant amount of their GDP (4 up to 11%) in order to mitigate the effect of water scarcity.

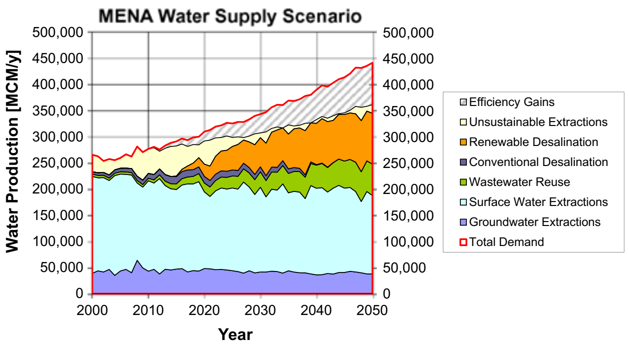

Fig. 1. Water supply for the MENA Region between 2000 and 2050 [4].

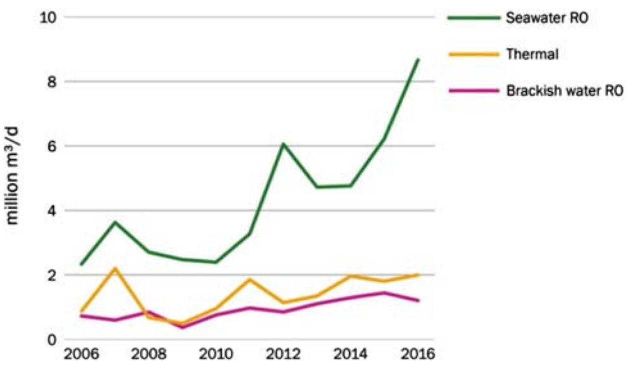

Fig. 2. GWI global forecast for annual contracted capacities of the main desalination technologies [5].

Summing up, the increasing water gap and the limitations of alternative water supply options call for further installation of new large desalination plants. Indeed, this already is an ongoing process which will become even more problematic in the following years, as statistical data confirm and projections show [5]. Fig. 2 presents past and expected short-term trends for new installed desalination plants. The analysis comprehends the expected trends for the two main desalination "families", i.e. reverse osmosis (RO) and thermal. A further differentiation between seawater and brackish water RO is made.

However, desalination is known as an energy intensive process; a large-scale installation will result in a relevant additional electricity and heat requirement, which will again require new power plants. Table 1 resumes the key power demand parameters for the most market-dominating desalination technologies. As electricity requirements of RO are significantly influenced by seawater salinity, two reference sites are presented (Mediterranean Sea: assumed salinity ca. 35,000 ppm; Arabian Gulf: assumed salinity ca. 45,000 ppm).

Looking at Table 1 (column "Total Energy Requirements"), it can be observed that RO performs better than all other thermal desalination technologies, with the exception of multiple effect distillation (MED) under high seawater salinity conditions. In this case, MED and RO present almost the same total power consumption (ca. 4.5 kWh/m^3). As explained in [6], electricity and heat consumption—which cannot be simply summed up in order to get the total power consumption of a desalination plant—are compared by means of the reference cycle method. This method bases on the idea that the steam (at ca. 70°C) which is used to drive the MED, could alternatively be expanded to generate an additional amount of electricity. This virtual additional electricity amount is expressed in kWh$_{el}$/m^3 in the column "Equivalent Power Loss". This method will be also adopted in the following analysis in order to estimate the heat cost of the MED. In the case of MSF and MED-TVC, the higher heat consumption in comparison to the MED is partly compensated by higher gain output ratio (GOR).

Table 1
Energy requirements of different desalination technologies [6, adapted]

Technology	Spec. El. consumption	Steam pressure	Thermal energy	Equivalent power loss	Total energy requirements
Unit	kWh$_{el}$/m^3	bar	kWh$_{th}$/m^3	kWh$_{el}$/m^3	kWh$_{el}$/m^3
SWRO (Med. Sea)	3.5	–	0	0	3.5
SWRO (Arabian Gulf)	4.5	–	0	0	4.5
MSF	4–5	2.2–2.5	80	10–20	14–25
MED-TVC	1–1.5	2.2–2.5	80	10–20	11–21.5
MED	1–1.5	0.35–0.5	60	3	4–4.5

2. General characterization of desalination Plants

New power plants for the supply of desalination units should be able to deliver firm capacity as—due to technical and economic considerations—large desalination plants are typically operated as base load plants. Beside investment cost, also energy cost will play an important role in the definition of the levelized water cost (LWC).

At this point, it is interesting to look at the annual cost structure of a typical conventional desalination plant. In Fig. 3, the cost structure of a typical RO plant is divided into three main factors:

- annual capital cost,
- operation and maintenance (O&M) cost, and
- electricity cost.

Further, a simplified sensitivity analysis of the cost structure for two different fuel cost is shown. It can be observed that doubling the fossil fuel cost (from 30 to 60 US$/MWh$_{th}$) results in a relevant increase in the electricity expenditures (from 34 to 48% of the total cost). In this example, the LWC (related to the whole desalination plant life) would increase by 28% from 1.23 to 1.58 US$/m^3 (see also Table 4).

The example of Fig. 3 aims to highlight the effect of fossil fuel escalation on water cost. Indeed, in the last years fossil fuel prices have been prone to strong fluctuations and a clear upward trend, as can be seen in Fig. 4. Coal, natural gas, and crude oil price escalation have been more than 400% in the last 10 years.

Considering that desalination capacities have—depending on the installed technology—a plant life of 25–35 years, the uncertainty about future fuel prices presents a severe economic risk factor for the new plants.

3. Renewable energy for desalination

In the light of the considerations exposed above, renewable energies have huge potential in order to reduce fossil fuel consumption, allowing at the same time for economic risk reduction and for minimization of adverse environmental effects [8]. These two key aspects are explained in detail after a brief introduction on main renewable energy technologies suitable for the MENA region. Focus is given to the fact that different technologies will supply different quality of power (fluctuating vs. flexible, firm power capacity).

3.1. Renewable energy cost developments

Renewable energy sources are characterized by high variability in time and space. Similarly to oil and gas reserves, renewable resources such as solar irradiance and wind velocity are particularly high in certain areas of the world. Renewable resources need to be tapped by means of new investments, plants, and—if necessary—infrastructures. Renewable energy technologies have not yet reached the end of their learning curve, i.e. each new installed capacity is—ideally speaking—cheaper than the previous one, due to major experience and scaling effects as well as technology improvements (Fig. 5). The values shown in Fig. 5 represent only general trends for specific assumptions with respect to site conditions and capacity expansion and should not be used for quantitative comparison.

The comparison of Figs. 4 and 5 highlights the large potential for renewable energies in terms of cost trends. Depending on technology, available resources, and financial boundary conditions, renewable energy technologies will achieve even larger power generation shares in the future energy mix. More information about technology-specific cost development can be found in [10–13].

3.2. Overview of renewable energy technologies for the MENA region

3.2.1. Wind

Wind power currently is after hydropower, the largest contributor to renewable electricity. The work-

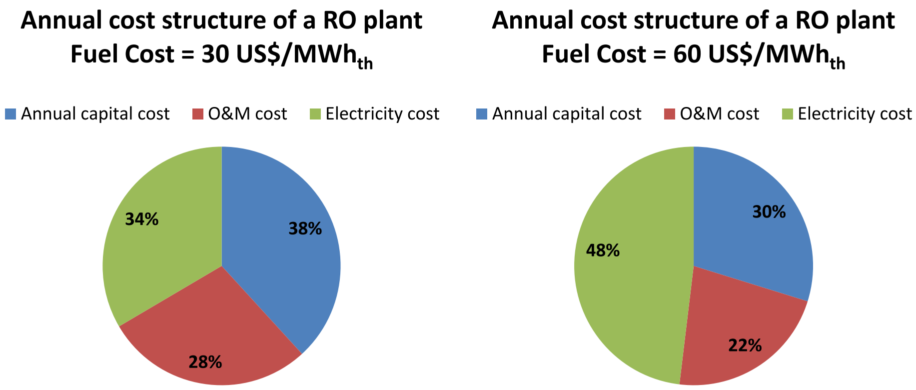

Fig. 3. Annual cost structure of a typical RO plant as function of fuel cost (on the left: fuel cost 30 US$/MWh$_{th}$; on the right: fuel cost 60 US$/MWh$_{th}$).

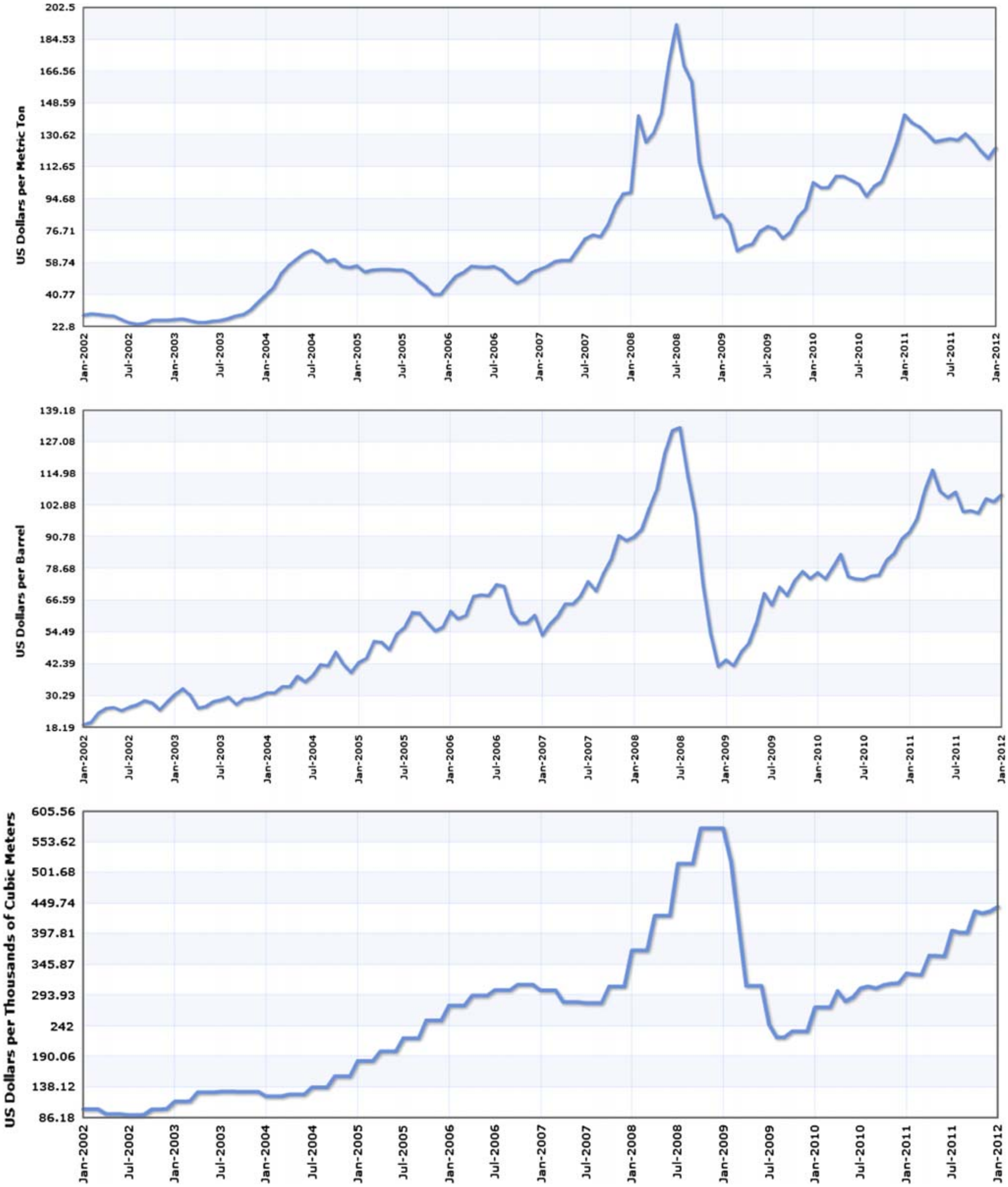

Fig. 4. Fossil fuel price trends in the last 10 years [7]; Australian steam coal (top), world market crude oil (center), and Russian natural gas (bottom).

ing principle of a wind turbine is simple: energy is extracted from the wind by means of a horizontal rotor, whereas the generator is housed at the top of the tower. As it can be seen in Table 2, the worldwide installed capacity amounts to 240 GW [14]. The impressive installation rate in the last years has driven the cost down and wind actually is after large-scale hydropower, the cheapest renewable option for electricity generation. Due to the relative technology maturity in comparison to other technologies (Fig. 5), further cost reduction potential for future installed wind power plants is limited. The typical capacity of new installed turbines is around 2 MW; however, turbine models up to 7 MW are under construction.

3.2.2. Photovoltaic (PV)

PV is a highly modular technology, which directly transforms incoming solar irradiation into electricity. PV systems make use of the global irradiance, with the exclusion of concentrating PV (CPV), which use only the direct share of the irradiation. PV can be used for on-grid and off-grid applications, starting from few watts and up to several megawatt plants. The largest market share is currently taken by crystalline silicon technologies. However, in the last years thin film gained a relevant market share (9%), and also CPV is being developed [15]. As can be seen in Fig. 5, in the last years, the average electricity production cost have achieved an important reduction due to an elevated decrease in the module investment cost.

3.2.3. Concentrating solar power (CSP)

CSP systems uses concentrated solar radiation to generate high temperature heat, which is used to drive a conventional power cycle and to produce electricity. Unlike PV, CSP only makes use of direct beam irradiance (Direct Normal Irradiance [DNI]). Main components of a CSP plant are solar field, thermal energy storage, and conventional power block. The option of a relatively cheap thermal energy storage (if compared with batteries or compressed air energy storages [CAES]) make CSP an attractive option in order to reach high shares of renewable generation without causing any fluctuations on the grid [16]. In simple words, CSP is nothing but a conventional power plant which can be fueled either with solar energy or with fossil fuel. Depending on the plant design, such a plant could supply an annual solar share higher than 70%. This means CSP is an excellent choice in regions with high DNI resources for both:

- flexible cover of evening peak loads (with small thermal energy storage and fossil backup) and
- base load operation (with large thermal energy storage and fossil fuel backup).

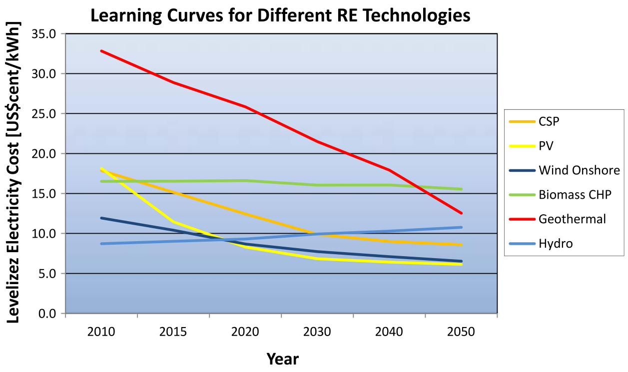

Fig. 5. Learning curves for different renewable energy technologies [9, adapted for PV to specific MENA conditions].

In addition, CSP also holds potential for generation of other energy carriers such as solar hydrocarbon fuel [17] and electricity export to Europe for balancing power [18].

3.2.4. Preliminary comparison

Both solar and wind technologies present huge potentials in the MENA region. Each technology has different performance characteristics, raising the question, which technology—or better—which technology mix will provide most economic and sustainable power supply for seawater desalination. Table 2 gives some preliminary information on key characteristics of wind power, PV, and CSP.

Wind and PV are fluctuating energy sources, while CSP is able to supply firm or flexible power on demand. Indeed, CSP can be considered the “all-in-one” solution, because of the option of integration with thermal energy storage and of hybridization by fossil fuels within the same power block. On the contrary, Wind and PV are requiring—beside battery or—if available—CAES systems—an external backup such as a conventional power plant in order to deliver firm power as required by large desalination plants. Table 2 shows that specific investment cost are higher for CSP than for Wind and PV; however, the investment cost for storage and backup are higher for Wind and PV than for CSP.

Table 2
Preliminary comparison of analyzed technologies [13,14]

Characteristic	Unit	Wind	PV	CSP
Used resource	–	Wind velocity	GTI	DNI
Power dispatch type	–	Unpredictable, fluctuating	Predictable, fluctuating	Firm or flexible, depending on requirements
Typical capacity range	MW	>0.05	>0.005	>20
Plant life time	y	25	25	35
Capacity factor	–	<0.45	<0.25	<0.75
Worldwide installed capacity	GW	238	67	2
Investment cost	US$/ kW_{el}	2,000	2,600	4,500–7,000
Storage options[a]	–	Batteries, CAES	Batteries, CAES	Thermal storage
Storage investment cost	US$/ kWh_{el}	650	650	100–200
Backup options	–	Diesel generators, conventional power plants	Diesel generators, conventional power plants	Backup boiler
Backup cost	US$/ kW_{el}	1,500	1,500	370

[a] Hydro Pump Storage is not available in MENA.

One could argue that wind and PV power can be easily fed into the local electricity grid, while a desalination plant could be as well fed by electricity from the grid, in this way avoiding the need for storing electricity in batteries, pump storage or CAES and using other power plants on the grid as backup. This is true if one wants to reduce the consumption of fuel by an existing conventional power park. When wind power and solar energy is available, production of the existing plants can be reduced, and during calms and at night, conventional capacity will again take over supply.

However, the addition of load in quickly growing electricity markets like the MENA will always require the installation of an equivalent additional firm power supply capacity, in order to avoid power outages, because one can assume that existing capacity would suffice to cover existing demand, but not additional one. Especially when adding a continuous load such as that of a desalination plant, firm power capacity for continuous supply must also be added to the grid.

At the end of the day, the optimal sustainable mix will depend on available resources, proportion of the installed capacities for each technology and fossil fuel cost. The problem is further complicated by the fact that future capital cost of different renewable technologies and fuel cost are not known in advance.

In the last years, Germany and other European countries introduced a feed-in tariff system in order to accelerate the market introduction of PV and other renewable technologies, which is now taken as a model for several nonEuropean countries [15]. Furthermore, other recent works describe how innovative financing schemes in MENA countries could accelerate the market introduction of CSP and other renewable energy technologies by means of international insured power purchase agreements (iPPA) and adequate tariff structures [19].

3.3. Technical constraints and methodology comparison

As wind and PV power generation are characterized by large fluctuations, these plants will not necessarily operate at full power all the time, but only when wind speed and solar irradiation would allow for it. At other times, excess power production may be dumped. Renewable nonflexible electricity generation will require special management of the power system to maintain grid stability and reliability. However, high wind and PV penetration shares will be possible by additional system flexibility through a combination of flexible generation, load management, enhanced interconnection, and additional electricity storage [20].

The fluctuating and intermittent character of most renewable energy technologies contrasts with the operation requirements of large desalination plants, which are typically operated as base load plants in order to guarantee continuous water supply. While on the one hand thermal desalination units need continuous thermal supply, so that heat and power generation intermittency by a CSP plant would not be allowed; on the other hand, RO systems will require continuous electrical energy, which can be supplied in principle either by renewable power plants (no matter if Wind, PV and/or CSP) or by fossil backup systems or indirectly by the electricity grid.

Differing boundary conditions can be assumed in order to compare different technology options. The aim of this work is to underline how the assumptions which are taken as a basis for the comparison significantly influence the final result. For example, CSP is misleadingly supposed to be an expensive option if compared with other renewable technologies [21], mainly due to the fact that different power qualities are taken as a basis for the comparison. However, one should be aware that different power qualities correspond to different amount of externalized cost.

Within the next sections, the following methodologies are compared:

3.3.1. Intermittent renewable supply

It is assumed that the renewable energy power plant generates on an annual basis the power amount required by the desalination plant. In order to satisfy this condition, the renewable power plants typically have a larger capacity than the capacity required by the desalination plant, due to the fact that wind and PV are intermittent power generation technologies. This means that in some hours of the year, the power plant generates more power than needed and the surplus is fed into the grid, while at periods with few or no RE power production the grid acts as a backup. It is assumed that the grid is able to accept at any time all power production surpluses as well as to dispatch power demand for the desalination whenever required. In other words, it is assumed that an ideal, infinite storage is available at no additional cost and free of energy losses to buffer renewable energy fluctuations of any kind. Under this assumption, no power dumping is needed. This method bases on the idea that an ideal high capacity and stable grid is available and the maximal renewable energy generation is small in comparison to the total load.

3.3.2. Direct supply

The method described above is a rather optimistic approximation of the real world. In reality, conventional power plants allowing for the feed in of renewable power generation surpluses will be forced into part-load operation when renewable power excess occurs, and operate at full load otherwise. This will lead to higher fuel consumption due to lower part-load plant efficiency. Start-up procedures will be more frequent and will consume additional fuel. The capacity factor of these backup plants will be reduced, decreasing their annual return on investment and economic performance, and raising their cost of operation and maintenance.

Furthermore, whenever RE power plants are not in operation, or when they supply less power than required, backup power will be required. The installation of new fossil backup plants is required since the desalination plant represents a new additional load in a system characterized by high-demand growth rates. Therefore, the direct supply method includes these effects and their additional cost. This means that all cost for the desalination supply is taken into account and are not externalized as it was the case in the first method. Surplus RE export is allowed and is remunerated with a given tariff (two cases are presented), while fossil backup is based in one case on partially subsidized prices and in another case on fossil fuel world market prices.

4. Model assumptions

4.1. Input data

The simulation is carried out with hourly time steps for one year; therefore, in a first place hourly input variables are required by the program. This data include ambient temperature, wind velocity, solar irradiance (direct normal, global horizontal, diffuse), and electricity demand for desalination.

The hourly wind data have been scaled from measurement height at 50 m to the wind turbine hub height by means of the logarithmic wind velocity profile law. The ground roughness factor is assumed to be 0.05 m, which can be considered a good first estimate for desert environments. The global horizontal irradiance data have been transformed to global-tilted irradiance by consideration of the PV modules tilt angle.

The used data are real data gathered by [22,23] in a specific location within the MENA region. They can be considered as typical values for a site with good solar and wind resources. The annual sum of direct normal and global horizontal irradiance amount to 2,516 and 2,350 kWh/m^2/y, respectively; while the annual average wind velocity at hub height is 7.0 m/s. Here, we do not want to focus on the results of a specific site analysis, but show the impacts of different analysis methods on performance and cost calculations.

4.2. Technologies and simulation

The scenario modeling and simulation are carried out with the INSEL software [24], a modular simulation environment that uses a graphical interface for analysis of power systems with focus on renewable energies.

Commercial wind power and PV modules are available in a software library, which has been used for the current work. Due to the high number of simulation runs, CSP was modeled by means of a simplified model implemented in Excel and basing on available literature and DLR in-house knowledge [25]. Further information on the implemented CSP model can be found in [26].

Within this work the following technologies have been selected:

- *Wind*: 2 MW Wind turbines are considered. The hub height is assumed to be 90 m. A characteristic power generation line as function of wind velocity has been considered. It is assumed that the wind turbine starts producing electricity at a hub wind velocity of 3 m/s, reaches nominal capacity at 12 m/s, and is switched off at wind velocities higher than 25 m/s. Availability and wake losses are considered by an overall loss factor of 0.85 [27].
- *PV*: standard commercial polycrystalline PV modules and inverters have been selected. The PV modules are assumed to have fixed mounting; the tilt angle has been optimized in order to maximize annual electricity production. The high modularity of PV systems allows scaling the plant capacity to the desired requirements. The INSEL models take into account the effect of ambient temperature on module efficiency. System losses due to shadowing, soiling, and ohmic wiring are also considered.
- *CSP with thermal energy storage and backup*: state-of-the-art CSP power plants with parabolic through and molten salt thermal energy storage have been considered. The power block consists of a conventional steam cycle with once-through cooling. The plant is also provided by a 100% thermal capacity fossil backup boiler in order to eventually bridge times with low or no available solar energy from solar field or thermal storage.
- *Fossil backup plants*: conventional power blocks with nominal efficiency of 33% (average power park efficiency) are assumed. Part-load behavior is considered by a characteristic line.
- *Batteries*: state-of-the-art lithium-ion batteries are considered. The average battery efficiency is optimistically assumed to be 90% [28].
- *Desalination*: desalination plants are simply modeled as power consumers. Specific electricity and heat consumption for RO and MED plants are as in Table 1. For RO, an average electricity consumption of 4.2 kWh/m^3 has been assumed. All analyzed cases are designed to supply a 100,000 m^3/day desalination plant. Under these assumptions, a RO plant will approximately require 17.5 MW$_{el}$ firm power, while an MED with the same capacity (GOR of 12 is assumed) will need around 6.3 MW$_{el}$ and ca. 265 MW$_{th}$. Due to the heat requirement, the

Table 3
Overview on investment and operation cost assumptions [4, adapted, 10–13]

CAPEX and OPEX assumptions		
Wind		
Spec. CAPEX	US$/kW	2,000
Spec. OPEX	% Tot. Inv./y	1.5
PV		
Spec. CAPEX	US$/kWp	2,500
Spec. OPEX	% Tot. Inv./y	2.0
CSP		
Spec. CAPEX solar field	US$/m^2	420
Spec. CAPEX thermal storage	US$/kWh$_{th}$	75
Spec. CAPEX backup boiler	US$/kW$_{el}$	370
Spec. CAPEX power block	US$/kW	1,500
Spec. CAPEX once-through cooling	US$/kW$_{el}$	150
Spec. OPEX	% Tot. Inv./y	2.5
Backup and Storage		
Spec. CAPEX backup plant	US$/kW$_{el}$	1,500
Spec. OPEX backup plant	% Tot. Inv./y	1.5
Spec. CAPEX battery	US$/kWh	910
OPEX battery	% Tot. Inv./y	3.0
RO		
Spec. CAPEX	US$/m^3	2,100
Spec. OPEX	US$/m^3	0.35
MED		
Spec. CAPEX	US$/m^3	3,200
Spec. OPEX	US$/m^3	0.35
Financial assumptions		
Debt period	y	25
Discount rate	%	6.0

gross electrical power to be installed in this case will amount to around 120 MW_{el} (assumed a gross steam turbine efficiency of 33%).

4.3. Economic and financial assumptions

Table 3 presents an overview on key specific investment, operation, and maintenance cost. The selected values are taken from available literature [10–13,29] and DLR in-house expertise. Investment costs include EPC cost, infrastructure, site preparation, and contingencies. The accuracy of these data is assumed to be in the range of ±25%, which is considered satisfactory within the aim of the current work.

In opposition to PV and wind, CSP can be designed with different solar field and thermal storage layout in order to supply the same amount of electricity. For this reason, the cost structure of CSP as presented in Table 3 is divided into the single plant components.

5. Results and discussion

5.1. Intermittent renewable supply

Within the first methodology, the focus is given to the single technologies. The following cases are compared as standalone RE power plants, without consideration of externalities:

- wind + RO,
- PV + RO,
- CSP + Storage + RO, and
- fossil power + RO (low and high fossil fuel price).

The wind and PV plants are designed in order to provide on annual basis the energy required by the RO plant which is 153 GWh/y, whereas the CSP layout (solar field and thermal energy storage size) is optimized in order to minimize the levelized electricity cost (LEC) of a state-of-the-art turbine (50 MW) with the same annual net electricity generation. An MED case is not considered here, since it is assumed that an equivalent large-scale heat storage as in the case for electricity (the grid) is not available.

5.1.1. Results

Table 4 summarizes main results for the first mentioned methodology. In this case, due to the fact that the RE plants are designed in order to generate on annual basis, the power required by the RO without consideration of any externality, the results are simply reflecting the different investment cost as already presented in Table 3. It can be seen that wind power has the lowest LEC not only among the RE cases, but also in comparison with conventional, fuel-powered desalination. Due to the higher investment cost, PV and CSP provide higher LEC and LWC.

5.2. Direct power supply

Within the direct supply methodology, a different approach has been chosen. In this case, power has to be supplied directly on demand, just as required by the desalination unit at each time step. This implies the consideration of storage, backup, and grid management costs. The following configurations are analyzed:

- wind + battery + external fossil backup + RO,
- PV + battery + external fossil backup + RO,
- CSP + Storage + internal fossil backup + RO or MED, and
- RE-Mix + external fossil backup + RO.

Within the last case, fluctuating renewable energy technologies (wind and PV) are assumed to have feed-in priority in comparison with fossil backup. PV and wind power plants are assumed to generate power free of constraints as long as the generated power does not exceed a given grid reliability limit. CSP acts as a renewable backup, i.e. at times with high PV and wind power generation CSP is operated at partial load conditions or even shut down, while the heat collected in the CSP solar field is stored in the thermal energy storage for later use.

Due to the fact that the total cost of power supply is considered in these cases, the assumption met within the previous methodology—RE plant designed to provide on annual basis the power needed by the desalination—is replaced by this analysis by the following conditions:

- RE penetration shares of 40 and 80% (annual direct desalination supply). These set values do not have particular technical meaning; rather they serves to highlight the sensitivity on results of medium and high RE share in the power generation mix. The installed capacity of RE and—if required—energy storage has been iterated in order to reach the lowest LEC under the given constraints.
- Average lifetime fuel prices of 30 and 60 US$/$MWh_{th}$. The proposed values are calculated taking representative natural gas prices in MENA (ca. 22 US$/$MWh_{th}$) [30] and on the European market (ca. 43 US$/$MWh_{th}$) [7] as current values and

Table 4

Result overview for the case intermittent renewable power generation in comparison with fossil fueled desalination

Intermittent RE power supply						
	Unit	Wind + RO	PV + RO	CSP + RO	Fossil + RO (low fuel price)	Fossil + RO (high fuel price)
Installed capacity wind	MW	63.3	0.0	0.0	0.0	0.0
Installed capacity PV	MW_p	0.0	77.9	0.0	0.0	0.0
Battery capacity	h	0.0	0.0	0.0	0.0	0.0
Installed capacity CSP	MW	0.0	0.0	50.0	0.0	0.0
CSP solar multiple	–	0.0	0.0	1.5	0.0	0.0
CSP storage capacity	h	0.0	0.0	1.0	0.0	0.0
Total annual power gen. RES	GWh/y	153.3	153.3	153.3	0.0	0.0
Direct annual power gen. RES	GWh/y	94.5	63.7	61.9	0.0	0.0
Annual required grid imports	GWh/y	58.8	89.6	91.4	153.3	153.3
Annual grid exports	GWh/y	58.8	89.6	91.4	0.0	0.0
Annual power demand desalination	GWh/y	153.3	153.3	153.3	153.3	153.3
Total annual RE cover ratio	%	100.0%	100.0%	100.0%	0.0%	0.0%
Direct Annual RE Cover Ratio	%	61.6%	41.6%	40.4%	0.0%	0.0%
Tariff for Export	$US\$cent/kWh_{el}$	8.11	12.31	16.68	–	–
Fossil Fuel Price	$US\$/MWh_{th}$	–	–	–	30.0	60.0
Annual export revenue	Mio. US$/y	4.77	11.03	15.24	0.00	0.00
Annual grid management cost	Mio. US$/y	1.35	1.99	2.05	0.00	0.00
LEC RES only[a]	$US\$cent/kWh_{el}$	8.11	12.31	16.68	0.00	0.00
Electricity Cost Desalination	$US\$cent/kWh_{el}$	8.11	12.31	16.68	10.69	19.70
Annual Desalination Heat Cost	Mio. US$/y	0.00	0.00	0.00	0.00	0.00
LWC	$US\$/m^3$	1.13	1.30	1.47	1.23	1.58

[a] Export tariff and grid management cost not considered.

Table 5
Estimation of future gas prices for MENA and European market

	Unit	Low price scenario	High price scenario
Current gas price	US$/MWh$_{th}$	21.7	43.4
Escalation rate	%/y	5	15
Plant life time	y	25	
Average gas price	US$/MWh$_{th}$	34.3	57.2

applying a price escalation rate of 5 and 15%/y, respectively, as shown in Table 5. For the analysis, we use the average gas price along the plant life time of 25 years. All prices are accounted on real cost basis. For simplicity, the gas price value from Table 5 has been rounded; further, only the two extreme cases are presented within this paper, i.e. the case 40% RE-share and 30 US$/MWh$_{th}$ fossil fuel price, and the case 80% RE-share and 60 US$/MWh$_{th}$ fossil fuel price.

- As last analysis, the tariff for eventual power exports has been set in one case to the LEC of the RE generation mix (so that a certain technology is not penalized in the case of high power export rates) and in a second case to a fixed value of 6.0 US$cent/kWh$_{el}$. This roughly corresponds to the current average marginal power price in MENA [30]. The plant design has been optimized for the first tariff case, as presented in the result tables. A different optimal configuration was found for the last analyzed case, the mix of renewable energy technologies.

5.2.1. Results

Table 6 presents key results of the case with low RE share (40%) and low fossil fuel prices (30 US$/MWh$_{th}$). At a first glance, it can be seen that both wind (26.1 MW) and PV (60.4 MW) need to be significantly oversized with respect to the desalination capacity (17.5 MW). However, this does not apply for CSP, which has a net installed capacity equal to the desalination capacity. This particular characteristic of CSP is due to the thermal energy storage with a size of approximately four full-load hours. Consequently, CSP produces power on demand and does not generate any power that must be exported to the grid.

In opposition to the methodology presented before, within the direct power supply method the cost of fossil power backup capacity is taken into account (both investment and fossil fuel cost) as well as additional externalities such as grid management cost due to part-load operation of existing fossil power plants at times with renewable surplus power production. The consideration of these factors leads to a higher levelized cost for backup electricity. In Table 6 two LEC are shown: the first—"LEC RES only"—considers the power production by renewable power plants only, while the second—"LEC Mix"—considers backup cost, grid management, and feed-in tariff for power exports. Under grid management, other power plants are forced to operate at part-load conditions at times with high-renewable power generation. The "LEC RES only" values mainly represent the electricity cost from the point of view of a private project developer; they express the ideal value of renewable power generation in absence of any constraints. For these reasons, they cannot be considered as LEC for a defined power supply; such a comparison would be affected by a certain degree of distortion. The larger the power capacity that has to be exported to the grid, the larger is the difference between the two calculated LEC. In order to obtain a fair comparison for a defined power supply such as a desalination plant, the "LEC Mix" values taking into account all externalities should be used.

In all analyzed scenarios except the two CSP cases, the LEC calculated for the individual renewable energy plants are lower than the LEC of the energy mix. PV generates large power surpluses, which cause high grid management cost and results in a disadvantage in particular if the feed-in tariff for power export is set low, as in the second case (6.0 US$cent/kWh instead of 12.31 US$cent/kWh). For this case, a PV/Battery system would provide slightly lower LEC and LWC, because less power must be exported at a tariff that does not cover the real cost.

At the analyzed site, wind power generation patterns are clearly more distributed than for solar systems, so that the target of 40% can be easily reached without causing relevant power export and grid management cost. Under these assumptions, wind combined with a fossil backup provides lowest specific electricity and water production prices.

The CSP/MED system is designed in order to satisfy the heat requirements of the thermal desalination. This means that relevant electricity surplus is generated. In this case, grid management cost are set to zero as well as export revenues, due to the fact that the surplus power generation is constant because of the base-load operation of the MED. The heat cost has been evaluated according to the reference cycle method, whereas a CSP with once-through cooling (similar to the CSP + RO case) has been taken as reference plant. The electricity cost reported in Table 6 refers to the reference plant, while the higher LEC of

Table 6
Result overview for the case 40% direct renewable power generation and 30 US\$/MWh$_{th}$ fossil fuel cost (neutral and fixed tariff case)

Direct RE Power Supply, Case 1—RE-Share: 40%, Fossil Fuel Price: 30 US\$/MWh$_{th}$

	Unit	Wind + RO	PV + RO	CSP + RO	CSP + MED	Mix + RO
Installed capacity wind	MW	26.1	0.0	0.0	0.0	26.1
Installed capacity PV	MW$_p$	0.0	60.4	0.0	0.0	0.0
Battery capacity	h	0.0	0.0	0.0	0.0	0.0
Installed capacity CSP	MW	0.0	0.0	17.5	120.0	0.0
CSP solar multiple	–	0.0	0.0	1.6	1.9	0.0
CSP storage capacity	h	0.0	0.0	4.2	5.0	0.0
Total annual power gen. RES	GWh/y	63.2	118.9	61.4	958.2	63.2
Direct annual power gen. RES	GWh/y	61.4	61.4	61.3	61.3	61.4
Annual required grid imports	GWh/y	91.9	91.9	92.0	92.0	91.9
Annual grid exports	GWh/y	1.8	57.5	0.1	0.0	1.8
Annual power demand desalination	GWh/y	153.3	153.3	153.3	54.8	153.3
Total annual RE cover ratio	%	41.2%	77.5%	40.0%	625.0%	41.2%
Direct annual RE cover ratio	%	40.0%	40.0%	40.0%	40.0%	40.0%
Tariff for export (Tariff = LEC power mix)	US\$cent/kWh$_{el}$	8.11	12.31	11.83	12.02	8.11
Annual export revenue	Mio. US\$/y	0.15	7.08	0.01	0.00	0.15
Annual grid management cost	Mio. US\$/y	0.04	1.36	0.00	0.00	0.04
LEC RES only[a]	US\$cent/kWh$_{el}$	8.11	12.31	11.83	12.02	8.11
LEC Mix[b]	US\$cent/kWh$_{el}$	10.74	12.98	11.88	12.02	10.74
Electricity cost desalination	US\$cent/kWh$_{el}$	10.74	12.98	11.88	12.02	10.74
Annual desalination heat cost	Mio. US\$/y	0.00	0.00	0.00	15.20	0.00
LWC	US\$/m^3	1.24	1.32	1.28	1.62	1.24
Tariff for Export (Tariff = Fixed Value)	US\$cent/kWh$_{el}$	6.00	6.00	6.00	6.00	6.00
Annual export revenue	Mio. US\$/y	0.11	3.45	0.00	0.00	0.11
Electricity cost desalination	US\$cent/kWh$_{el}$	10.77	15.35	11.88	12.02	10.77
LWC	US\$/m^3	1.24	1.41	1.28	1.62	1.24

[a] Export Tariff and Grid Management Cost not considered.

[b] Considering export tariff and grid management cost.

Table 7
Result overview for the case 80% direct renewable power generation and 60 US$/MWh$_{th}$ fossil fuel cost (neutral and fixed tariff case)

Direct RE power supply, Case 2—RE-Share: 80%, Fossil fuel price: 60 US$/MWh$_{th}$						
	Unit	Wind + RO	PV + RO	CSP + RO	CSP + MED	Mix + RO
Installed capacity wind	MW	231.0	0.0	0.0	0.0	67.2
Installed capacity PV	MW$_p$	0.0	69.4	0.0	0.0	0.0
Battery capacity	h	0.0	4.0	0.0	0.0	0.0
Installed capacity CSP	MW	0.0	0.0	17.5	120.0	17.5
CSP solar multiple	–	0.0	0.0	3.8	3.9	1.2
CSP storage capacity	h	0.0	0.0	19.0	19.0	5.0
Total annual power gen. RES	GWh/y	559.5	196.5	122.8	1019.8	189.3
Direct annual power gen. RES	GWh/y	122.7	122.6	122.6	122.6	122.7
Annual required fossil backup	GWh/y	30.6	30.7	30.7	30.7	30.6
Annual grid export	GWh/y	436.9	14.0	0.2	0.0	66.5
Annual power demand desalination	GWh/y	153.3	153.3	153.3	54.8	153.3
Total annual RE cover ratio	%	365.0%	128.2%	80.1%	665.2%	123.5%
Direct annual RE cover ratio	%	80.0%	80.0%	80.0%	80.0%	80.0%
Tariff for Export (Tariff = LEC Power Mix)	US$cent/kWh$_{el}$	8.11	23.17	18.81	18.61	12.66
Annual export revenue	Mio. US$/y	35.43	3.24	0.03	0.00	8.41
Annual grid management cost	Mio. US$/y	17.55	3.23	0.01	0.00	2.92
LEC RES only[a]	US$cent/kWh$_{el}$	8.11	23.17	18.81	18.61	12.66
LEC Mix[b]	US$cent/kWh$_{el}$	23.42	26.03	18.90	18.61	14.57
Electricity cost desalination	US$cent/kWh$_{el}$	23.42	26.03	18.90	18.61	14.57
Annual desalination heat cost	Mio. US$/y	0.00	0.00	0.00	25.20	0.00
LWC	US$/m^3	1.73	1.83	1.55	1.98	1.38
Tariff for Export (Tariff = Fixed Value)	US$cent/kWh$_{el}$	6.00	6.00	6.00	6.00	6.00
Annual export revenue	Mio. US$/y	26.21	0.84	0.01	0.00	0.01
Electricity cost desalination	US$cent/kWh$_{el}$	29.44	27.60	18.91	18.61	16.32
LWC	US$/m^3	1.96	1.89	1.55	1.98	1.45

[a] Export Tariff and Grid Management Cost not considered.

[b] Considering Export Tariff and Grid Management Cost.

the CSP/MED has been completely allocated to the thermal desalination plant (Heat Cost Desalination in Table 6).

In the next table (Table 7), the results for the direct energy supply with 80% renewable share and high fossil fuel prices (60 US\$/MWh$_{th}$) are presented.

Due to the excellent wind velocity resources, wind power is able to reach 80% of annual direct power supply without recurring to electricity storage. However, in this case extremely large power surpluses are generated; the installed wind capacity is ca. 13 times higher than the capacity required by the desalination plant (Fig. 6). The elevated power export capacity in combination with the high fossil fuel prices for backup leads to significant grid management cost (approximately 15.3 US\$cent/kWh), which is approx. six times higher than in the previous scenario.

A combined wind/battery system with ca. 1 h battery capacity would provide slightly lower LEC and LWC in the case of fixed low tariff for export; however, a higher battery capacity (2 h or more) would result in high investment cost, whereas the battery would be the majority of the time either completely empty or totally charged, which would significantly reduce its lifetime.

PV is able to generate electricity only at certain hours of the day, so that the renewable direct power supply cannot be simply increased above certain limits (ca. 45% of the annual power share) by scaling up of the plants. To increase the direct renewable share beyond this point, a battery storage system will be required (pump storage or compressed air storage cannot be considered as easily available in the MENA region). The installation of a four full-load hour battery allows the achievement of the 80% target (Fig. 7), whereas power export and the related grid management cost can be limited. At times with high solar irradiation, the PV power production by far exceeds the desalination electricity requirements, so that the battery can be charged. In summer, the battery is sometimes fully charged; in this case, PV surplus generation will be completely fed to the grid.

Adding current battery investment cost to the PV system results in a high final LEC of 26 US\$/kWh. Accordingly, the LWC is around 1.9 US\$/m^3.

It is also interesting to note that the differing power generation patterns of wind and PV result in completely different optimal configurations. In the case of wind, the use of battery would not lead to significant advantages in economic terms. This is due to the unregularly intermittent and fluctuating wind power generation, with the consequence that the capacity utilization of the battery would be by far not optimal.

On the contrary, PV in desert environments presents variable but regular power generation patterns. Therefore, in this case, the utilization of the battery capacity is high. Fig. 7 shows that the battery charge/discharge cycle has a well defined and regular daily pattern.

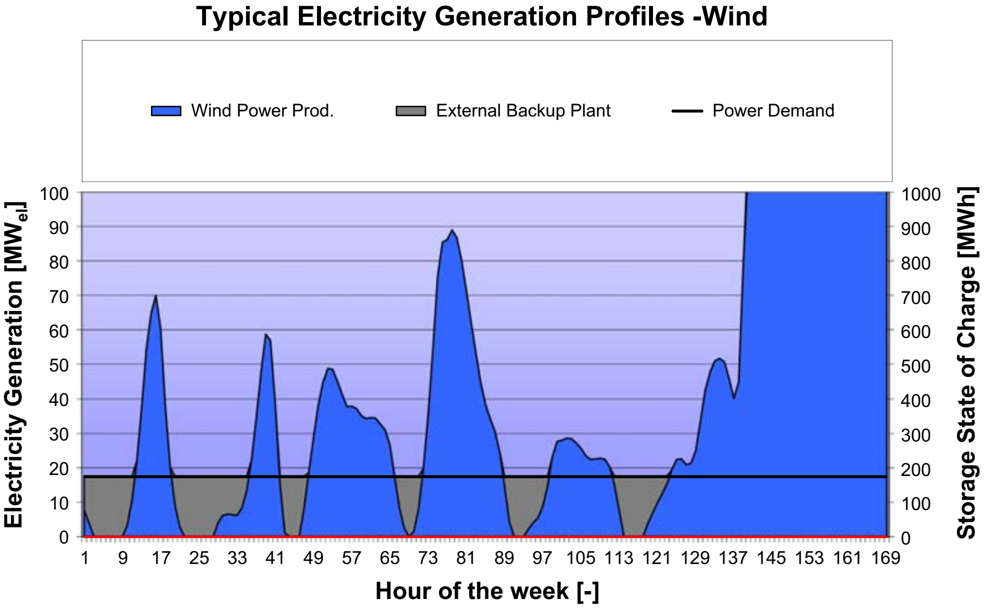

Fig. 6. Typical wind power generation profile for the case 80% direct renewable power share and 60 US\$/MWh$_{th}$ fossil fuel cost (neutral tariff for electricity export).

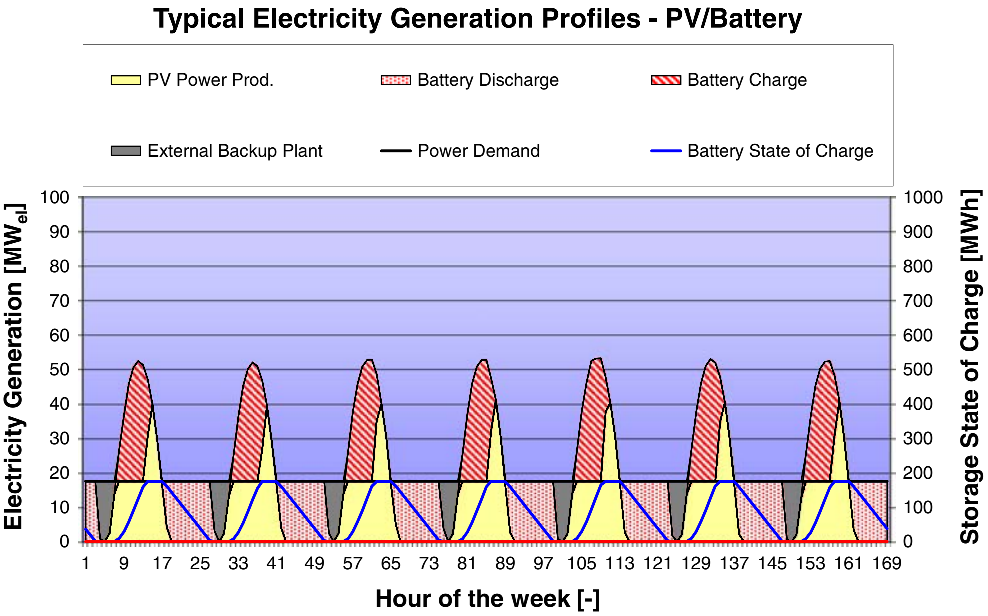

Fig. 7. Typical PV/battery power generation profile for the case 80% direct renewable power share and 60 US$/MWh$_{th}$ fossil fuel cost (neutral tariff for electricity export).

The CSP/RO system provides in this case lower LEC in comparison to the Wind/RO and the PV/RO case. The CSP plant is designed with large thermal energy storage capacity (19 full-load hours), which allows for storing thermal energy surpluses during sunshine hours and supplying power on demand during evening and even night hours. As can be seen in Fig. 8, at some times the thermal storage is fully charged. At these times, the solar field has to be partially defocused, causing suboptimal plant overall efficiency and LEC increase.

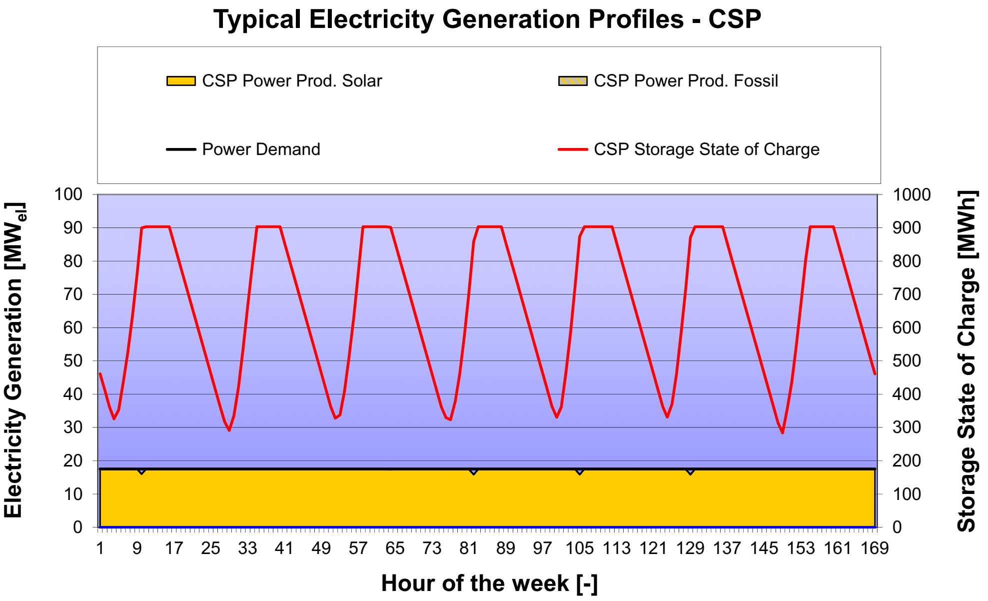

Fig. 8. Typical CSP/thermal energy storage power generation profile for the case 80% direct renewable power share and 60 US$/MWh$_{th}$ fossil fuel cost (neutral tariff for export).

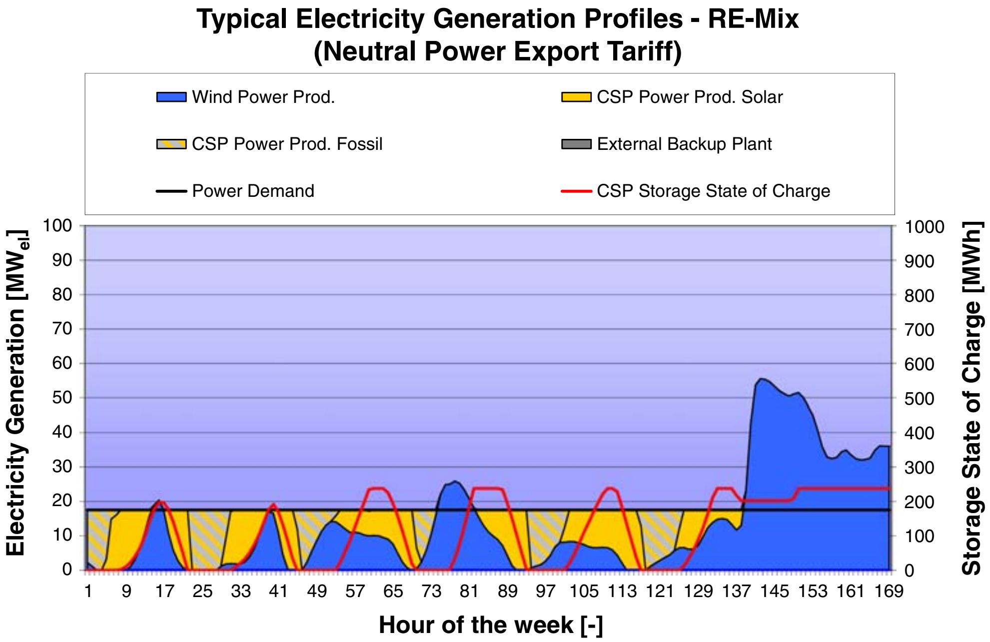

Fig. 9. Typical RE mix (CSP/Wind) power generation profile for the case 80% direct renewable power share and 60 US$/MWh$_{th}$ fossil fuel cost (neutral tariff case for export).

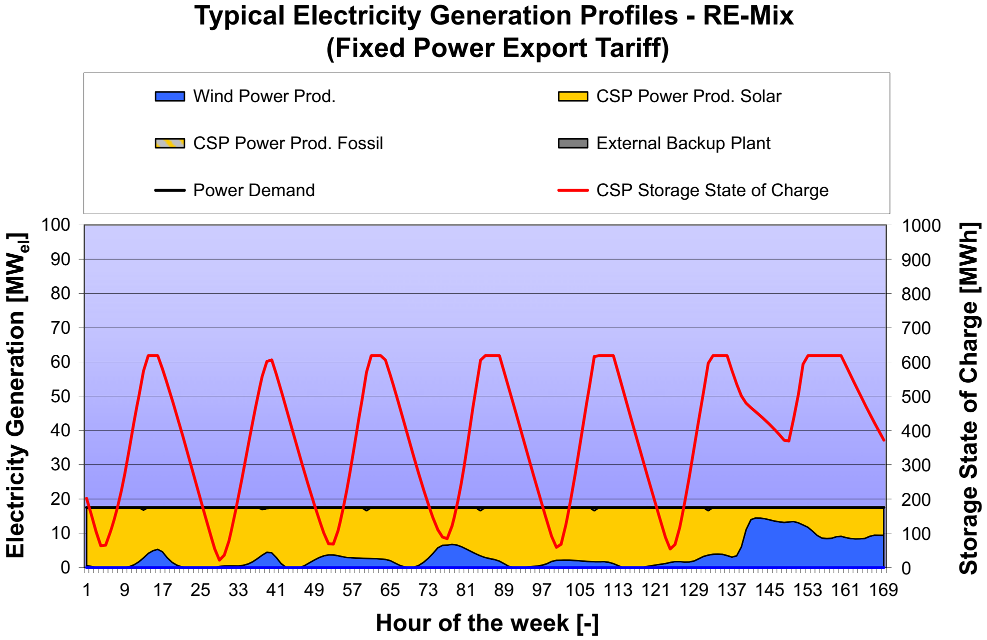

Fig. 10. Typical RE mix (CSP/Wind) power generation profile for the case 80% direct renewable power share, 60 US$/MWh$_{th}$ fossil fuel cost and fixed export tariff (6,0 US$cent/kWh).

For this reason, it seems interesting to analyze the combination of fluctuating and flexible renewable energy sources such as wind and CSP, combining a cheap variable source like wind energy with a technology that is able to provide power on demand and that can be easily integrated with a cost-effective thermal energy storage and fossil fuel backup. The economic results shown in the last column of Table 7 confirm this supposition. The CSP/wind combined system provides under the chosen assumptions the lowest LEC and LWC values.

Finally, Figs. 9 and 10 show how different feed-in tariff values for power export to the grid influence the configuration and the operation of the CSP/wind plant. In the first case (Fig. 9), the feed-in tariff is equal to the "LEC RE only" system, so that power exports have a neutral effect on the economic calculation. In this case, the wind installed capacity is ca. 3.8 times the desalination capacity, while the CSP plant is equipped with 5 h thermal storage.

Otherwise, if a low tariff is chosen (6.0 US$cent/kWh), power exports have a negative effect on plant economics. In this case, the optimal wind capacity is the same as the desalination capacity. Consequently, the optimal CSP storage has a clearly larger capacity (13 full-load hours).

6. Conclusions

In the near future, the MENA countries will face increasing water scarcity problems; countermeasures should be taken as soon as possible in order to minimize the related negative impacts on national economies. Installation of new desalination plants must be considered among these countermeasures. Renewable energies can significantly contribute to sustainable water desalination, as they account for the reduction of greenhouse gas emissions. In addition, renewable energies represent an effective instrument to guarantee stable energy prices. While fossil fuel prices are characterized by high volatility and a clear trend upwards, the investment cost of renewable energy has been steadily decreasing during the past decades due to economies of scale and learning effects. Once installed, renewable power plants have predictable and stable costs, while the operation of fossil fueled power plants is characterized by high risk and uncertainty, as the future trend and volatility of fossil fuel prices is unknown.

Another point discussed here is the comparison of different renewable energy technologies. Two different methods were adopted for comparison: in the first case, the renewable power plant park is designed in order to deliver on an annual basis for the same amount of energy as that required to cover the desalination load. This means that at times when power production exceeds the desalination needs, surplus power is fed into the grid, while at times with too low renewable energy supply deficits are compensated by electricity from the grid. In this case, the electricity grid is assumed to act as ideal storage device, without cost, losses, or capacity limitation. It is shown that under these assumptions variable renewable power options such as wind and PV achieve the lowest specific electricity and water cost.

However, MENA countries are characterized by rapidly increasing power demand, so that the installation of additional load such a new desalination plant will require the installation of equivalent firm supply capacity. As this quality of power supply cannot be provided by wind or PV plants alone, backup capacity will be required. Such backup plants will be forced to operate at part-load conditions whenever the renewable electricity generation will satisfy or exceed the desalination power requirements. This will cause additional cost due to the fact that those plants will run with lower plant efficiencies.

Therefore, in order to get comparable and resilient results when comparing different solutions to cover an additional desalination load, a second methodology is proposed. Within the second methodology, options with equal power supply quality are compared, taking into account overall system cost. This means that power supply for the desalination plant must be guaranteed at any time, whereas backup and grid management cost are also taken into account. In this case, the optimal power generation mix is a function of site-specific available renewable resources, specific investment cost, fuel cost, and share of renewable power generation on the total power requirements. Also the impact of different financial boundary conditions on the optimal plant design is shown by means of a sensitivity analysis on a feed-in tariff for renewable power.

An exemplary case study with hourly meteorological input data for a typical site in MENA and with a high share of renewable energy suggests that an optimal power generation mix for desalination will consist of low cost, variable wind, and PV power complemented by slightly more expensive balancing power from a CSP plant in hybrid solar/fossil fuel operation mode.

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