Economic and Social Commission for Western Asia

Developing the Capacity of ESCWA Member Countries to Address the Water and Energy Nexus for Achieving Sustainable Development Goals

Water-Energy Nexus Operational Toolkit
Renewable Energy Module

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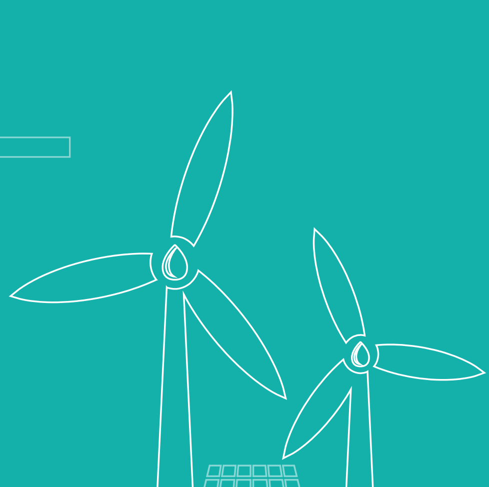


Contents

Introduction	**11**
Renewable energy technologies assessment for water and wastewater applications	**17**
Renewable energy technologies assessment for electricity production	**43**
Key performance indicators for RE technologies	**52**
Renewable energy technologies: financial perspective	**54**
Conclusion and recommendations	**58**
Annex	**60**
Bibliography	**65**

List of tables

Table 1. Typical values for operational parameters in biogas production in WWTPs	20
Table 2. CSP plants in Arab countries	30
Table 3. Principal characteristics of different desalination processes	33
Table 4. Seawater characteristics variation in the Arab region	33
Table 5. Characteristics of the most common renewable desalination schemes	35
Table 6. RE proliferation targets as set by most Arab countries, 2013	44
Table 7. Solar and nuclear energy: qualitative comparative analysis	46
Table 8. Renewable power: installed capacity and targets in Arab countries	47
Table 9. Key uses of water for energy and potential water quality impacts	50
Table 10. Summary of key RE effectiveness indicators	53
Table 11. Estimated cost to generate anaerobic digester gas electricity	56
Table 12. Capital costs of two main CSP desalination configuration options	57

Table A1. Comparison of Concentrated solar power systems	60
Table A2. Comparison of principal features of solar thermal storage technologies	62

List of figures

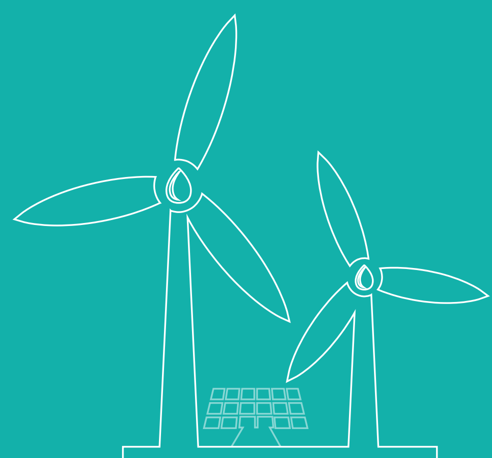
Figure 1. The water, energy and food security nexus	12
Figure 2. RE opportunities and various elements in the water, energy and food nexus	13
Figure 3. Breakdown of global GHG emissions, 2010	14
Figure 4. Average annual global growth in RE capacity and biofuels production across the three end-use sectors: power, heating and transport	14
Figure 5. Global RE share by application and sector in 2013/2014 and as projected by REmap	15
Figure 6. Global power generation in 2013 and as projected in 2030	16

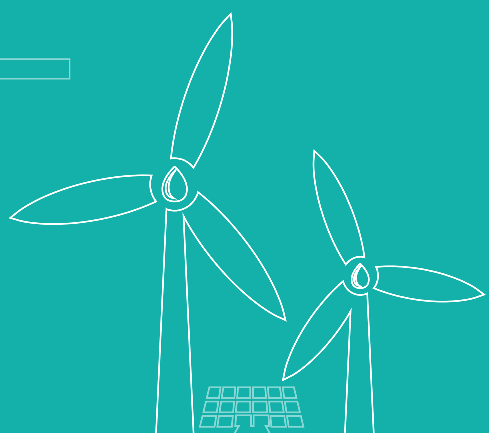
Figure 7. Amount of energy required to provide 1 m^3 of safe water for human consumption from various water sources 17
Figure 8. RE across the water supply chain 18
Figure 9. Process flow schematic of a wastewater treatment plant which produces energy 19
Figure 10. Schematic diagram of a solar water pump 23
Figure 11. Schematic diagram of a standalone hybrid system with a backup generator for water pumping applications 24
Figure 12. Principles for feeding solar thermal heat for pre-heating of supply water for steam boilers 27
Figure 13. Key stakeholders involved in Prosol I and their linkages 27
Figure 14. Annual contracted desalination capacity by region 28
Figure 15. Cumulative contracted desalination capacity by country, 2015 29
Figure 16. Global RE desalination by energy source, 2009 32
Figure 17. Cost-optimized pattern of future water supply for the MENA region under the average climate change scenario (business as usual), 2000-2050 32
Figure 18. Possible pathways for integrating RE resources with different desalination technologies 34
Figure 19. Schematic diagram of PV-RO system 36
Figure 20. Schematic diagram of CSP-MED system 37
Figure 21. Biofuels classifications and their stage of production advancement, 2011 38
Figure 22. Schematic diagram depicting the production process of different industrial products from algae 39
Figure 23. Diagram of a proposed solar-enhanced oil recovery system for oil sands 41
Figure 24. Potential application in petroleum refining: off-site reforming and cracking 42
Figure 25. Share of various fuel types in total electricity generation by world region, 2013 43
Figure 26. A practical configuration for the integration of wind and hydropower resources 48
Figure 27. Flowchart of embedded water in energy 49
Figure 28. Water use for primary energy production 51
Figure 29. Water use for electricity generation by cooling technology 52
Figure 30. Costs and savings of renewables by sector, 2030 55
Figure 31. Solar heat production costs compared with electricity and natural gas-based heating in different regions 56
Figure 32. Desalinated water costs for various combinations of desalination processes powered by RE sources 57
Figure 33: The range of levelized cost of electricity from utility-scale renewable technologies, 2010 and 2014 58
Figure 34. Weighted average cost of electricity by region for utility-scale renewable technologies, compared with fossil fuel power generation costs, 2013/2014 59

Abbreviations and explanatory notes

AC	alternating current
AD	anaerobic digestion
ANME	National Agency for Energy Conservation (Agence Nationale pour la Maîtrise de l’Energie)
BOD	biochemical oxygen demand
Btu	British thermal unit
BRIC	Brazil, Russia, India and China
BW	brackish water
CC	capital cost
CHP	combined heat and power
CNG	compressed natural gas
CPCs	compound parabolic concentrators
CSP	concentrated solar power
DC	direct current
EC	European Commission
ED	electrodialysis
EOR	enhanced oil recovery
ESCWA	Economic and Social Commission for Western Asia
ETCs	evacuated tube collectors
FNME	Tunisian National Energy Conservation Fund (Fonds National de Maîtrise de l’Energie)
FPCs	flat-plate collectors
GEF	Global Environment Facility
GHG	greenhouse gases
GoT	Government of Tunisia
GW	gigawatt
GWh	gigawatt-hour
HRT	hydraulic retention time
ICS	integral collector storage
IEA	International Energy Agency
INDCs	intended nationally determined contributions
IR	interest rate
IRENA	International Renewable Energy Agency
IWRM	integrated water resources management
kWe	kilowatt-electric
kWh	kilowatt-hour

LCOE	levelized cost of electricity
LNG	liquefied natural gas
MATTM	Italian Ministry for the Environment for Protection of Land and Sea (Ministero dell'Ambiente e della Tutela del Territorio e del Mare)
MED	Multi-effect distillation
MEDREC	Mediterranean Renewable Energy Center
MEDREP	Mediterranean Renewable Energy Program
MENA	Middle East and North Africa
MENAREC	Middle East and North Africa Renewable Energy Conference
MGD	millions of gallons per day
MSF	Multi-stage flash distillation
MVC	mechanical vapor compression
MWh	megawatt-hour
ODM	organic dry matter
OECD	Organization for Economic Co-operation and Development
PE	population equivalent
PJ	petajoule
PT	parabolic trough
PV	photovoltaic
R&D	research and development
RE	renewable energy
RCREEE	Regional Centre for Renewable Energies and Energy Efficiency
RET	renewable energy technology
RO	reverse osmosis
SD	solar dish
SDGs	Sustainable Development Goals
SDSN	Sustainable Development Solutions Network
SE4All	Sustainable Energy for All
SMBs	small modular biopower systems
ST	solar tower
STB	Tunisian National Bank (Société Tunisienne de Banque)
STEG	Tunisian Company of Electricity and Gas (Société Tunisienne de l'Electricité et du Gaz)
SW	seawater
TVC	thermal vapor compression
TWh	terawatt-hour
UNEP	United Nations Environment Programme
WEO	World Energy Outlook
WWTPs	wastewater treatment plants





Introduction

The United Nations Economic and Social Commission for Western Asia (ESCWA), as part of its efforts to help member countries find an integrated approach to their Sustainable Development Goals (SDGs), is implementing a United Nations Development Account project to develop the capacity of member States to examine and address the water and energy nexus.

To achieve this, ESCWA is using two parallel and complementary tracks. The first targets high-level officials in ministries for water and energy, who will be trained on how to incorporate the nexus in policies and strategies at national and regional levels by means of a regional policy toolkit. This is comprised of seven modules based on priorities identified during an intergovernmental consultative meeting in 2012.[1] The seven priorities which were endorsed by the ESCWA Committees on Water Resources and on Energy are the following:[2]

a. Knowledge and awareness-raising;
b. Increasing policy coherence;
c. Examining the water and energy security nexus;
d. Increasing efficiency;
e. Informing technology choices;
f. Promoting renewable energy;
g. Addressing climate change and natural disasters.

The second track targets water and energy service providers by means of three technical interventions addressed through an operational toolkit made up of the following three modules:

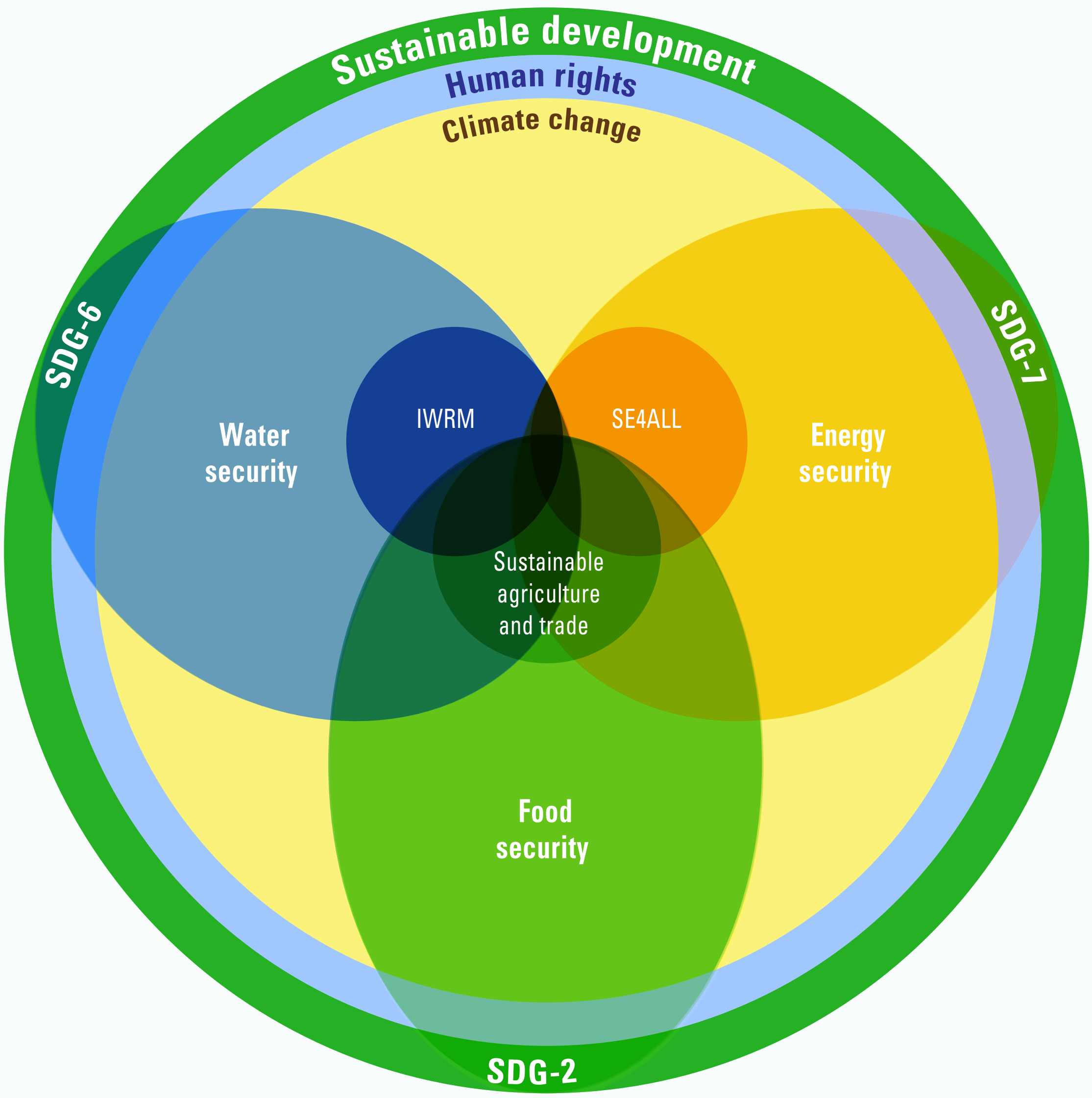
a. Resource efficiency: to improve efficiency during the production and consumption of water and energy resources and services;
b. Technology transfer: for water and energy considerations when pursuing the transfer of new technologies regionally;
c. Renewable energy: to assess costs and benefits related to applying renewable energy technologies in the region.

Each module will be discussed in one of three regional technical workshops, which will bring together participants doing similar work in different sectors.

Background

The water, energy and food nexus describes how the resources of water, energy and food are interdependent and cannot be "easily disentangled".[3] Though the nexus is usually described in terms of water, energy and food; some references have introduced additional dimensions to the nexus (e.g. climate[4]) while others have replaced food with another dimension (e.g. land[5]). A schematic diagram of the water, energy and food security nexus, from the perspective of ESCWA, is shown in figure 1. The figure shows the different SDGs as well as the institutional and policy frameworks (e.g. Integrated Water Resources Management (IWRM) for water security) which have to do with each of the dimensions of the nexus. It is important to note that water and energy are always considered to be integral components of the nexus, regardless of the overall

Figure 1. The water, energy and food security nexus



Source: United Nations Economic and Social Commission for Western Asia (ESCWA), 2015.

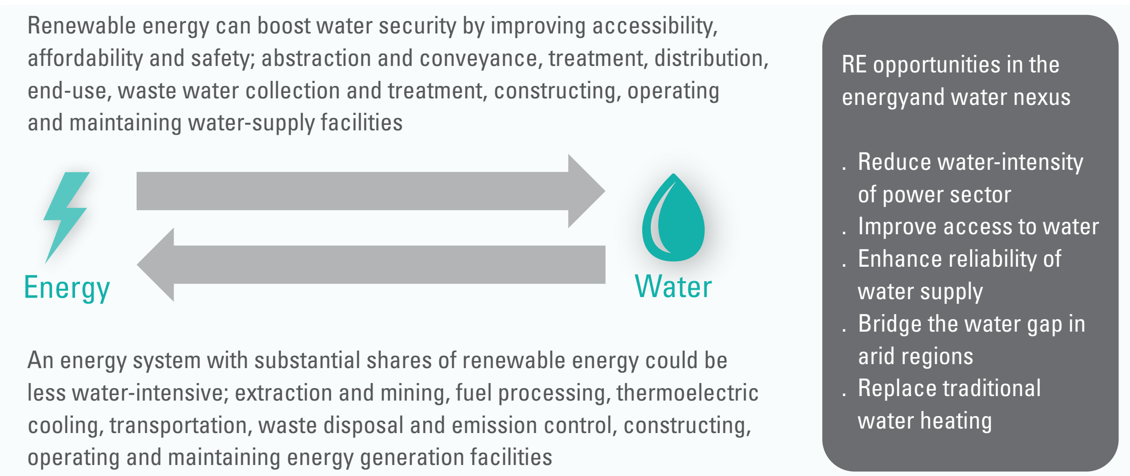
structure of the nexus and the institution proposing this structure, and therefore it is these two dimensions that this toolkit discusses.

There are many ways in which renewable energy (RE) can strengthen the water and energy nexus. These relationships and opportunities are shown in figure 2. As a result, RE use can improve water security by providing the power needed by water-related activities such as water distribution and wastewater treatment. Along the same lines, RE can strengthen energy security by providing energy sources that are less water intensive.

RE is therefore of considerable importance in any discussion about a sustainable energy future for the Arab region, and such alternative energy sources are imperative if the national energy policy goals of Arab countries are to be achieved. Indeed, the use of RE has many advantages. These include the reduction of pollution, an inherent byproduct of the use of conventional sources of energy. Other benefits of RE use include the mitigation of greenhouse gases (GHG) emission, improving energy security by diversifying energy sources, improving energy access, facilitating economic development through the creation of jobs, reducing dependence on nonrenewable sources of energy, and potentially reducing conflicts due to the use of limited conventional energy resources.[6] These benefits are of considerable significance for Arab countries since they are facing fast-growing rates of urbanization, in addition to rising rates on unmet water demand, as well as experiencing among the highest energy consumption rates in the world. Thus the use of RE would assist in addressing these issues while allowing Arab countries to develop in a more sustainable manner. As an example, as shown in figure 3, energy is the greatest source of GHG emissions, and so replacing conventional fuel sources with renewable sources would reduce emissions and assist in mitigating climate change. This also clarifies the relevance of considering the climate as part of the nexus, as shown in figure 1.

However, there are also disadvantages associated with the use of RE. These include the intermittency of most RE sources, high capital costs (in part due to costly energy conversion technologies), higher levelized costs, potential environmental and social concerns (e.g. the food versus fuel debate with respect to the use of biomass resources), and the greater spatial

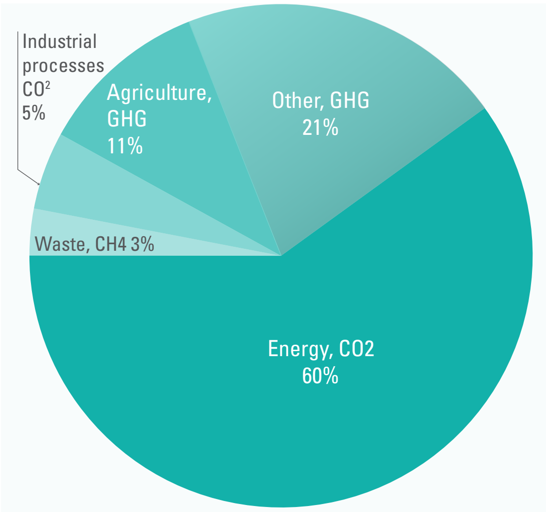
Figure 2. RE opportunities and various elements in the water, energy and food nexus



Source: International Renewable Energy Agency (IRENA), 2015a.

requirements of some RE technologies. The intermittency of some RE sources necessitates the provision of backup power (typically through conventional plants/ energy sources in the case of large-scale grid-connected systems and energy storage in the case of distributed generation systems). Some of these disadvantages may be expected to be eliminated as RE technologies continue to further develop and are more widely commercialized.[7] The greater spatial requirement for some RE technologies has the potential of leading to competition with other land applications such as biodiversity conservation and agriculture (i.e. food). When considering this point, it is clear why some studies of the nexus have replaced the dimension of food with that of land.

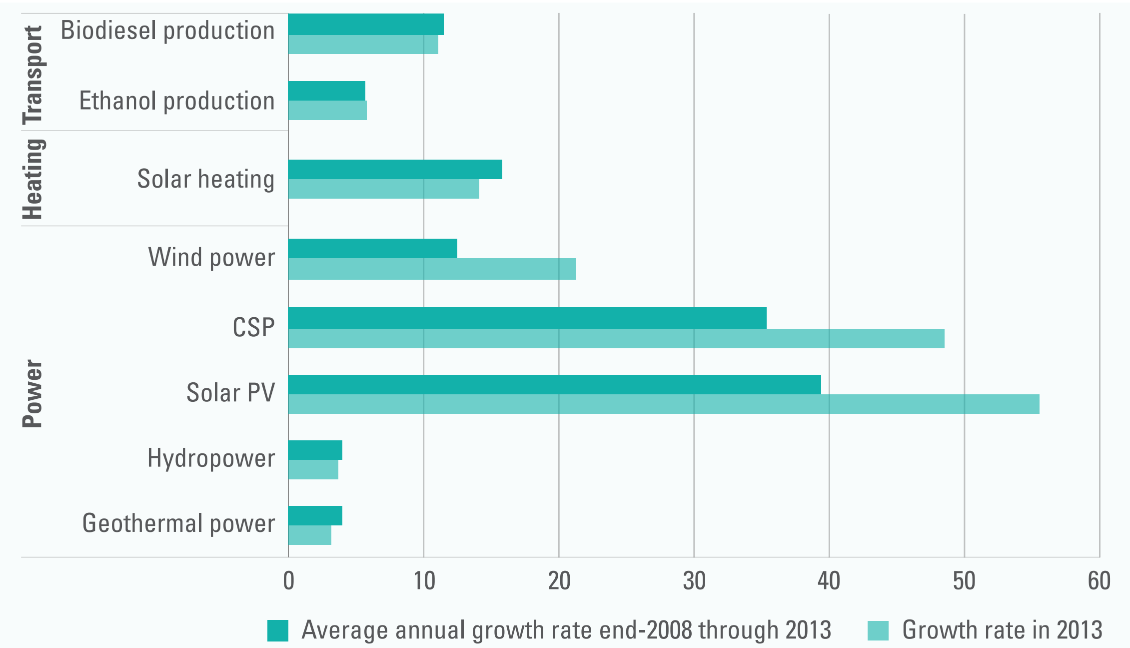
Figure 3. Breakdown of global GHG emissions, 2010



Source: IRENA, 2016a.

Figures 4 and 5 show how the global deployment of RE has grown in the recent past (figure 4) and how further growth is expected to take place in the next few years (figure 5). Figure 4 shows how, for different end-use sectors, the use of RE has increased from 2008 to 2013, as well as how much growth there has been in 2013 alone. It is clear that the

Figure 4. Average annual global growth in RE capacity and biofuels production across the three end-use sectors: power, heating and transport



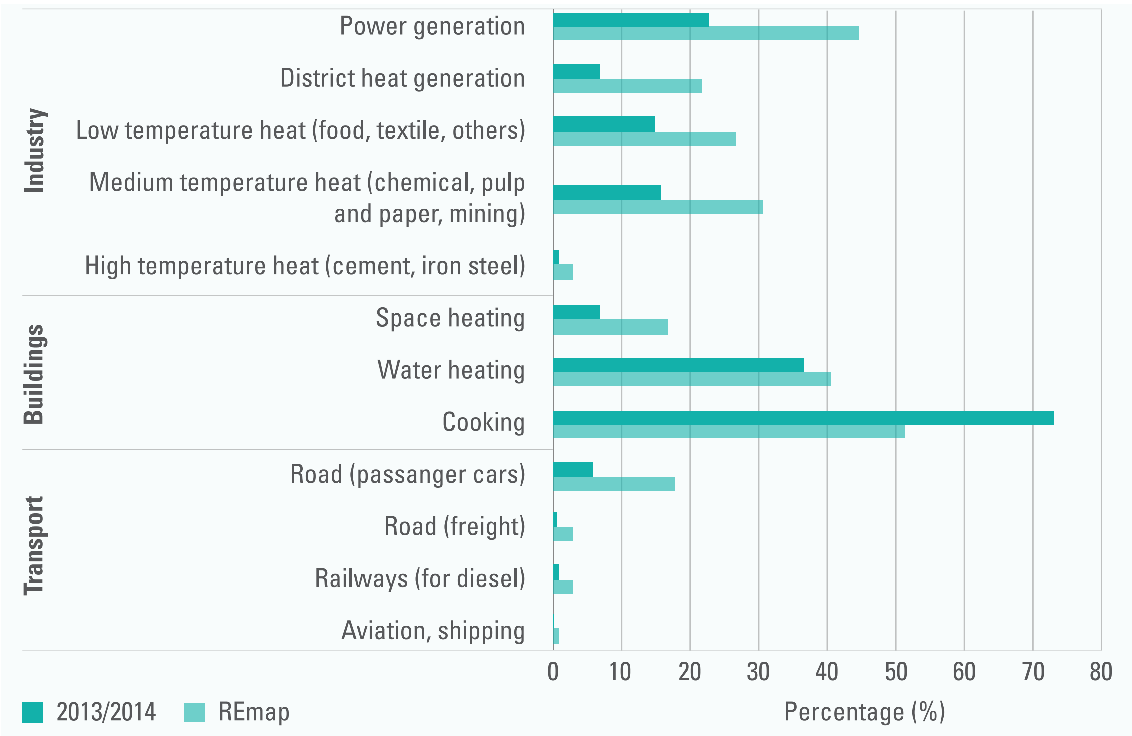
Source: IRENA, 2015a.

growth in 2013 has generally been greater than, or similar to, the average annual growth of the previous four years. Such substantial growth in RE deployment is expected to continue.

Sustainable Energy for All (SE4All) is a global initiative that was launched in 2011 by United Nations Secretary-General Ban Ki-moon. It involves all sectors of society and aims to achieve three objectives by 2030, one of which is doubling the share of renewable energy in the global energy mix.[8] As a result, organizations such as the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) have created roadmaps for a RE future. As part of the roadmap of IRENA, referred to as"REmap", a review of the best practices of different countries has been performed, and accordingly given rise to discussions on how doubling the share of renewables in the world's energy mix by 2030 (compared to 2014 values) can be achieved.[9] Thus, figure 5 shows the REmap projected growth in the share of RE in different applications belonging to different sectors in 2030, compared to the actual values reported in 2013/2014. It is clear that the greatest growth needs to be achieved in the transport and industrial sectors, including the power generation sector.

Looking at power generation in particular, figure 6 gives an idea of how RE contribution is forecasted to increase from 2013 to 2030 (according to REmap), while also showing the percentage of different types of power sources in overall power generation. Therefore, though coal and natural gas are expected to continue to be important fuels for power generation, the percentage of technologies such as wind, solar photovoltaic (PV), and geothermal is forecasted to increase substantially.

Figure 5. Global RE share by application and sector in 2013/2014 and as projected by REmap



Source: IRENA, 2016a.

There is indeed much potential for RE use in the Arab region. This module discusses the implementation of RE technologies in the water and energy sectors of Arab countries. The greatest potential in the region is for technologies related to solar energy (i.e. CSP and PV). Wind energy, geothermal energy, and hydropower do have potential, but that is only true for some countries.[10] Nevertheless, there are some large-scale hydropower projects in countries with river basins (e.g. Egypt and Iraq)[11] and there is also potential for microhydropower projects in the region. Biomass energy has the lowest potential in the region overall with respect to the availability of modern biomass for producing biofuels. Nevertheless, the use of traditional sources of biomass to produce energy, particularly for cooking purposes, is quite prevalent in the least developed Arab countries.[12] This module, while primarily focusing on solar and wind RE technologies due to their greater potential, will also discuss other RE technologies with respect to particular applications or countries as appropriate.

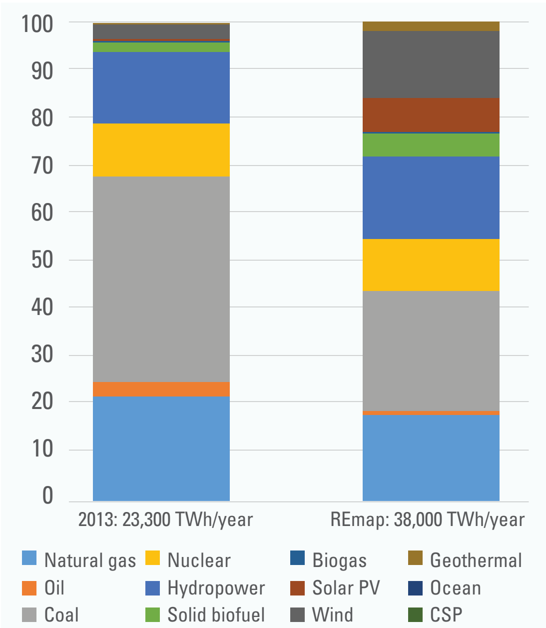
Objectives

The primary objective of this toolkit is to strengthen the capacity of ESCWA member countries, in terms of enhancing their ability to achieve an integrated and sustainable management of water and energy resources, thereby contributing to their sustainable development. This toolkit focuses on improving the technical capacity of government officials who manage or oversee the provision of water or energy services in ESCWA member countries. It provides them with technological strategies that can be used to integrate water and energy nexus considerations into their operations, activities and projects.

Though the nexus is governed through an institutional or policy response,[13] its implementation relies on technical interventions which may assist in the improvement of process efficiencies or the effectiveness of resource use.[14] The successful implementation of these technologies is only possible through access to comprehensive information about the technological options available, so that more informed decision-making can take place. It is this information which this toolkit aims to provide.

The current water and energy nexus operational module aims to assist in building capacity for exchange and collaboration across disciplines, based on a common language and common set of assessment tools, techniques and indicators for pursuing commercialized RE technologies at the operational level, such as during investment planning or the operation and maintenance of water and energy utilities or wastewater treatment plants. Consequently, the costs and benefits related to the application of appropriate RE technologies in the Arab region, specifically in the context of the water and energy nexus, are discussed in this module. It contains guidelines

Figure 6. Global power generation in 2013 and as projected in 2030



Source: IRENA, 2016a.

for entities responsible for water and energy services. Moreover, the module describes key performance indicators used in the water and energy industries, insofar as RE is concerned. It is the resulting analysis using established indicators which enables long-term planning and a more efficient management of national natural resources. For this planning to be effective, the collected data and statistics must be sufficient to allow for the strengthening of analytical capacity, particularly in the area of RE use, thus facilitating evidence-based policymaking and policy assessment in the interrelated fields of water and energy.

Renewable energy technologies assessment for water and wastewater applications

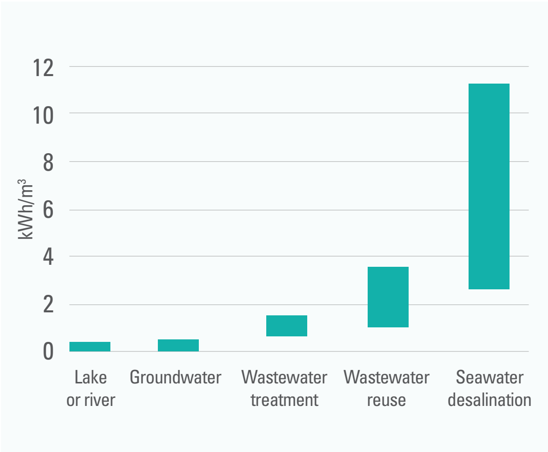
The water and energy nexus refers to both the relationship between water that is used for the production of energy (such as in the production of hydroelectricity and in cooling processes in power plants), and energy that is used in the extraction, treatment, distribution and disposal of water of various types (e.g. drinking water, wastewater). Since this module focuses on RE, it is the latter relationship which will be discussed more closely in the following pages. Figure 7 shows the amount of energy required to provide 1 m^3 of safe water for human consumption from various water sources. Though there is much variation in the amount of energy needed to treat seawater (SW), it is obvious that it requires the greatest amounts of energy. This is of much relevance for Arab countries that tend to rely on desalination for their water needs. Along the same lines, figure 8 shows where RE inputs may be used in the water supply chain, each stage of which will be discussed in the forthcoming pages. In addition, the data of figure 7 may be considered to be of relevance when discussing the 'desalination/treatment' and 'wastewater treatment' phases of figure 8.

Water and wastewater treatment

As shown in figure 7, wastewater treatment processes require energy. This energy can be provided by RE sources such as solar, wind, biomass and biofuel-related sources.[15] Solar energy is of particular significance when it comes to wastewater treatment. Direct solar radiation can be used for the actual treatment processes along with solar detoxification, in which chemicals (which help improve the plant's performance) are used alongside biological treatment.[16]

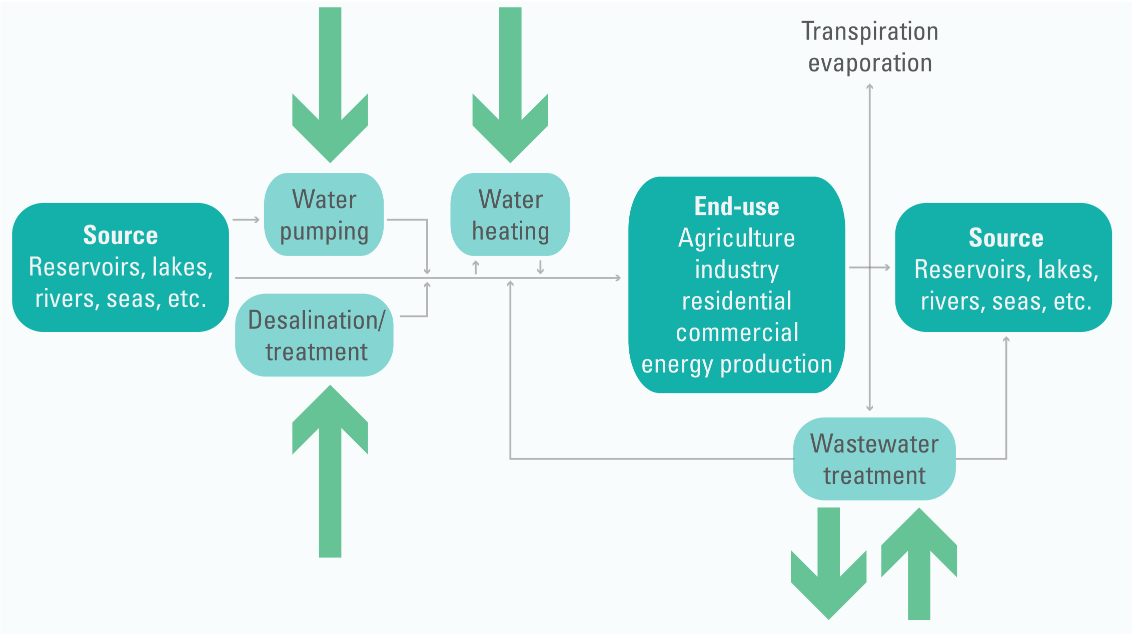
Additionally, the sewage sludge produced during the primary and secondary stages of wastewater treatment can be converted to biogas (primarily a mixture of methane and carbon dioxide) using anaerobic digestion (AD), as shown in figure 9,

Figure 7. Amount of energy required to provide 1 m^3 of safe water for human consumption from various water sources



Source: United Nations World Water Assessment Programme (WWAP), 2014.

Figure 8. RE across the water supply chain



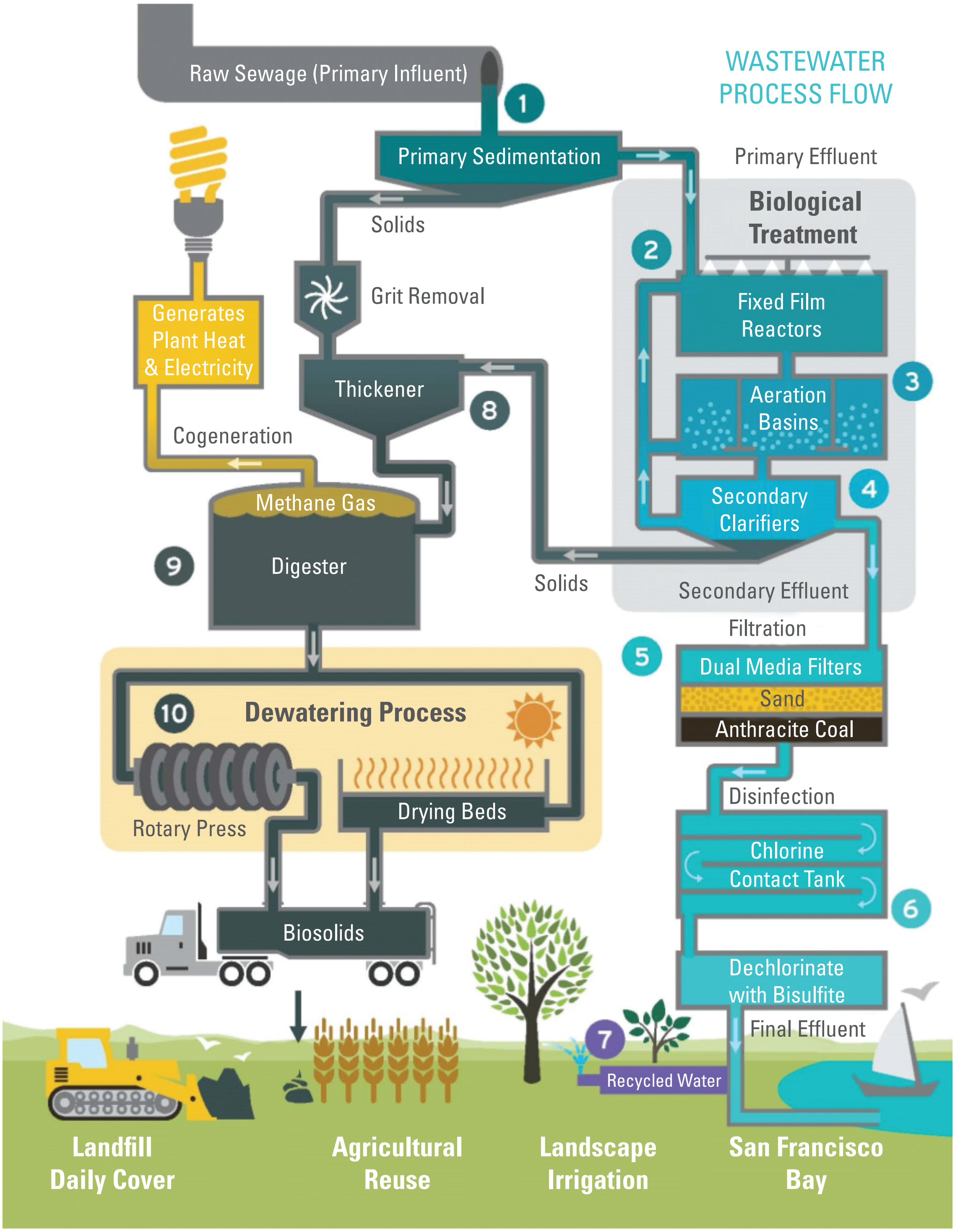
Source: IRENA, 2015a.
Note: Green arrows indicate RE inputs.

which depicts this process for Silicon Valley. This biogas can then be converted into electricity and used to contribute in powering the wastewater treatment plant. Figure 9 also shows where power is produced and consumed in the plant. The advantages of anaerobic digestion of sewage sludge are widely recognized and the technology is already well established in several countries.

Heat recovery has also been integrated into the above systems to increase overall energy efficiency. The system is therefore referred to as a combined heat and power (CHP) system, which is a cost-effective and reliable option for wastewater treatment plants (WWTPs) that have anaerobic digesters. The thermal energy produced can be used to meet space heating requirements and fulfill digester heat loads. The CHP system provides the plant with electricity at lower costs and reduces external fuel requirements, thereby improving the plant's power reliability.[17] At the same time, the CHP system has limited benefit in Arab countries since the ambient temperatures in the region are already relatively high and tend to be similar to those required for anaerobic digestion. Indeed, "climate is the most important factor determining digester heating requirements".[18] However, such cogeneration may be more useful in certain regions and during certain seasons due to lower temperatures at such places and times. In order to improve the efficiency of the CHP system, sometimes the water content of the sludge is reduced before it enters the anaerobic digester, or is pretreated with the assistance of disintegration technologies which help improve gas yields.[19]

The conversion of the chemical energy in the biogas into electricity can be achieved with the use of internal combustion engines or micro-turbines. Internal combustion engines can have a variety of sizes (i.e. from a few kilowatt-electric [kWe] to more than 4 Megawatt-electric [MWe]), while micro-turbines have a much smaller range of 30-250 kWe. However, both of these technologies have limited device power efficiencies (i.e. 25-35 per cent) and so alternatives such as fuel cells have increasingly been considered recently.[20]

Figure 9. Process flow schematic of a wastewater treatment plant which produces energy



Source: Silicon Valley Clean Water (SVCW), 2012.

In general, one million gallons per day (MGD) of wastewater can generate biogas which can produce 26 kilowatts (kW) of electricity and 2.4 million (Btu) per day of thermal energy through a CHP system.[21] Other typical values of operational parameters for WWTPs containing anaerobic digesters are shown in table 1. The descriptions for some of the parameters are also provided in the table.

Table 1. Typical values for operational parameters in biogas production in WWTPs

Operational Parameters	Typical Values	Description
Hydraulic retention time (HRT)	16-25 days	The theoretical period for which the sludge stays in the AD reactor and in which the microorganisms can transform the organic matter into biogas.
Temperature	35-39°C	Most AD reactors in WWTPs operate at mesophilic temperatures. As sewage sludge has high water content, a better ratio between energy supply for heating and energy gain is thus achieved. For the same reason, the optimal temperature is lower than in other mesophilic AD plants.
Gross gas production and degradation of ODM	450-500 L/kg ODM or 18-26 L/PE/day	As biogas results from the microbial degradation of ODM (organic dry matter), gross gas production and degradation of ODM are in direct relationship. The proportion of ODM in the sludge and its degradation rate depend on various factors, such as sludge types, sludge age, process characteristics of the water cleaning process and HRT.
Degradation of ODM	45-55%	
Methane content in biogas	63-67% CH4	Biogas from sewage sludge has a high methane content compared to biogas from other feedstock.
Utilization of the biogas produced	95-99% (optimal range)	Indicates how much of the produced biogas is used for power, heat or biofuel production. The residual part is flared.
Electrical Efficiency of biogas conversion by CHP	100 kW: 25-35% 100-500 kW: 5-40% > 500 : 38-45%	The priority is focused on electric efficiency, because heat is usually available in sufficient quantities in plants with CHP.
Electricity autonomy of the WWTP (in case of CHP use)	< 10,000 PE: 37% >100,000 PE: 68-100%	Electricity and heat autonomy indicate the ratio of energy generated to energy used in the WWTP. Larger plants achieve higher levels of autonomy due to more efficient processes (higher production, lower losses). Complete heat autonomy is already being achieved by many plants, while complete energy autonomy today is achieved only by very advanced and sophisticated plants.
Heat autonomy of the WWTP (in case of CHP use)	90-100%	

Operational Parameters	Typical Values	Description
Electric energy generated	10-20 kWh/PE/year	
Electric energy for AD	1-2.5 kWh/PE/year	
Electric energy for sludge dewatering	0.5-3.5 kWh/PE/year	
Thermal energy for sludge and reactor heating	8-16 kWh/PE/year	

Source: Bachmann, 2015.

Note: PE, population equivalent (ratio of the pollution load [biochemical oxygen demand per day] arriving at the WWTP from domestic and industrial users and services to the individual pollution load in household sewage produced by one person.)

Water pumping and transport

Renewable energy options which can be used to power water pumping and transport activities include wind pumps, solar pumps, and biofuel pumps. Wind pumps may be mechanical or electrical. Each of these technologies is discussed below.

Mechanical wind pumps (windmills)

During the 20th century, more than 8 million windmills were manufactured in the United States of America, and they have primarily been used to pump water in domestic, industrial, and agricultural settings. Due to the success of this technology, it has been replicated worldwide.[22] Though many windmills are still in use in countries such as Australia, Argentina, and the United States, the technology tends to be given less preference than modern wind turbines due to its lower efficiency (4-8 per cent), since its blades are not actual airfoils. The windmill can have any of the following pump configurations: a piston pump, a reciprocating pump or a positive displacement pump. When the force exerted by the wind is strong enough to enable the wind pump crank to lift the weight of the pump rods, the piston and the water in it, as well as to overcome the friction, the pump starts operating. The wind speed and the pumps diameter determine the amount of water delivered by pumping at a certain level. Pumps with large diameters deliver greater amounts of water but also require greater amounts of torque to begin operation. In general, to achieve favorable operation, the size of the pump should be such that it runs when speeds of about 75 per cent of local mean wind speeds are attained.[23] Additionally, local wind speeds required for wind turbines to produce electricity are typically of about 3 m/s.[24]

Modern windmills are able to achieve improved efficiency due to incorporating features such as variable-stroke designs and counterbalances attached to the actuating pump beam. Such counterbalances reduce the starting rotor torques required by these 'third generation' systems to begin pumping. Consequently, such windmills can "produce high torque at low wind speeds and provide rotor speed control at high wind speeds".[25] In addition, replacing traditional windmill plates with a smaller number of proper airfoil blades also helps increase efficiency while decreasing costs. Mechanical wind pumps are used commercially for low wind speeds with an overall conversion efficiency of 7-27 per cent at average wind speeds. What is more, their use is limited to flat plain areas.[26] Mechanical windmills have therefore been used primarily in remote locations for water pumping applications, though there has been a trend towards switching to solar PV water pumping systems. The main drawback of using mechanical windmills tends to be the high maintenance requirements of the system (particularly with respect to the piston pumps used). Small wind turbines do not tend to be used as an alternative to mechanical windmills in remote locations; in fact, in Egypt diesel is primarily used as the energy source for remote water pumping systems with powers greater than 10 kW.[27] Nevertheless, studies have been carried out which have proven the potential of small-scale water turbines in Egypt, particularly for water pumping in agricultural processes and off-the-grid electricity generation,[28] and have shown the economic feasibility of using such small-scale wind turbines (where the adoption of turbines with rated powers greater than 200 kW has been recommended).[29] Indeed, both Egypt and Morocco have been recognized as very suitable regions for small-scale wind installations.[30] Yet another example is Oman, where a wind-powered electric water pumping system has successfully been installed in a remote area.[31]

Electrical wind turbines for powering water pumps

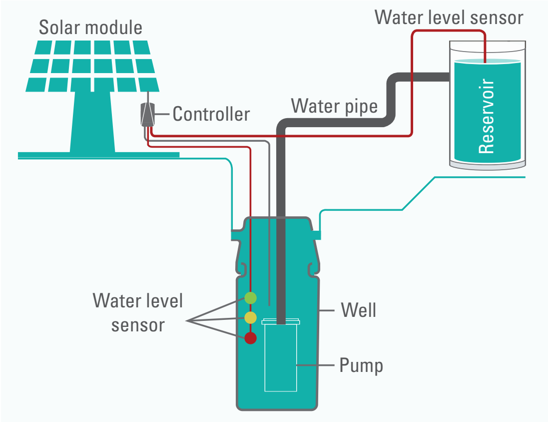
Electrical wind turbines can generate direct current (DC) or alternating current (AC), which powers DC or AC motors respectively; thereby making pumping water possible. Such turbines are most suitable for centrifugal pumps. In the case where the turbine is directly coupled with an AC motor, batteries and inverters are not required as part of the setup. Such technology also has the advantages of greater flexibility in terms of where wind turbines are located (i.e. it is possible to locate wind turbines on elevated ground to benefit from greater wind speeds), better performance at higher speeds, and fewer moving parts (thus less maintenance is required). Yet another advantage which they have is that surplus electric power can be stored using inverters and battery banks, therefore allowing the wind turbines to be used for various applications such as lighting. Electrical wind turbines also start operating at higher wind speeds (e.g. an average wind speed of 4-5 m/s is required to start pumping water using a wind turbine of 1.5 kW rated output). In fact, electric wind turbines become competitive with windmills for water pumping applications when they are operated above an average wind speed of 5-6 m/s.[32] Pumps operated using electrical wind turbines have double the efficiency of windmills and are more cost-effective than pumps powered using diesel fuel, PV technology or traditional windmills. In fact, wind turbines designed optimally can reach efficiencies slightly above 40 per cent.[33] Electric wind turbines are commercially available at a variety of power ratings (from 50 watts to a few megawatts).[34]

Solar (PV) pumps

PV pumps use solar radiation as their source of energy, as shown in figure 10. They consist of PV arrays that capture solar radiation and convert the radiant energy directly into electricity (DC). DC electricity could be changed into AC by using an inverter; the AC would be used to operate the electric motors which drive the water pump. Such pumps have the drawback of high investment costs; nevertheless such costs can be made up for by the low operation and maintenance costs during the long service life of the technology.[35] What is more, in the recent past, due to falling costs associated with PV technology, such pumps have become much more cost-effective, at least as far as the basic technology is concerned.

In the case where an AC motor is used, an inverter is added to the system, and this, along with components such as batteries, makes the system more expensive.[36] A less costly alternative to using the inverter for the AC motor is the use of tank full sensors and a simple controller with low voltage. This helps make the system more flexible and autonomous,[37] as shown in figure 10.

Figure 10. Schematic diagram of a solar water pump



Source: Au-Yeung, 2016.

PV pumps are known to be a reliable technology which permits close matching between the specifications of the pump and the amount of water required. They are also suitable options for small communities or individual households. Moreover, due to the intermittency of solar power, the pump system, including its water storage capacity and the capacity of its battery storage system (which is usually part of the system), should be configured to take into account the solar resource and water demand profiles. In more complex setups, a backup system, such as a wind generator or a gird connection, may be needed as a supplementary energy source for days when solar radiation is poor[38]. Additionally, a variety of studies which evaluate the performance of PV water pumping systems have been carried out in the Arab world. For example, a 2004 study carried out in Egypt found that the efficiency of pumping systems can be increased by up to 20 per cent by using manual tracking three times a day, a 2013 study carried out in Saudi Arabia found that the electronic array configuration should be considered in order to match the maximum power points of the PV array with the pump, and a 1999 study carried out in Algeria showed how such systems can contribute to the socioeconomic development of remote Sahara regions.[39]

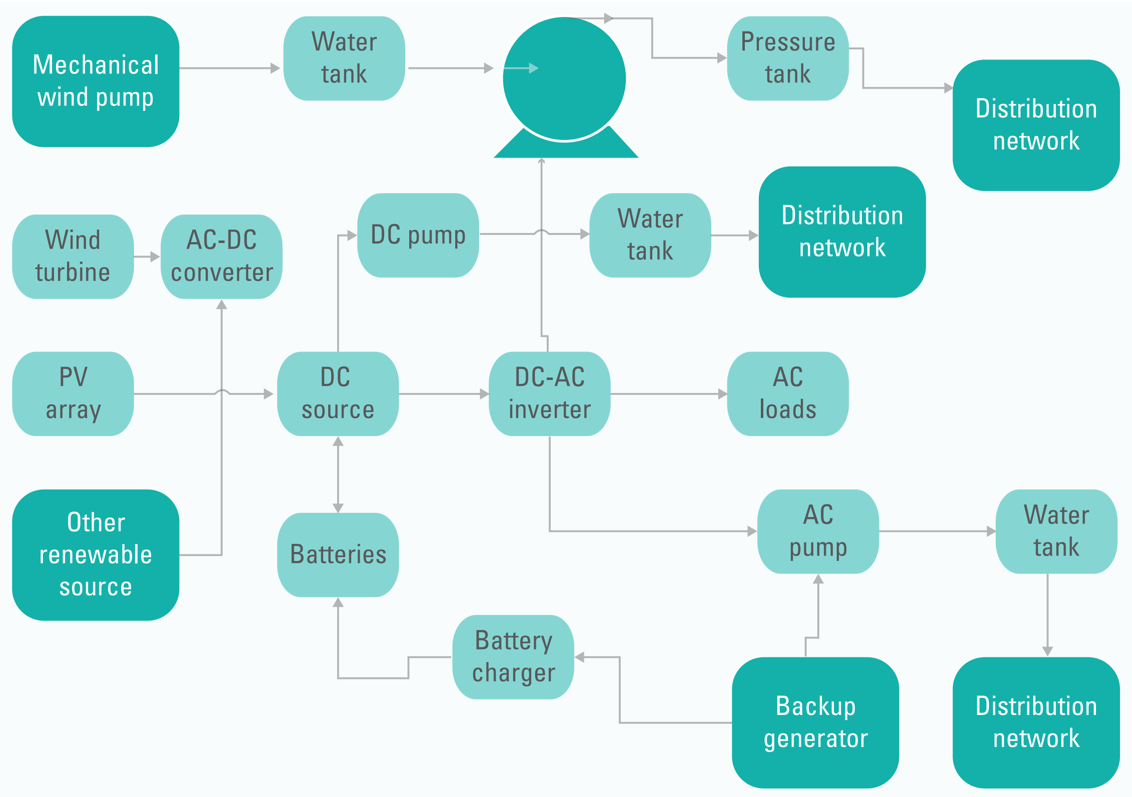
Biofuel pumps

Such pumps are particularly useful for rural applications. Biofuels can save up to 80 per cent of the fuel requirements of diesel engines. They can similarly be used as a fuel in internal combustions engines which are used for water pumping purposes.[40] A new technology in this area are Small Modular Biopower Systems (SMBs) which can use any type of agricultural residue to generate heat or electricity. They can be used for other applications like water purification systems in addition to powering water pumps. Even cattle dung can be used to provide the biogas needed to power the engines. They have the potential for powering entire villages (of small or medium size) as well as urban centers.[41]

However, biofuel pumps do have some limitations. The biomass fuel tends to have low calorific values and this makes such systems less economically viable; they tend to be feasible only where biomass is freely available and in dual fuel engine pumps (e.g. using both diesel and biofuel). Biofuel water pumping systems also have higher operation and maintenance costs than other renewable energy powered water pumping systems.
The use of biofuels also significantly affects the performance of the engines, due to factors such as the corrosion of their components and the low calorific values already mentioned. There are also additional energy losses when power is being transmitted from the engine

to the pump.[42] It is consequently clear why biofuel pumps have not been studied very closely, in view of their limited potential. Moreover, in water-scarce Arab countries, valuable agricultural land would ideally be used to produce food and not fuel. As a result, in such regions biofuel pumps would only be considered a viable alternative if they are powered with waste biomass or with biomass which does not have significant fresh water requirements. An exception to be mentioned here is the Sudan; where 65 million tonnes of ethanol was being produced in 2016 and this figure is expected to increase to 200 million tonnes in 2017.[43] In fact, biomass made up 56.3 per cent of the country's energy balance in 2014,[44] though this biomass has mainly been in the form of charcoal and wood and has been used primarily for small-scale applications, such as for providing domestic and industrial heat.[45] However, the Sudan is investing substantially in bioenergy to reduce its oil imports and facilitate reforestation. Currently, researchers in the country are at the pilot stage of cultivating jatropha, a viable source of biomass, and are also researching the possibility of using biofuel in the transportation sector such as in jet fuel. In addition, Kenana Sugar Company (KSC) in the Sudan had announced in 2013 that it would launch a project where ethanol would be used as a gasoline additive to improve vehicle emissions and increase octane.[46] Indeed, the Sudan has the natural resources (e.g. agricultural land and water resources)[47] which make the growth of biomass viable, and so the use of biofuel to power the water sector (as part of agricultural activities, for instance)[48] would be an important component of its energy landscape going forward.

Figure 11. Schematic diagram of a standalone hybrid system with a backup generator for water pumping applications



Source: Argaw, 2004.

Hybrid water pumping systems

Possible combinations for hybrid water pumping systems include PV with diesel, wind with diesel, wind with PV, and PV with other RE sources. For example, various studies have discussed the potential and viability of hybrid systems which use both wind turbines and PV panels, which can lead to greater reliability and greater outputs.[49] The hybrid system can also include battery storage, inverters, a backup generator, etc. Figure 11 shows a schematic diagram of a hybrid water pumping system powered by three RE sources, including wind and solar energy. Hybrid systems have the advantages of greater reliability than a system depending on a single RE source. This reliability also makes it possible to use such systems to power integrated applications (e.g. water pumping and street lighting). Additionally, as RE technology develops, such hybrid systems are becoming less costly than individual PV or wind systems. They are also able to achieve smaller sizes for the overall power system since they can use components of smaller sizes. Nevertheless, capital costs for such systems can be quite high and highly skilled individuals are required for their maintenance.[50]

Water heating

Using solar energy for water heating has become quite common, particularly in the residential sector. Such technology is also increasingly being used in the commercial and industrial sectors as well. After all, the heating of water is one of the most energy-intensive parts of the water cycle.[51] As a result, RE sources, such as solar and geothermal energy, are increasingly being used to replace conventional energy sources insofar as water heating is concerned. An example from the Arab region is Tunisia, where Prosol (Tunisian Solar Program) has led to a ten-fold increase in solar water heating installations from 2004 to 2011.[52] The costs associated with such systems depend on several factors such as the location and size of the installation, though, in general, solar water heaters are competitive with heaters powered by gas or electricity (capital costs are high but are made up by lower operational costs). The payback period for solar water heaters varies extensively from one location to another. A study carried out in the United States found that the payback period for solar water heating systems used in residential buildings varied from 4 to 13 years, depending on the city where the system was installed and the system configuration (the conventional electrical water heating system in each city was used as the benchmark).[53]

Yet another study performed using a 1,000 liter installed capacity solar water heating system at a university hostel in India found the payback period to be approximately two years.[54] A 2011 study conducted considering residential buildings in Oman found the simple payback period to be approximately 20 years. It was only when government assistance towards the system capital costs was considered that the payback period was decreased to 7-10 years.[55] In some cases, such solar water heating systems are part of hybrid systems that provide both space and water heating. Simulation software such as TRNSYS can be used to accurately design solar thermal systems, taking into account factors such as the demand profile.[56]

Typical solar thermal water systems can be used to heat water to temperatures of up to 125 °C or, if more advanced versions are used, up to 250 °C. They consist of technology such as flat-plate collectors (FPCs) and evacuated tube collectors (ETCs).[57] FPCs can be glazed or unglazed. Unglazed FPCs consist of a metal or polymer dark absorber plate. Glazed FPCs are similar, with the addition of an enclosure made of one or more glass or plastic covers. ETCs, on the other hand, tend to consist of parallel rows of transparent glass tubes. Each of these tubes is made up of an inner metal absorber tube and an outer glass tube. The metal tube is connected to a fin which has a coating that absorbs solar energy while preventing radiative heat loss. The vacuum between the glass and metal tubes eliminates convective and conductive heat losses. ETCs are commonly used for commercial applications. A third type of collector is referred to as the integral collector storage (ICS) system. Also known as the 'batch' system, this type of collector consists of an insulated glazed box which has one or more black tanks/tubes. The water that needs to be heated first passes through this setup where it is preheated. It then continues on to a conventional backup water heater.[58] ICS systems are therefore reliable systems and represent solar collectors used particularly for water heating purposes. They are also simple systems as they combine both water heating and storing applications in one setup; this eliminates the need for components such as circulation pumps and leads to fewer mechanical parts.[59] ICS systems work best in mild climates where temperatures below freezing are rarely encountered; they are therefore suitable for the Arab region. Moreover, for the domestic water heating sector in Arab countries, FPCs may be considered to be a better option than ETCs.[60] Not only are they cheaper, but they can provide heat at temperatures of up to 80 °C, which is sufficient for water heating applications. Moreover, ETCs have the advantage of working better in low irradiation conditions,[61] but this is not relevant for Arab countries that tend to have the advantage of high irradiation levels.

With even more advanced solar process heat technologies, where solar concentrator technologies are used independently or along with FPCs and ETCs, temperatures of up to 400°C can be achieved. Examples of these concentrator technologies are compound parabolic trough concentrators and Linear Fresnel collectors. As a result of achieving such temperatures, almost half of the heat demand of the industrial sector can potentially be fulfilled.[62] To make this possible, solar thermal heating can be integrated into industrial plants, particularly small and medium-sized plants, while they are being built. To increase the benefit from such installations, heat storage must also be considered when sufficient solar radiation is not available.

The FPC and ETC technology is mature and has great potential for low temperature industrial process heat systems, particularly in countries with growing industrial sectors. Examples of industrial sectors which are most suited for such technology are the food and beverage, textiles, chemical, paper and plastic industries. In some industries, solar thermal technology can also be used to assist in powering cooling processes which are currently powered by electric chillers.[63]

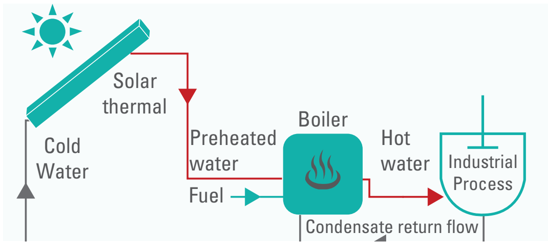
Solar thermal systems can be used to generate industrial process heat by providing an additional source for pre-heating the supply water used in steam boilers (in the case that high temperature feedwater is required for industrial processes [figure 12]). On the other hand, they may be used to directly provide the feedwater for such industrial processes (in the case that low temperature feedwater is required for industrial processes).[64] In both cases, conventional fuels are used, but they would be required in lower amounts due to the presence of solar heating systems. Such hybrid systems allow the overall system to meet demands larger than would be possible with the solar heating system alone. In fact, 20 per cent of the heating demand of a plant can be met with solar process heating systems. This is known as the solar fraction and often depends on the amount of roof space at the plant that can be used to mount solar panels.[65]

Prosol (Tunisian Solar Program)

In 1996, a 35 per cent subsidy on the capital cost of solar water heaters was put into effect in Tunisia, as a result of a project supported by the World Bank and funded by the World Bank's

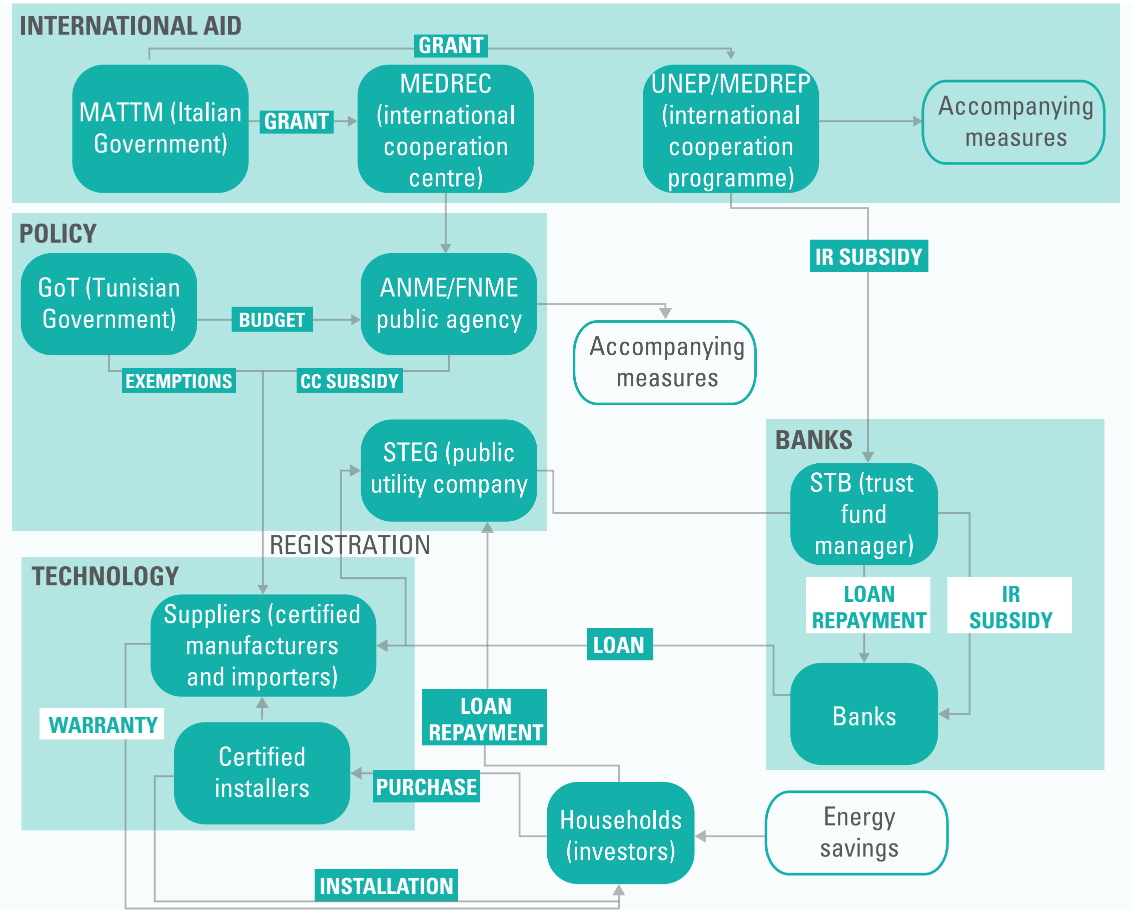
Global Environment Facility (GEF) Program and the Belgian Government. Though this project did help stimulate the growth of the solar water heater market, this growth was not sustainable and lasted only as long as the funding was available. Then, in 2005 the Tunisian Government started its own "Programme Solaire" (Prosol). Prosol not only provided solar water heater capital cost (CC) subsidies (a 20 per cent CC subsidy for solar water heaters in the residential sector), but also provided loans through commercial banks at a reduced interest rate to residential consumers. These loans were repaid through the state electricity utility

Figure 12. Principles for feeding solar thermal heat for pre-heating of supply water for steam boilers



Source: IRENA and IEA-ETSAP, 2015.

Figure 13. Key stakeholders involved in Prosol I and their linkages



Abbreviations: ANME, National Agency for Energy Conservation (Agence Nationale pour la Maîtrise de l'Energie); CC, Capital Cost; FNME, Tunisian National Energy Conservation Fund; GoT, Government of Tunisia; IR, Interest Rate; MATTM, Italian Ministry for the Environment for Protection of Land and Sea; MEDREC, Mediterranean Renewable Energy Centre; MEDREP, Mediterranean Renewable Energy Program; STB, Tunisian National Bank (Société Tunisienne de Banque); STEG, Tunisian Company of Electricity and Gas (Société Tunisienne d'Electricite et du Gaz); UNEP, United Nations Environment Programme.

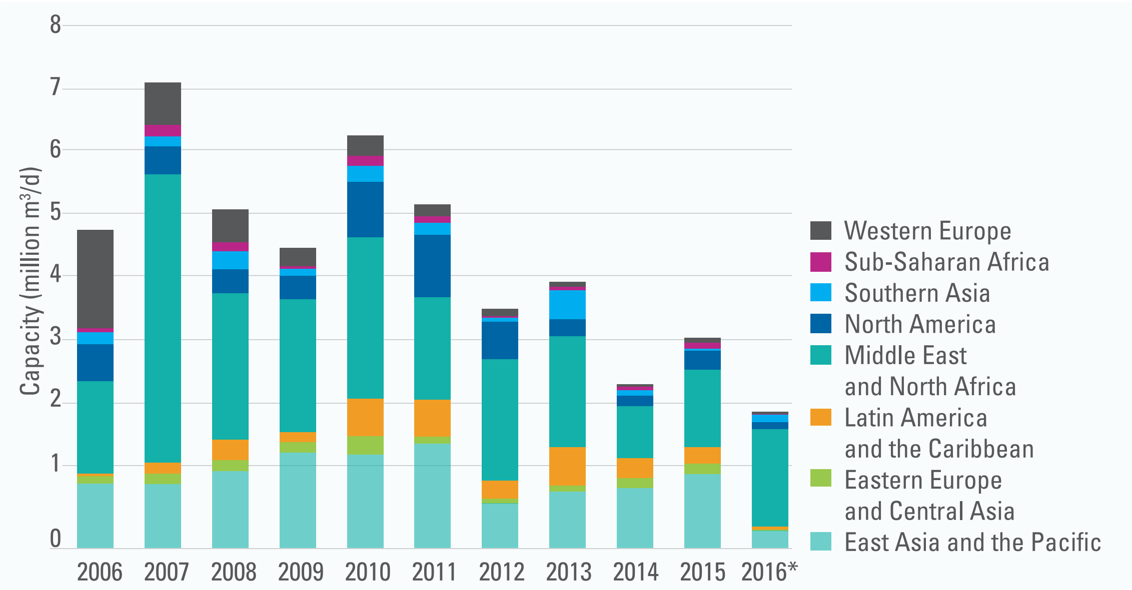
Source: Trabacchi, Micale and Frisari, 2012.

(Tunisian Company of Electricity and Gas/Société Tunisienne d'Electricite et du Gaz [STEG]) via electricity bills. Thus Prosol had the advantage of involving the state utility in the roles of debt collector, guarantor and enforcer. This helped overcome the absence of consumer credit for RE investments and reliable credit performances. Awareness-raising campaigns addressing consumers and commercial banks facilitated the capacity building of technology providers and financial institutions, allowing them to develop long-term expertise and knowledge.
A National Fund for Energy Conservation (FNME) was also established by law to support energy efficiency and RE initiatives; it was to be funded by customs duties on air-conditioning systems and tax revenues from motor vehicle registrations. The different entities which were involved in the first phase of Prosol are shown in figure 13. The second phase of Prosol came into effect in 2007, funded by $21.8 million from the Tunisian Government and $0.2 million from the Italian Government.[66] The improvements in the implementation of Phase II were informed by the experience of Phase I.

In terms of Prosol's achievements, from 2005 to 2010, it led to:

- A total public and private investment of $134 million.
- A five-fold increase in the annual installed capacity of solar water heaters, assessed in terms of collector area, to an installed base of 119,000 systems.
- A net gain in the public budget. The shift in consumer demand caused by the program led to a decrease of $15.2 million in Tunisia's fossil-fuel subsidy outlay. These savings are forecasted to increase to $101 million over the lifespan of the solar water heaters. This value easily compensates for the $21.8 million initially invested by the Government in Prosol.
- Avoiding the consumption of 251 kilotonne of oil equipment (ktoe) of fossil fuels over the lifespan of the solar water heaters.
- Avoiding 715 kilotonne (kt) of CO^2 emissions over the lifespan of the solar water heaters.
- The creation of about 3,000 new jobs.[67]

Figure 14. Annual contracted desalination capacity by region



Source: Virgili, Pankratz and Global Water Intelligence (GWI), 2016.
Note: *values through June 2016.

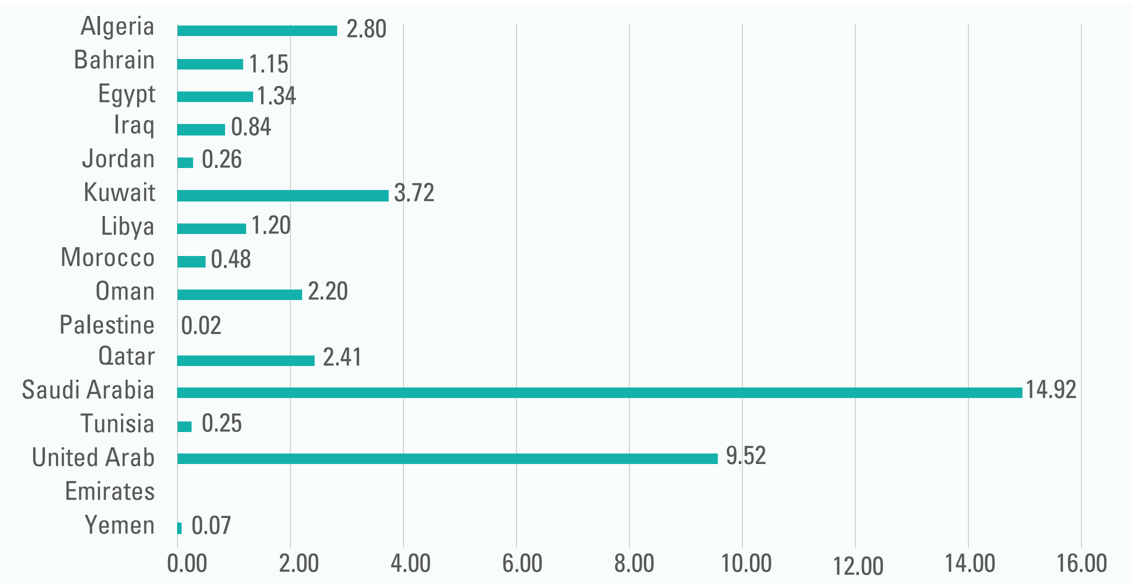
Thus Prosol has helped increase Tunisia's energy independence and improve its economic development. It has also shown how employing public resources, in this case utilities, in the support of RE investments can lead to shifts in demand away from conventional energy sources, even if fossil fuel subsidies are present. An important reason for Prosol's success was its training program and the accreditation scheme that it established for installers and suppliers, along with incorporating solar water heater certification and performance labeling into the process, as well as supplier-provided solar water heater component guarantees and after-sales maintenance contracts. Technology failure rates were thus reduced to a mere 1 per cent approximately. Additionally, the presence of the Tunisian National Agency for Energy Conservation (ANME), a dedicated and capable agency which assisted in the design, promotion, implementation and management of the program, was also an important part of Prosol's success; ANME also helped build capacity at all stages of the value chain and addressed implementation challenges by coordinating between local and international stakeholders.[68]

Desalination

Many Arab countries rely substantially on desalination in order to meet their water needs. This is shown in figure 14 as the new contracted desalination capacity for various parts of the globe, on a yearly basis from 2006 to 2016. The MENA region has claimed the lion's share in contracted capacity almost every year, and 2016 has been no exception. The significance of desalination in Arab countries is also clear from figure 15, which shows the cumulative contracted desalination capacity of different Arab countries in 2015.

Figure 16 shows a breakdown of the renewable-energy-powered desalination market, by RE type, in 2009. It is clear that solar energy had the greatest segment. Though desalination is an

Figure 15. Cumulative contracted desalination capacity by country, 2015



Source: Alvarado-Revilla, 2015.

Table 2. CSP plants in Arab countries

Country	Plant	Technology	Status	Power
Algeria	DLR - Algeria CSP tower pilot plant	Central receiver (power tower)	Development	7 MW
	Hassi R'mel ISCC	Parabolic trough - ISCC	Operational	25 MW
	Hassi-R'mel II	Parabolic trough	Announced	70 MW
	Meghaier	Parabolic trough	Announced	70 MW
	Naama	Parabolic trough	Announced	70 MW
	Beni Abbes	Central receiver (power tower)	Announced	150 MW
	El Oued	Central receiver (power tower)	Announced	150 MW
Egypt	Kuraymat ISCC	Parabolic trough - ISCC	Operational	20 MW
	Marsa Alam	Parabolic trough	On hold	30 MW
	West Nile CSP Project	To be announced	Planning	100 MW
	Kom Ombo CSP project	Parabolic trough	Development	100 MW
	TAQA Concentrated Solar Power Plant	Central receiver (power tower)	Planning	250 MW
Jordan	WECSP Project	Fresnel	Under construction	1 MW
	Abengoa Solar Jordan CSP plant	To be announced	Planning	25 MW
	Catalyst Private Equity Jordan CSP plant	To be announced	Planning	50 MW
	EJRE Maan CSP plant	To be announced	Planning	50 MW
	Evolution Solar Jordan CSP plant	To be announced	Planning	50 MW
	Mitsubishi Jordan CSP plant	To be announced	Planning	50 MW
Kuwait	Shagaya project KISR	Parabolic trough	Planning	50 MW
	Al Abdaliyah Integrated Solar Combined Cycle (ISCC)	Parabolic trough - ISCC	Development	60 MW
Lebanon	Zeenni Trading Agency CSP plant Bsarma El Koura	Parabolic trough	Planning	2.8 MW
	Zeenni's Trading Agency 50 MW CSP plant	To be announced	Planning	50.00 MW
Libya	Libia Fresnel	Fresnel	Unconfirmed	15 MW
Morocco	CNIM eCare Solar Thermal Project	Fresnel	Development	1 MW
	Airlight Energy Ait Baha CSP Plant	Parabolic trough	Operational	3 MW
	Tan Tan CSP-Desal Project	To be announced	Unconfirmed	20 MW
	Aïn Beni Mathar ISCC	Parabolic trough - ISCC	Operational	20 MW
	Noor Ouarzazate 3	Central receiver (power tower)	Under construction	150 MW
	Noor Ouarzazate 1	Parabolic trough	Operational	160 MW
	Noor Ouarzazate 2	Parabolic trough	Under construction	200 MW
	Noor Midelt	To be announced	Planning	400 MW

Country	Plant	Technology	Status	Power
Oman	Petroleum Development Oman EOR plant	Parabolic trough	Operational	7 MW
	Miraah: Solar EOR Steam Plant	Parabolic trough	Planning	1 GW
Qatar	Sahara Forest Project	Parabolic trough	Operational	Pilot facility
Saudi Arabia	Princess Nora University solar water heating	Flat Plate Collectors	Operational	17 MW
	Saudi Electricity Company (SEC) Duba ISCC Power Plant Phase 1	Parabolic trough-ISCC	Under construction	50 MW
	Waad Al-Shamal ISCC Project	Parabolic trough - ISCC	Under construction	50 MW
	Taiba ISCC	To be announced	Planning	180 MW
Tunisia	El Borma ISCC	Tower - ISCC	Planning	5 MW
	Akarit TN-STEG Concentrated Solar Power plant	Parabolic trough	Planning	50 MW
	Elmed CSP Project	Parabolic trough	On hold	100 MW
	TuNur Phase 1	Central receiver (power tower)	Development	250 MW
	TuNur Phase 2	Central receiver (power tower)	Development	2,000 MW
United Arab Emirates	Solar Beam Down Plant	Central receiver (power tower)	Operational	0.10 MW
	Dish Stirling Pilot Project	Dish stirling	Operational	0.11 MW
	Shams 1	Parabolic trough	Operational	100 MW
	DEWA CSP Project-Phase 1	Central receiver (power tower)	Planning	200 MW

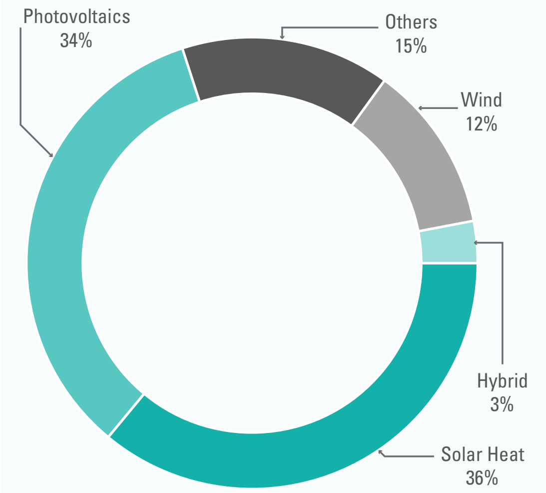
Sources: CSP Today, 2016; IRENA, 2016c; Servicios Avanzados de Comunicación y Marketing SL (SACM), 2015.

energy-intensive process, by powering it with RE, some of its drawbacks can be overcome. RE desalination has the advantage of reduced GHG emissions. In addition, other environmental impacts caused by the use of fossil fuels, such as loss of biodiversity due to the extraction of oil and coal and air pollution, can be prevented.

Currently in Arab countries, existing RE desalination systems have small capacities (up to 100 m^3/d) and only a small number of medium-sized installations are in use. The largest PV desalination plant which will be using membranes with nanotechnology is currently being built in Khafji, Saudi Arabia. This desalination plant, which is expected to be commissioned in 2017, will have a capacity of 60,000 m^3/d.[69] Other RE desalination plants are operational in Egypt, Jordan, Morocco, and the United Arab Emirates,[70] but they are mostly of pilot size and do not amount to full utility scale production.

Figure 17 shows the cost-optimized pattern of future water supply for the Middle East and North Africa (MENA) under the average climate change scenario. It can be seen that, along with wastewater reuse, CSP desalination is expected to increase exponentially over the next few decades and to comprise a substantial portion of the water supply of the Arab world in 2050. As a result, though there are various types of RE which may be used to power desalination (as can be seen in figure 16), it is CSP which is expected to have increasing utilization in some Arab countries. In fact, the CSP potential of the MENA region was estimated to be 462,000 TWh annually; this is a value that is about 350 times greater than the region's annual energy consumption (as of 2012). In contrast, the PV potential for the region is 356TWh annually (about 31 per cent of the region's 2012 electricity use).[71] In addition to this large potential in the region, CSP has the advantages of greater scalability to both small and large applications, significant potential for future development (and therefore cost reduction), being the only economically viable RE technology which can store power and provide it on demand, having the potential to provide the electrical baseload and heat as needed (heat which can be readily stored and efficiently retrieved), and working well with and being particularly suitable for utilities and large-scale desalination technologies. However, it does have the disadvantage of requiring water for cooling and steam generation, unlike PV and wind technologies.[72]

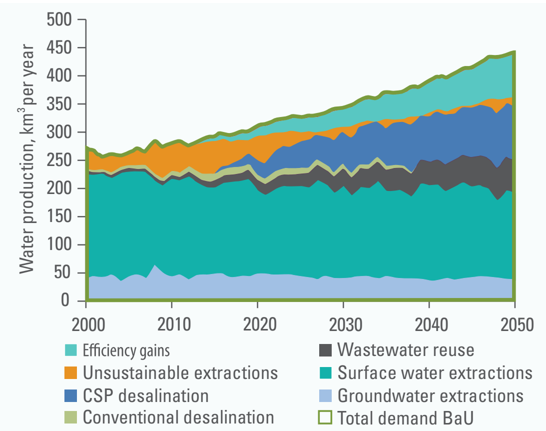
Figure 16. Global RE desalination by energy source, 2009



Source: World Bank, 2012.

CSP plants are considered to be an essential part of the RE targets of many Arab countries. This is clear from table 6, which will be discussed later on in this report. Meanwhile, table 2 shows the different CSP plants which are in operation or in the pipeline in different Arab countries. It is clear that they are mostly power plants which would inevitably be used to power some desalination-related activities as well. The only CSP plant which has been specifically referred to as a desalination plant is the Tan Tan CSP-Desal Project in Morocco, which is currently unconfirmed. In general, the CSP-MED hybrid solution has received much interest in the GCC region as a potential pathway for integrating renewable energy sources into an existing thermal desalination-dominated market. Moreover, Masdar Institute of Science and Technology in Abu Dhabi is carrying out a project where renewable-powered membrane desalination is being studied.[73] The RE sources being explored include both CSP and PV technology.

Figure 17. Cost-optimized pattern of future water supply for the MENA region under the average climate change scenario (business as usual), 2000-2050



Source: World Bank, 2012.

Table 3. Principal characteristics of different desalination processes

Characteristic	Type of process Phase change	Non-phase change	Hybrid
Process nature	Thermally-driven process: MED, MSF, MVC, TVC (evaporation and condensation)	Pressure/concentration gradient driven: RO (membrane separation), ED (electrochemical separation)	Thermal + membrane: membrane distillation, MSF/RO, MED/RO
Membrane pore size	-	0.1-3.5 nm	0.2-0.6 μm
Feed temperature	60-120 °C	< 45 °C	40-80 °C
Cold water stream	May be required	-	20-25 °C
Driving force for separation	Temperature and concentration gradient	Concentration and pressure gradient	Temperature and concentration gradient
Energy	Thermal and mechanical	Mechanical and/or electrical	Thermal and mechanical
Form of energy	Steam, low-grade heat or waste heat and some mechanical energy for pumping derived from fossil fuels or renewable sources	Requires prime quality mechanical/ electrical energy derived from fossil fuels or renewable sources	Low-grade heat sources or RE sources
Product quality	High quality distillate with TDS < 20 ppm	Potable water quality TDS < 500 ppm	High quality distillate with TDS 20-500 ppm

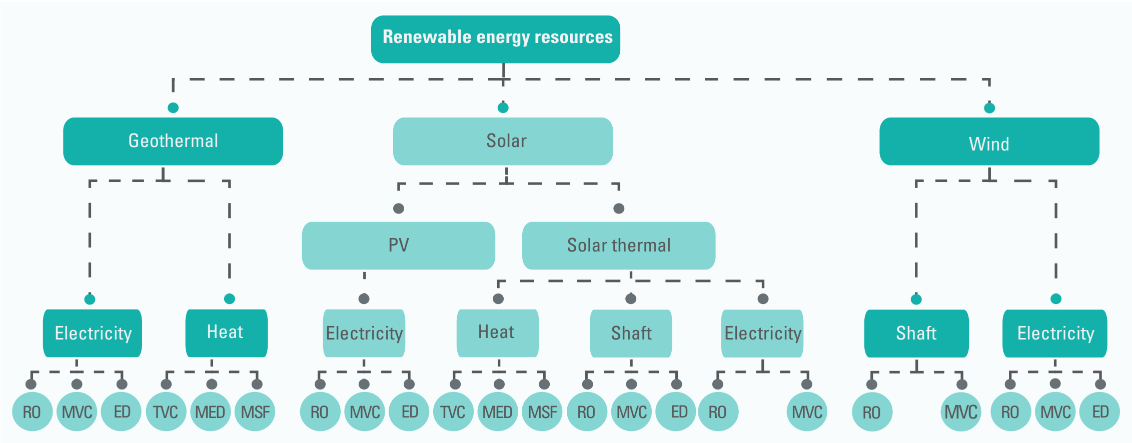
Source: Gude, Nirmalakhandan and Deng, 2010.

Table 4. Seawater characteristics variation in the Arab region

Water source	Salinity (mg/L)	Temperature (°C)
Mediterranean and Atlantic	38,000-41,000	15-30
Red Sea and Indian Ocean	41,000-43,000	20-35
Gulf water	45,000-47,000	20-35

Source: World Bank, 2012.

Figure 18. Possible pathways for integrating RE resources with different desalination technologies



Sources: Al-Karaghouli and Kazmerski, 2011; IRENA, 2015a.

Desalination processes are broadly classified as either thermal or membrane-based technologies, as per the separation process used. In the Middle East, thermal desalination has historically been dominant, but membrane-based technologies have rapidly been developing for the past five decades and therefore exceed thermal processes in the region, insofar as new plant installations are concerned.[74] There are various type of desalination technologies, such as multi-effect desalination (MED), multi-stage flash (MSF), thermal vapor compression (TVC), electrodialysis (ED), mechanical vapor compression (MVC), and reverse osmosis (RO); of which MSF and RO are the most widely implemented technologies. Table 3 provides a summary of the characteristics of these different technologies. It is also important to note that the salinity of the water to be desalinated and its temperature are important factors to consider when deciding which type of desalination technology to use.[75] Table 4 also shows how these characteristics vary for the waters of the Arab region. For example, due to the high salinity of Gulf waters, using RO to produce water is more expensive than using MED[76] and the CSP-MED process is considered to be more energy efficient than the CSP-RO process.[77] Other factors to consider as part of the feasibility analysis of an RE desalination plant are RE availability in the location and any pretreatment requirements for feedwater input.

Figure 18 shows possible pathways for integrating RE resources with different desalination technologies. It is clear that most renewable technologies (with the exception of PV), can provide energy in various forms: heat, electricity, or shaft power. Thermal desalination technologies such as MSF can benefit from all these energy forms, while membrane-based desalination processes can only be directly coupled with electricity (or shaft power) as their sources of power. Though the combinations shown in figure 18 are all possible configurations for desalination systems powered by RE, they are not all amenable to being applied on a commercial scale. Therefore, the most common configurations are presented in table 5 along with data on their associated energy requirements, as well as information concerning the current stage of their development. Table 5 shows how solar stills, solar multi-effect humidification, PV-RO and wind-RO are the combinations which are currently being applied as RE powered desalination. In the following section, each of the RE types which can be used to power desalination will be discussed, with a greater focus on those configurations which are already being applied or have greater potential to be applied.

Table 5. Characteristics of the most common renewable desalination schemes

	Technical capacity (m^3/d)	Energy demand (kWh/m^3)	Development stage
Solar stills	< 0.1	Solar passive*	Application
Solar multi-effect humidification	1-100	thermal: 100 electrical: 1.5	R&D; application
Solar membrane distillation	0.15-10	thermal: 150-200	R&D
Solar/CSP multi-effect distillation	> 5,000	thermal: 60-70 electrical: 1.5-2	R&D
Photovoltaic reverse osmosis	< 100	electrical: BW: 0.5-1.5 SW: 4-5	R&D; application
Photovoltaic electrodialysis reversed	< 100	electrical: only BW:3-4	R&D
Wind reverse osmosis	50-2,000	electrical: BW: 0.5-1.5 SW: 4-5	R&D; application
Wind mechanical vapor compression	< 100	electrical: only SW:11-14	Basic research

Source: IRENA and IEA-ETSAP, 2012.
Note: * Incident short wave radiation is transmitted and absorbed as heat.

Solar desalination systems

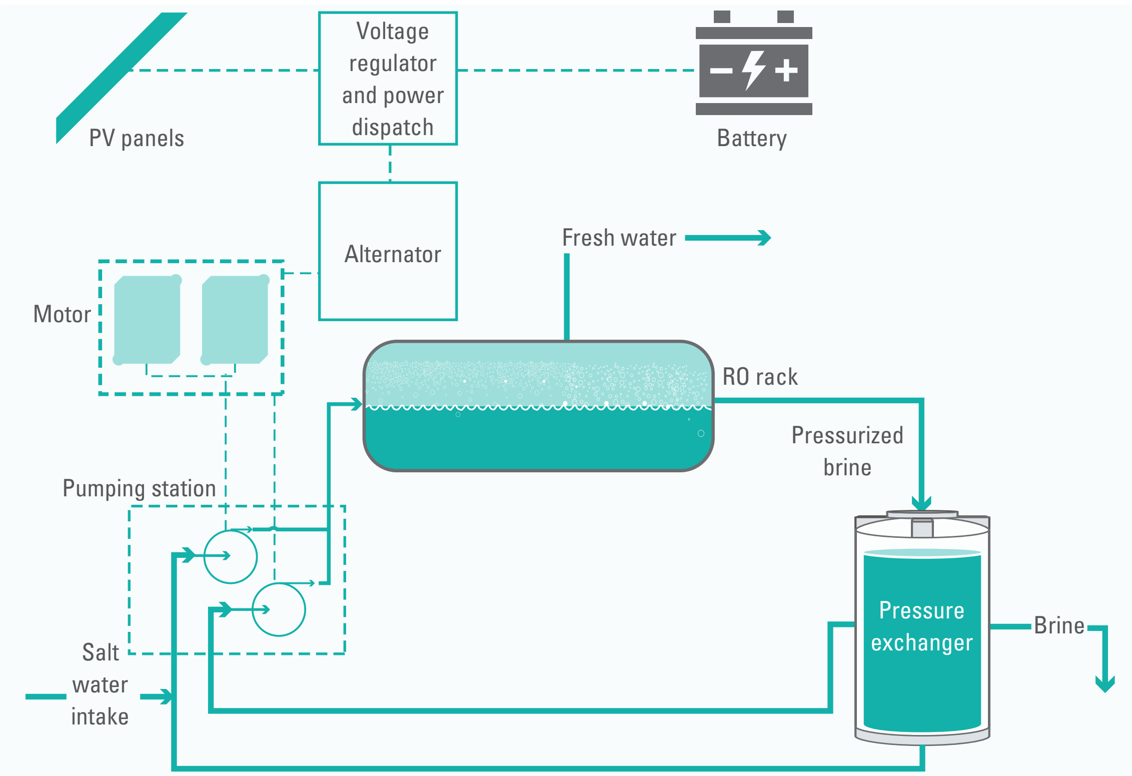
Solar energy systems may be classified as solar thermal or PV systems. In solar thermal systems, solar heat provides the energy input, while in PV systems, solar energy is directly converted to electrical energy. Solar energy systems are direct collection systems if they use solar energy to directly produce distillate in the solar collector. If they combine conventional desalination units with solar energy collection devices, they are known as indirect collection systems. Direct collection systems tend to have large land area requirements and lower productivities, though they are competitive at small desalination plant capacities due to their lower costs and simpler setups.[78]

PV desalination: PV technology may be connected directly to the ED or RO desalination processes. A PV cell converts solar energy directly into DC. A PV system consists of several modules or arrays, each of which consists of several solar cells. PV systems can be either flat-plate systems or concentrating systems. In addition, PV systems require careful maintenance and operation of their storage systems. Several small-scale PV-based desalination systems are being used around the world, particularly in remote areas and on islands. For example, there is a PV-RO system in Riyadh, Saudi Arabia, which processes brackish water (BW) with a capacity of 5 m^3/d and enables local inhabitants to use inland BW reserves.[79, 80, 81]

Concentrator PV (CPV) systems have the advantages of greater efficiencies and can be more compact systems for a certain power output. In the past, the CPV industry has struggled to compete with the prices for PV technology. As a result, some leading CPV companies have gone out of business while others are facing difficulties in scaling up their businesses, since raising the capital needed for such efforts has been challenging. Nevertheless, there is potential for CPV technology to reach even higher efficiencies which would help reduce the costs of this technology.[82]

A schematic diagram of a PV-RO system is shown in figure 19. This is considered to be one of the most promising forms of RE-powered desalination, particularly in remote areas.[83] RO uses the electricity (after being converted to AC form) to power the pumps. The system also includes storage batteries which assist in sustaining or smoothing the system operation during insufficient levels of solar radiation (e.g. overnight and cloudy hours). PV-RO systems can be used with either BW or SW. For each application, different membranes are used as part of the desalination process, though in both the regular replacement of batteries is a cost to be considered, especially if large PV arrays are being used. What is more, with brackish water RO, higher recovery ratios can be achieved and the process is less costly than for seawater RO. Seawater has an osmotic pressure much higher than that of brackish water, as a result of which the seawater desalination process consumes more energy and requires stronger components mechanically and a bigger PV array.[84]

Figure 19. Schematic diagram of PV-RO system



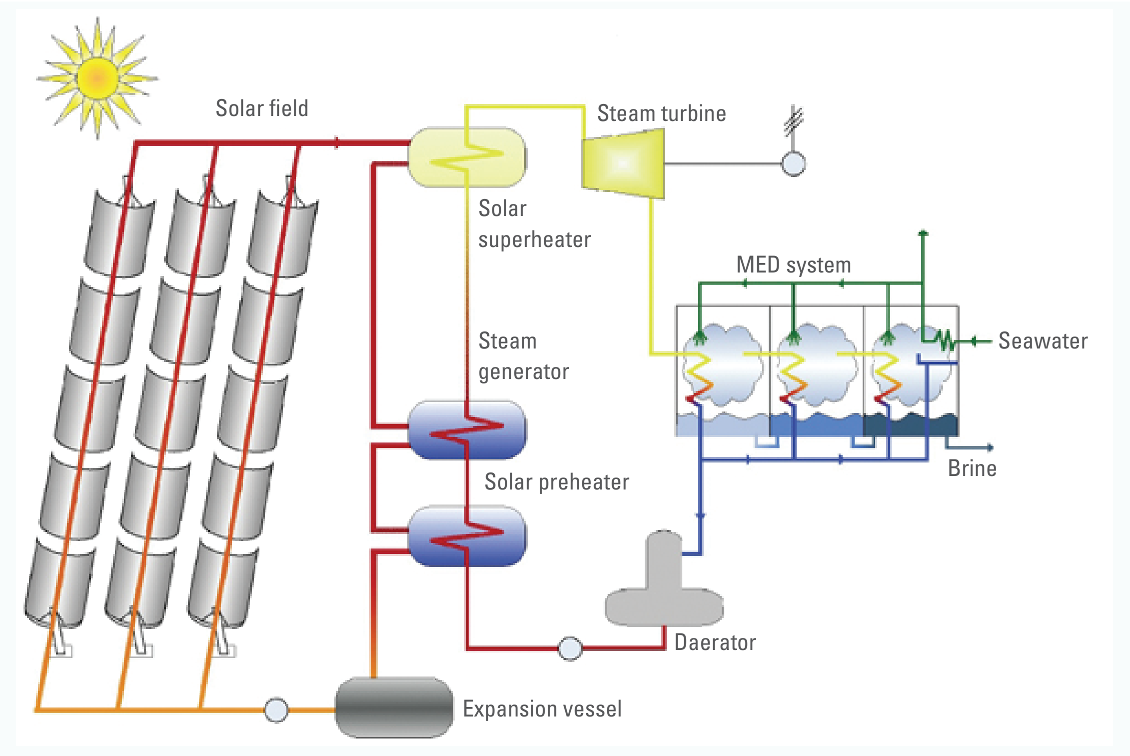
Source: Kim and others, 2013.

Solar thermal desalination: CSP is a type of technology used in solar thermal desalination. The pros and cons of CSP as a technology have already been discussed. In this section, the incorporation of this technology with desalination processes is considered. Figure 20 shows an example schematic diagram of a CSP-MED system where parabolic trough technology is being used. CSP technology usually concentrates solar radiation using glass mirrors which can continuously track the sun position.

Table A1 in the annex compares different concentrating solar power collecting systems. Currently, the parabolic troughs shown in figure 20 are known to be the most proven concentrating solar power collecting system[85] (i.e. they are the most mature, with the greatest amount of commercial operating experience[86]).

CSP based on parabolic trough technology, which is considered the most commercialized CSP technology, can be used with both membrane and thermal desalination processes, since it collects solar radiation and provides high temperature heat which can be used for electricity generation. Though this is not shown in figure 20, CSP plants can often contain thermal storage systems, which help provide a continuous source of power or may be used in combination with conventional fuel sources in a hybrid plant. The plant in figure 20, for example, produces water as its main product but can also generate electricity as a byproduct. Moreover, CSP technology is more suitable for medium and large-scale desalination installations than PV technology.[87] A comparison of the principal features of solar thermal storage technologies is provided in table A2 in the annex.

Figure 20. Schematic diagram of CSP-MED system



Source: Zachary and Layman, 2010.

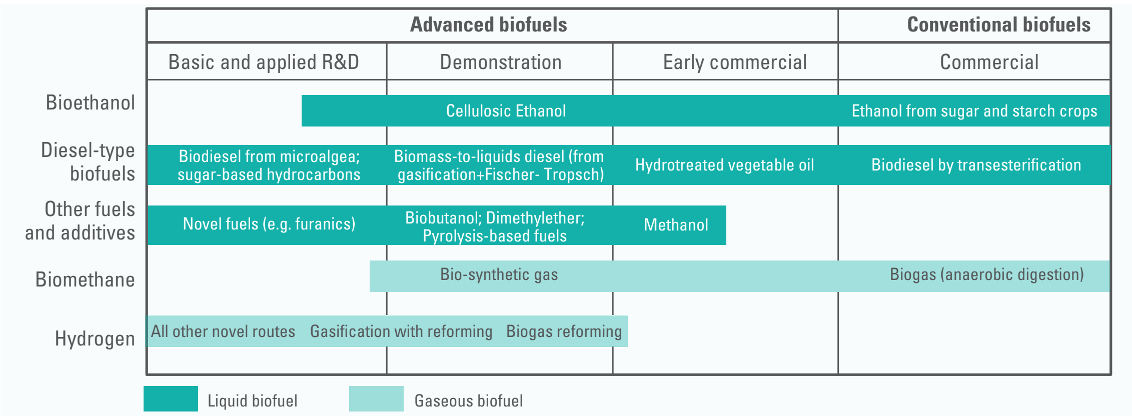
Wind powered desalination

Wind turbines can supply mechanical power or electricity to desalination plants. They are considered to be a mature technology that is available commercially, similar to PV technology. Another similarity between the two technologies is that they are more suitable for powering small-medium scale desalination operations (e.g. wind-RO combinations can produce 50-2,000 m^3/day[88]). Wind energy is also suitable for coastal areas where the wind potential is greater and more predictable. Wind turbines can have vertical or horizontal axes of rotation. Those with a horizontal axis of rotation are known to have greater power generation efficiencies and therefore are more commonly used.[89] As with solar energy, the issue of intermittency is also a concern for wind energy. Thus, energy storage or a backup power system may be required to ensure that there is no hindrance in the desalination process, and this may be possible with the installation of a hybrid system.[90] Wind energy is usually associated with the powering of the RO, ED or MVC desalination processes. In the case of MVC, the mechanical energy of the wind turbine is directly used for vapor compression without requiring a further conversion into electricity, making the process more efficient.[91]

Geothermal desalination

Geothermal energy can be used to produce both heat and electricity and can therefore be used to power both thermal and membrane-based desalination processes. Geothermal reservoirs are usually specified as being either low temperature (<180 °C) or high temperature (>180 °C) reservoirs.[92] At the same time, moderate and high temperature reservoirs can directly be used for thermal desalination technologies. If the geothermal source is at a pressure high enough, shaft power can be used directly to power mechanically driven desalination. In contrast, geothermal fluids at high temperatures can be used to produce electricity which would power RO or ED desalination plants.[93] On the other hand, low-temperature geothermal energy (70-90 °C) is most suitable for MED. One of the greatest advantages of geothermal energy is that it is a continuous energy source, and so energy storage options need not be applied. It can also provide desalinated water at relatively low cost, though capital costs can be high. The suitability of using

Figure 21. Biofuels classifications and their stage of production advancement, 2011



Source: Biernat, Malinowski and Gnat, 2013.

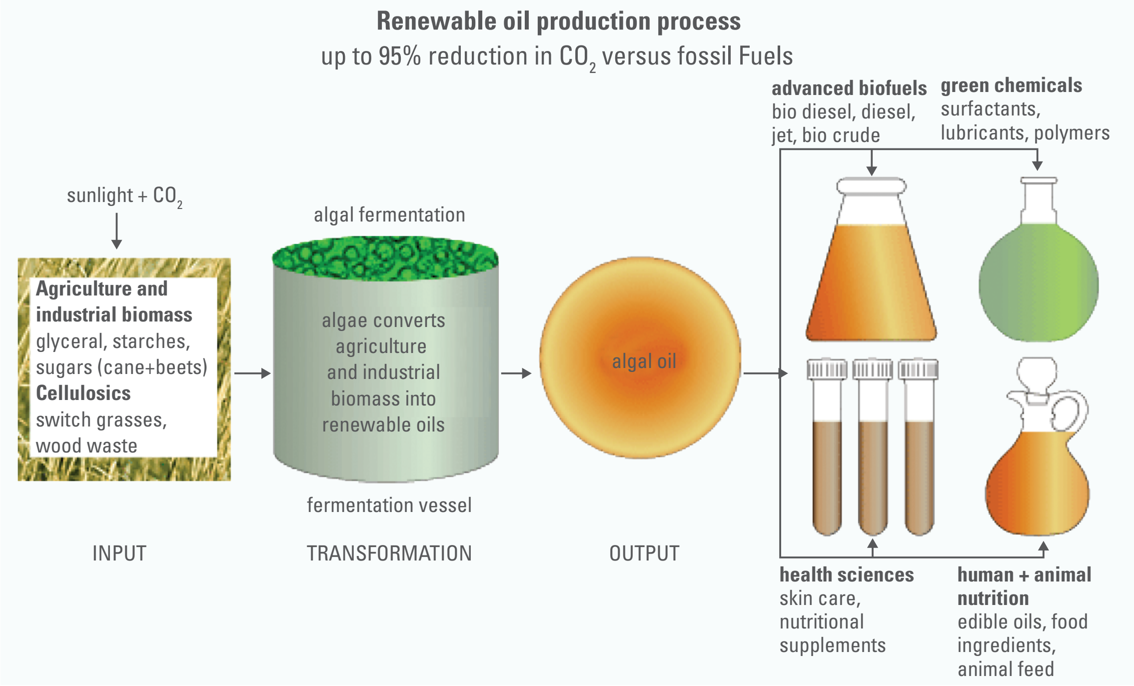
such an energy source depends substantially on local conditions.[94] A recent study in the United Arab Emirates found that the coupling of geothermal energy with MED or RO can be a reliable way to supply a steady water output, though the technology is still not financially viable relative to RO and MED powered by fossil fuels. However, in the case of coastal areas of the Gulf region, geothermal powered RO, and to a lower extent geothermal powered MED, have the potential to be cost-effective.[95]

Industrial process water

Production of bioenergy from industrial wastes

The production of biogas from sewage sludge in wastewater treatment plants has already been discussed in some details. Other industrial plants may also produce organic waste or wastewater which may be used as a source of bioenergy. Figure 21 shows different types of biofuels and their stage of production advancement as of 2011. It can be seen that biogas generation from anaerobic digestion, as done at some wastewater treatment facilities, is a mature technology that is used worldwide. Besides sewage sludge, anaerobic digestion can be used for other industrial organic wastes as well. Once produced, biogas can be purified to form biomethane (by removing carbon dioxide and hydrogen) and can then be used as a transportation fuel (for example, bioCNG [Compressed Natural Gas]) or as a hydrogen source which may be used in fuel

Figure 22. Schematic diagram depicting the production process of different industrial products from algae



Source: Biernat, Malinowski and Gnat, 2013.

cells. Additionally, through the use of a catalyst, biogas (i.e. methane) can easily be converted to syngas (a combination of hydrogen and carbon monoxide). This syngas has applications in the chemical industry where it can be used to produce liquid fuel and other high-value products which can easily be separated once produced.[96]

As shown in figure 22, algae (microorganisms) are a medium which can be used to convert industrial biowastes into energy. The figure shows the multitude of applications of the algal oils produced. Algae have several advantages such as being easy to cultivate, since they can grow in places like the desert and oceans and even wastewater. They typically have fast growth rates, are well-suited to the complex, changing and non-sterile environment of wastewater, are able to convert carbon dioxide into energy, thereby assisting in reducing global warming, and absorb pollutants such as nitrogen and phosphorus, thus assisting in environmental remediation. The rate of growth of the algae and the biofuel which they produce depend on a number of factors such as the concentration, amount and type of substrate which they are feeding on (i.e. the organic matter/waste). In fact, algae used for the production of liquid fuels are able to reduce wastewater amounts significantly as a result of purifying it and removing toxic substances like heavy metals.[97]

Case study: the oil and gas industry

There is much potential for RE to meet the energy requirements of the oil and gas industry. This RE would primarily be in the form of solar or wind energy and would be used to power various instruments and equipment throughout the fossil fuel production process. RE can also be used to provide heating requirements with the help of solar thermal or geothermal systems. Such use of RE is particularly important for Arab countries, some of which are major oil producers and benefit from abundant solar radiation. In fact, it has been found that worldwide, the most important heavy oil reserves are located in areas which receive high solar radiation,[98] which supports the feasibility of using RE for such oil and gas operations. The use of RE in upstream applications in this industry is already being achieved. The same cannot be said about downstream applications, though RE options are expected to be used for the latter as well in the near future.

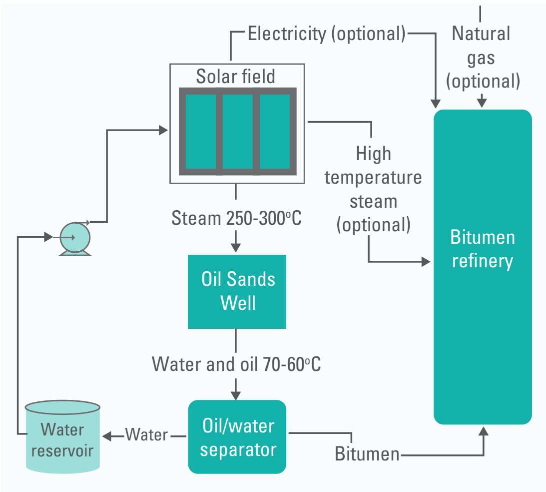
Currently, most of the major oil companies power their special field applications using PV panels.[99] Such applications include off-grid warning lights for offshore installations. The use of this PV technology has been a source of substantial financial savings for these oil companies. Other applications for which many oil companies are already using (or are planning to use) PV technology are to power the cathodic protection of well casings and pipelines from corrosion as well as to meet the power requirements of oil rigs and other remote oil-related installations, located both off-shore and on-shore.[100]

When using PV technology in locations such as the Gulf region, factors that need to be considered to improve the system performance are the amount of dust present (which must be removed from the PV panels regularly), bird droppings (which also need to be washed off the panels), high temperatures, particularly during the summer (which significantly reduce the yield of the panels), and variations in the load which can be addressed by having a buffer of at least a 15 per cent excess charge greater than the normal load.[101] More than ten years ago, Chevron Energy Solutions implemented a large-scale PV system called Solarmine for powering oil field operations in California, particularly for powering oil pumping units and processing plants. The array has a capacity of 490 kW (AC) and consists of 4800 solar panels, producing 1,000 MWh annually. The whole PV plant takes up an area of about 24,000 m^2. The performance of the plant was reported in 2005, and it was found that the plant had performed as per its design goals, sometimes even surpassing them by 5-10 per cent.[102] What is more, in September 2016, the Eni energy company concluded an agreement regarding the building of a 10 MW photovoltaic plant in the Bir Rebaa North field in Algeria.[103]

One of the main potential applications for concentrated solar thermal technologies in the oil and gas industry is the generation of steam, which is needed for heating and enhanced oil recovery (EOR) purposes. Solar thermal technology can produce steam at high pressures and temperatures (up to 550 °C). EOR requires steam in the range of 115-300 °C, so this is achievable using solar thermal technology. Moreover, the natural gas traditionally used to produce this steam for EOR is becoming more expensive due to short-falling supplies, while the use of alternative fuels such as coal would lead to substantial carbon emissions. As a result, CSP can provide a cost-effective and ecofriendly way of generating this steam. A demonstration plant in California, which began operation in 2010, has shown the viability of using CSP technology to generate steam which can be used to extract oil from an oil field. A similar 7 MW solar thermal plant is currently in operation in Oman, as mentioned in table 2. It combines a solar thermal plant with an already existing conventional steam-generating plant, a setup which is favored by other studies as well. The solar thermal plant houses the mirrors and receivers in a glass structure, so that they are protected from the harsh outdoor conditions. The solar thermal plant has helped decrease natural gas requirements by almost 49,500 gigajoule (GJ) annually and a 2014 report demonstrated how the plant, which generates more than 80 tons of steam daily, has been able to achieve more than 97 per cent of its theoretical output.[104] Another 1 gigawatte (GW) EOR CSP plant is being planned in Oman as well (table 2) and the Kuwait Oil Company (KOC) is also exploring the possibility of using CSP technology to power future EOR projects in the country.[105] With regards to oil sands and unconventional oil, a 2009 study showed the cost-effectiveness and reliability of using solar power to produce the steam which is used to achieve the recovery of bitumen from oil sands. The system discussed in this study uses the cogeneration of heat and electricity. Figure 23 shows the diagram of a proposed solar-enhanced oil recovery system for oil sands.

Solar energy can also be used in the oil and gas industry to power the desalination of the brine water which is produced from oil and gas wells. The treated effluent would not be harmful to the environment and the treated water could be reused in the plant itself or for some other applications (e.g. agriculture). In addition, the downstream processes which take place in the oil and gas industry are known to be energy-intensive, high temperature and

Figure 23. Diagram of a proposed solar-enhanced oil recovery system for oil sands



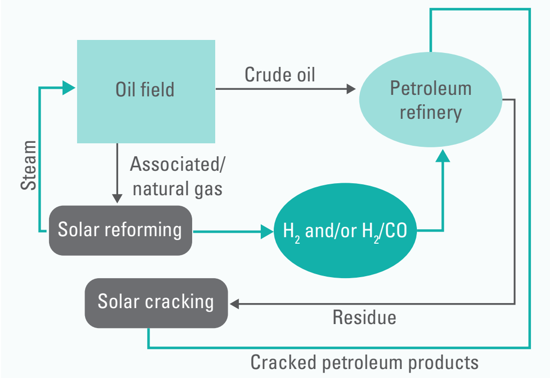
Source: Absi Halabi, Al-Qattan and Al-Otaibi, 2015.

high density processes. Examples are hydrogen production and distillation. As a result, solar thermal technology would be a promising option for these processes, though no such industrial-scale plant has been implemented for such applications.[106] This is due to challenges associated with these particular applications, such as limited land to set up solar installations and the intermittency of solar power, which means that any plant should be part of a hybrid system or should have energy storage options.[107] In order to address the challenge of limited land area, a potential solution is that the CSP setup could be located up-field at a distance from the refineries where open land may be readily available. Any immediate processing could take place at the isolated facility, after which the products may be transported to the refineries through pipeline. An example of such a setup is shown in figure 24, where hydrogen or synthesis gas is produced at an up-field location using solar reforming. Any excess heat produced off-site can also be used to fulfill thermal energy requirements at the refinery. Additionally, heavy residual oil from the refinery can be pumped up-field for solar cracking, the products of which can then be transported back to the refinery for further processing.[108]

Besides solar energy, other types of RE could potentially be employed, and are already being employed, in the oil and gas industry. For instance, Shell is using a combination of both wind turbines and PV panels to help power some of its monotower platforms.[109] A 2012 study also showed the potential for ocean thermal energy conversion in off-shore locations where the temperature difference between the sea bed and the shore is more than 20°C. Geothermal energy also has the potential to be used in the oil and gas sector; the temperature of oil formation can go up to 130-150 °C, and so the temperature difference between the oil formation and the surface can theoretically be used to generate heat. Water is injected as part of improved oil recovery operations, so a byproduct of these operations could be the generation of heat. Additionally, gasification of the different carbonaceous byproducts of industry processes (e.g. petroleum coke and vacuum residue) can be used to produce syngas which may also be used as an energy source.[110]

It must be remembered that although RE systems have a great potential, their implementation depends heavily on oil prices, which are continuously fluctuating. Nevertheless, RE options are expected to have increasing applications in the oil and gas sector, especially due to the increasing energy demand by this industry, resulting from reasons such as the growing use of more energy-intensive secondary and tertiary oil recovery techniques. Indeed, with the exception of a small number of applications in certain upstream areas, many RE installations currently operational or being planned in the oil and gas industry are for demonstration purposes, the results of which are expected to expand RE use in the industry. By 2035, solar energy is forecasted to provide about 5 per cent of the industry energy needs, which amounts to approximately 2 petajoule (PJ) of energy.[111]

Figure 24. Potential application in petroleum refining: off-site reforming and cracking



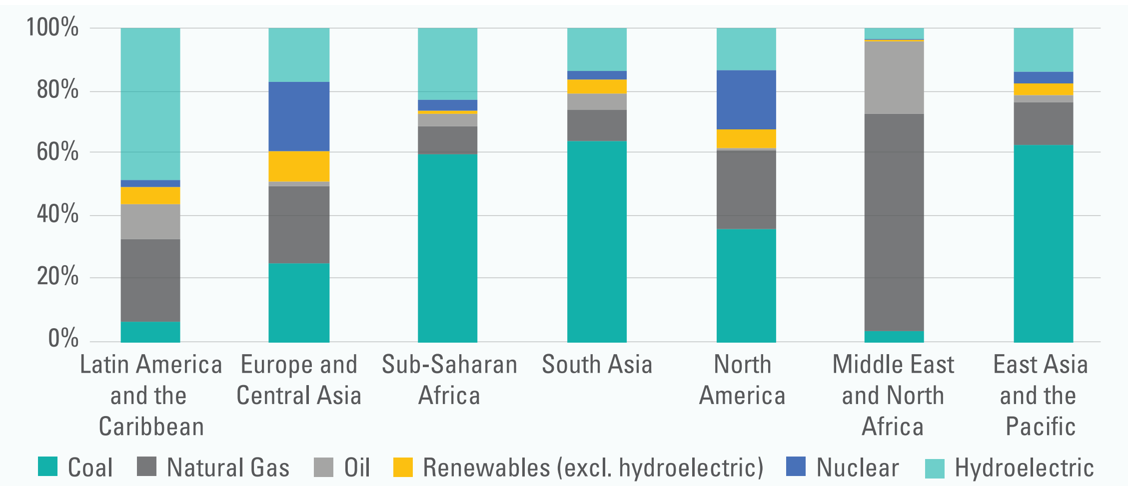
Source: Absi Halabi, Al-Qattan and Al-Otaibi, 2015.

Renewable energy technologies assessment for electricity production

Along with non-renewable sources, RE sources are being used worldwide as a source of energy for the production of electricity. Figure 25 shows the share of RE, in comparison to different types of fuel, used for electricity generation in different global regions in 2013. It is clear that the contribution of RE in the MENA region has been negligible in 2013 (0.32 per cent). However this contribution is expected to increase significantly due to the RE proliferation targets which many Arab countries have set for themselves. These targets are mentioned in table 6 and, for many of these countries, the more general issue of energy pricing reform has frequently been cited as the primary motivation for setting such targets.[112] This issue has been affected by the common concern in some countries about rapidly increasing domestic demand for fossil fuels (due in part to subsidized prices) and thus the increased amount of fossil fuel production which needs to be diverted away from the export market to fulfill this domestic demand. This comes at a substantial opportunity cost;[113] a situation which is being exacerbated by low oil prices.

Many Arab countries have announced new pledges towards sustainable energy through their Intended Nationally Determined Contributions (INDCs) on climate. In many cases, targets have been updated to reflect local requirements and circumstances. Additionally, the adoption of the "Pan-Arab Strategy for the Development of Renewable Energy 2010–2030" has also facilitated the setting of RE targets. This strategy was adopted at the third Arab Economic and Social Development Summit in 2013 under the umbrella of the League of Arab States; it has set long-term targets for RE electricity production and aims to scale up the use of RE in various sectors, such as desalination.[114] What is more, policymakers in Arab countries are well aware of the benefits of RE deployment. These include energy access and job creation, and have also affected conditions in favor of RE target-setting.

Figure 25. Share of various fuel types in total electricity generation by world region, 2013



Source: World Bank, 2015.

At the same time, one could argue that these targets are not ambitious enough. In fact, from 2014 to 2050, on a global scale, renewables are forecasted to account for almost 67 per cent of net power capacity growth, while the value for the same parameter for the MENA region is less than 15 per cent.[115] Differences are expected between what Arab countries are planning and what is forecasted to be achieved. Indeed, it is predicted that countries which rely on imported fuel to meet their power demands (e.g. Morocco) will be more aggressive in achieving their RE targets, as a result of the more supportive and enabling environment which they have created for such alternative technologies. At the same time, on a global scale, the IEA reports that the lowest long-term contract prices for new renewable power to be commissioned in 2016-2018 have been achieved in Arab countries (e.g. lowest prices in Egypt for onshore wind and lowest prices in United Arab Emirates and Jordan for utility-scale solar PV). The region is also expected to emerge as one of the fastest growing PV markets.[116] As a result, there is much potential in the region and this toolkit seeks to facilitate the adoption of RE technologies for the purpose of power generation in Arab countries.

Table 6. RE proliferation targets as set by most Arab countries, 2013

Country	RE Targets
Algeria	15% of electricity generation by 2020; 27% of electricity generation by 2030
Bahrain	5% of installed capacity by 2030
Egypt	20% of electricity generation by 2020
Iraq	10% of electricity generation by 2030
Jordan	15% of electricity generation by 2015
Kuwait	10% of electricity generation by 2020; 15% of electricity generation by 2030
Lebanon	12% of electricity generation by 2020
Libya	7% of electricity generation by 2020; 10% of electricity generation by 2025
Mauritania	20% of electricity generation by 2020
Morocco	42% of installed power generation capacity by 2020; 52% of electricity generation by 2039
Oman	10% of electricity generation by 2020
Palestine	25% of final energy by 2020; 10% (or at least 240 GWh) of electricity generation by 2020
Qatar	2% of electricity generation by 2020; 20% of electricity generation by 2030
Saudi Arabia	9.5 GW of renewable energy by 2023; 50% of electricity from non-hydrocarbon resources by 2032
Sudan	20% of electricity generation by 2030
Tunisia	25% of installed power capacity by 2030; 30% of electricity generation by 2030
United Arab Emirates	24% clean energy (including nuclear) in energy mix by 2021; Dubai: 7% of capacity by 2020 and 15% by 2030 (versus 'business as usual'); Abu Dhabi: 7% of electricity generation capacity by 2020
Yemen	15% of electricity generation by 2025

Sources: El-Katiri, 2014; IRENA, 2016b; Poudineh, Sen and Fattouh, 2016; Renewable Energy Policy Network for the 21st Century (REN21) and Institute for Sustainable Energy Policies (ISEP), 2013; REN21, 2016.

An alternative energy source which contributes significantly to the electricity generation energy mix in some countries is nuclear energy.

Table 7 compares qualitatively between solar and nuclear energy, describing the pros and cons of each technology. In terms of the implementation of nuclear energy in Arab countries, it has still not happened on a commercial scale (i.e. become operational), though some countries such as Algeria, Egypt, Jordan, Saudi Arabia, and the United Arab Emirates are currently planning or building nuclear energy projects. The United Arab Emirates is taking the lead in this area by being the first Arab country to build a nuclear power plant. Its flagship project, Barakah, will have an installed capacity of 5.6 GW, fulfilling almost 25 per cent of the country's electricity requirements. Its first phase is expected to become operational in 2017 and its final unit is scheduled to become operational in 2020. Similarly, Saudi Arabia is planning to build 16 nuclear reactors by 2032, which would fulfill 15 per cent of the country's electricity requirements. They will have a total installed capacity of 17 GW and the first reactor is expected to be operational in 2022. On the other hand, Jordan and Egypt have signed agreements with the Russian nuclear corporation to build 2,000 MW by 2023 and 4,800 MW by 2028 respectively.[117] Due to the safety risks associated with this technology, some Arab countries like Kuwait, Oman and Qatar have discontinued plans to invest in it. Other countries, such as Morocco and Tunisia, are studying the feasibility of using nuclear energy.[118] Nuclear energy also has the significant advantage of being a continuous source of electricity that can help a country meet its CO_2 emissions reduction targets. Thus, it is up to each country to independently decide whether the benefits of this energy outweigh the challenges associated with it.

Yet another important option for generating electricity on a small scale is microhydropower, hydropower systems which generate up to 100 kW of electricity. Such systems can be used by a large home, small businesses such as a small resort, small-scale farms, etc. A microhydropower system needs a device which can transform the energy of flowing water into rotational energy, which is then converted into electricity. This device can be a turbine, pump, or waterwheel; though the most common device used in Microhydro systems is the impulse turbine. In general, for efficient turbine operation, a minimum head (i.e. vertical change in elevation between the reservoir water level and the downstream water level) of 3 ft (approximately 0.9 m) is required, along with water flowing at about 20 gallons/minute.[119] Microhydro systems are usually run-of-the-river systems, which means they do not require components like dams or large water storage reservoirs. They can also be used to produce energy when integrated into water supply networks and wastewater infrastructure; indeed using microhydropower technology in the water industry is an area of expanding industrial activity and growing research as well.[120]

In microhydropower technology, a portion of water is diverted from the water source such as a river and is directed into a structure such as a channel or a pressurized pipeline which delivers it to the turbine or waterwheel. The resulting rotation spins a shaft which can be used for mechanical processes (e.g. pumping water) or can be used to power an alternator or generator and generate electricity. A microhydropower system can be off-grid or grid-connected, and this accordingly has implications on the components it has. For instance, off-grid systems tend to have batteries to store the electricity that they generate.[121]

Unlike other RE sources, microhydropower has the advantage of being a continuous source of power and not intermittent. Microhydropower also has the benefit of being less costly than wind or solar energy, particularly in terms of capital costs. Of course, this comparison is not taking into account the government subsidies for wind and solar power which are offered in many places. Furthermore, microhydropower installations tend to be simpler and thus easier to maintain. They can also generate energy from remote water sources. The major disadvantage of microhydropower is that it requires access to a suitable flowing water source, while solar and wind resources are more or less available everywhere. Yet another drawback of microhydropower is that each installation has its own peculiarities according to the specific location, and so a 'one size fits all' solution cannot be manufactured, as is possible to some degree with wind and solar energy installations. Moreover, government subsidies for microhydropower are unlikely, as the environmental impacts are different for each installation and would need to be determined on a case-by-case basis.[122]

Another option which has already been discussed to some extent is the integration of different fuel types to overcome the intermittency that tends to be associated with some types of RE. Usually, the combinations discussed are between a type of RE and a conventional energy source. A combination therefore worth exploring is that of wind power with hydropower. Hydropower can make up very effectively for the discontinuous nature of wind energy due to its flexibility. It can easily meet rapid changes in net load, provide energy storage, provide system ramping, and provide voltage support to wind systems due to supplying reactive power. Relative to fossil fuel energy generation, hydropower also has the advantage of a low capacity factor.[123] The capacity factor is the amount of electricity a power plant actually produces compared to the amount it would produce if it was operating at full nameplate capacity (the power output of the plant) all

Table 7. Solar and nuclear energy: qualitative comparative analysis

			Cost competitiveness		Water requirements		Land use	Environmental impact and long-term sustainability	Socioeconomic co-effects		Human resources and training
			LCOE	Balancing costs					Job creation	Local manufacturing potential	
Nuclear energy			++	+	Once-through cooling	--	++	--	+	+	+
					Wet cooling tower	-					
					Dry cooling tower	+					
Solar energy	**CSP**	PT			+		--	+	-	++	-
		SD	+	-							
		ST									
	PV		++	--	++		-	+	-	-	--

Abbreviation: LCOE, levelized cost of electricity.

Sources: Cour des comptes, 2014; ESCWA, 2015; Kost and others, 2013.

Notes: '+' and '-' denote that the type of energy being described is advantageous or disadvantages, respectively, with regards to the factor being discussed.

'++' denotes a greater level of advantage than '+';

'--' denotes a greater level of disadvantage than '-'.

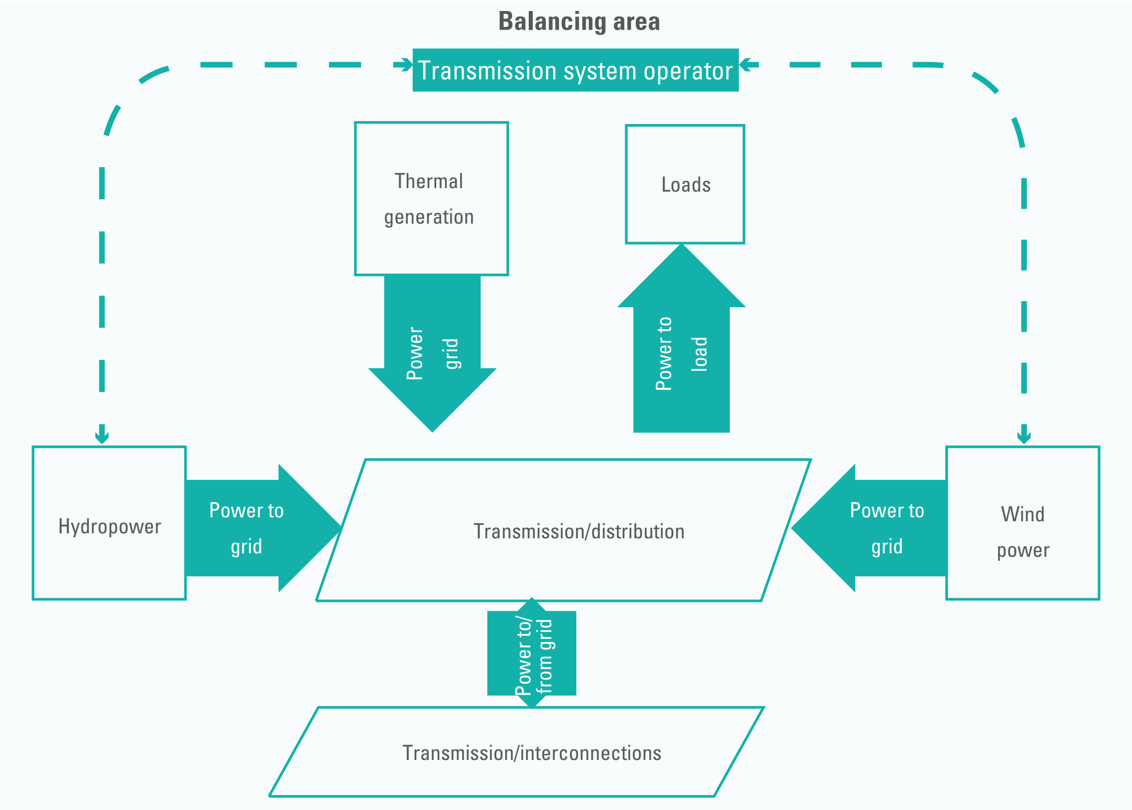
the time. Hydropower is also considered to be a low-cost means of electrical generation.[124] A schematic diagram for such a hybrid system is shown in figure 26. The blue dashed lines represent data/information flow. The wind and hydropower sources do not have to be located at the same generation site as long as they are connected to the same transmission network.

Table 8. Renewable power: installed capacity and targets in Arab countries

	Wind (MW)		PV (MW)		CSP (MW)		Hydro (MW)		Target Date
	Installed	Target	Installed	Target	Installed	Target	Installed	Target	
Algeria	10	1,010	270	3,000	25	-	228	-	2020
		5,010		13,575		2,000	-		2030
Bahrain	0.5	-	10	-	-	-	-	-	2030
Djibouti		300		200 (PV +CSP)		200 (PV +CSP)		-	2025
Egypt	810	7,200	90	2,300 +	20	-	2,874	-	2022
Iraq	-	-	3.5	300	-	-	2,513	-	2020
Jordan	197	800	15	800	-	100	12	-	2020
Kuwait	-	700	1.8	4,600	-	5,700	-	-	2030
Lebanon	-	400	20	150-100 (PV +CSP)	-	150-100 (PV +CSP)	280	400	2020
Libya	-	600	5	344	-	125	-	-	2020
		1,000		844		375		-	2025
Mauritania	34.4	30	18	30	-	-	30	-	2020
Morocco	790.5	2,000	15	2,000 (PV+ CSP)	183	2,000 (PV +CSP)	1,770	2,000	2020
		4,200		4,560 (PV +CSP)		4,560 (PV +CSP)		-	2030
Oman	-	-	-	-	7	-	-	-	-
Palestine	0.7	44	4	45	-	20	-	-	2020
Qatar	-	-	1.2	-	-	-	-	-	2030
Saudi Arabia	-	9,000	23.2	16,000	-	25,000	-	-	2040
Sudan	-	680	12	667	-	50	1,593	63	2020
		1,000		1,000		100		-	2030
Syrian Arab Republic		1,000		2,000		1,300			2030
Tunisia	245	1,755	20	1,510	-	460	66	-	2030
United Arab Emirates	0	-	33	5,000	100	-	-	-	2030
Yemen	-	400	3	8.25	-	100	-	-	2025

Source: IRENA, 2016b.

Figure 26. A practical configuration for the integration of wind and hydropower resources



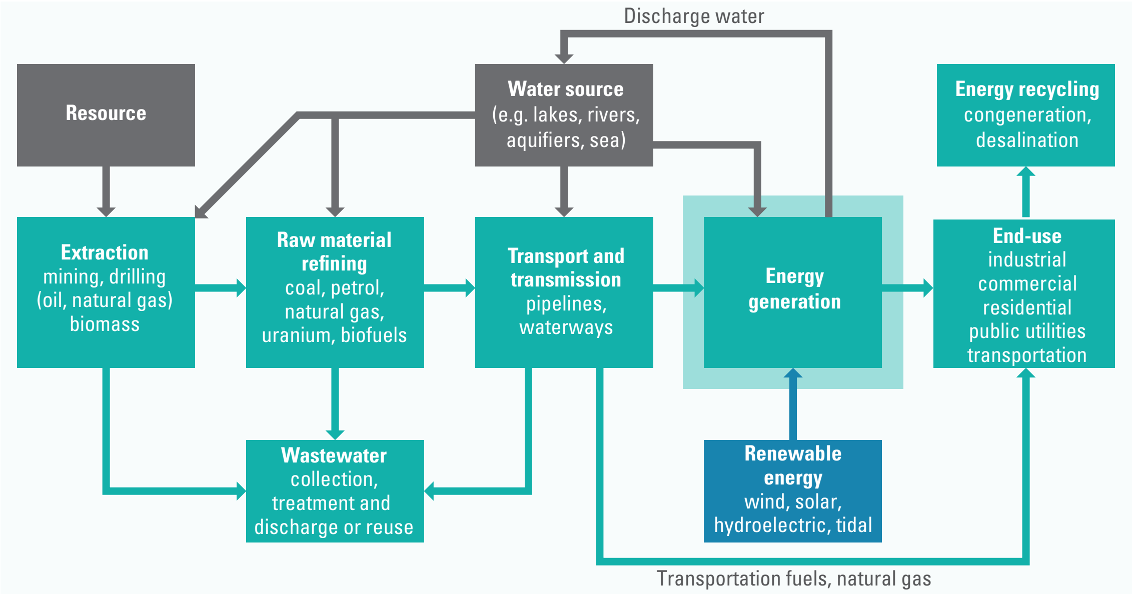
Source: Acker, 2011.

In the Arab region, though the potential of wind and hydropower resources is limited as compared to that of solar (both PV and CSP combined) resources,[125] significant potential for these resources exists in some countries. The countries of North Africa (i.e. Algeria, Egypt, Mauritania, Morocco and Tunisia) have significant wind potential.[126] This is evident from the installed wind capacity which they already have and the additional wind capacity they are expecting to add to their RE portfolios as per their RE targets, as is clear from table 8.[127] In general, the total estimated economic potential of wind energy in the MENA region is about 300 TWh. With regards to hydropower, some countries like Egypt and Iraq have greater potential,[128] and this is also clear from the installed hydro capacity which these countries have (table 8).[129] In terms of RE targets, the Arab countries leading the way are Lebanon, Morocco and the Sudan.[130] The total potential of hydropower generated electricity in the MENA region is about 182 TWh.[131]

Water usage in electricity production processes

Figure 27 shows the complete energy production process and the different ways and points in which water is involved in this process. It also shows where RE can be used to power the energy generation process. An integral aspect of studying the water and energy nexus is discussing how water is used in the production of electricity and how such processes can be made less resource-intensive. When RE options are used for electricity generation, the process by which electricity is generated varies significantly according to the technology being

Figure 27. Flowchart of embedded water in energy



Source: Water in the West, 2013.

employed. Consequently, the amount of water being used also differs according to the type of RE used. This section discusses these differences in water consumption rates.

Table 9 shows the main uses of water for energy and potential water quality impacts in primary energy production and power generation processes. It is clear that, depending on the technology being used, there are important differences between the uses of water in these processes and the resulting issues in terms of how water quality may be impacted. Not only are the uses of water considered for the actual power production processes, but the whole lifecycle of the fuel is considered in terms of how it is extracted and processed among other uses. It can therefore be assessed that, due to the nature of RE sources such as solar and wind energy, there are lower or non-existent water requirements, particularly during the ‘procurement’ stage of such resources, when these resources are first being harnessed as part of regular operations. This is very different from the process of EOR, for example, where obtaining the fuel is such a water-intensive procedure in the initial stages of the overall electricity generation process. The benefits of using RE to generate electricity in arid Arab countries are therefore obvious. Hydropower may be considered an exception since in this case water is the actual energy source; though the water used is primarily water withdrawn but not consumed.

Figure 28 shows the water consumed in the production of certain primary energy sources when they are entering the supply chain. It therefore accounts for the water consumed while these fuels are being extracted, processed and transported. With respect to bioenergy, it is an RE source with considerable water consumption rates. As shown in figure 28, the organic substances which are used as the feedstock for biofuel production (e.g. corn, sugarcane and soybean) consume significant amounts of water, even more water than required by some fossil fuels. This is due to the agricultural water requirements of these crops. As a result, due to the water stress in the MENA region, it is primarily the Gulf countries that are researching halophytes (crops which grow in saline environments) as a source of biofuels.[132] Such crops can grow in a large variety of saline habitats (e.g. coastal regions, inland deserts).[133] They are therefore a good fit for the salty waters of the Gulf.

Of the different processes which are part of electricity generation, it is the cooling process which tends to have the greatest water requirements.[134] The amount of water required also varies significantly depending on the type of cooling used (e.g. once-through cooling

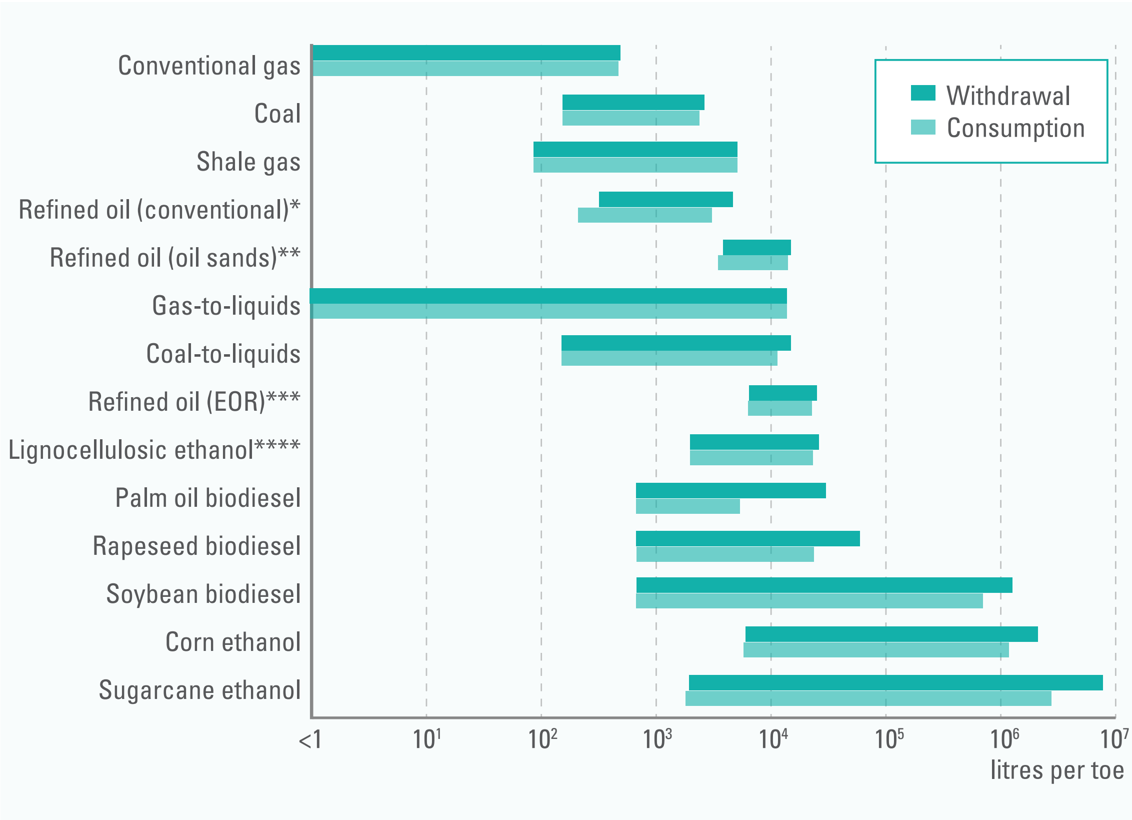
Table 9. Key uses of water for energy and potential water quality impacts

Primary energy production	Uses	Potential water quality impacts
Oil and gas	Drilling, well completion and hydraulic fracturing. Injection into the reservoir in secondary and enhanced oil recovery. Oil sands mining and in-situ recovery. Upgrading and refining into products.	Contamination by tailings seepage, fracturing fluids, flowback or produced water (surface and groundwater).
Coal	Cutting and dust suppression in mining and hauling. Washing to improve coal quality. Re-vegetation of surface mines. Long-distance transport via coal slurry.	Contamination by tailings seepage, mine drainage or produced water (surface and groundwater).
Biofuels	Irrigation for feedstock crop growth. Wet milling, washing and cooling in the fuel conversion process.	Contamination by runoff containing fertilisers, pesticides and sediments (surface and groundwater). Wastewater produced by refining.
Thermal power generation (fossil fuel, nuclear and bioenergy)	Boiler feed, i.e. the water used to generate steam or hot water. Cooling for steam-condensing. Pollutant scrubbing using emissions control equipment.	Thermal pollution by cooling water discharge (surface water). Impact on aquatic ecosystems. Air emissions that pollute water downwind (surface water). Discharge of boiler blowdown, i.e. boiler feed that contains suspended solids.
Concentrating solar power and geothermal	System fluids or boiler feed, i.e. the water used to generate steam or hot water. Cooling for steam-condensing.	Thermal pollution by cooling water discharge (surface water). Impact on aquatic ecosystems.
Hydropower	Electricity generation. Storage in a reservoir (for operating hydro-electric dams or energy storage).	Alteration of water temperatures, flow volume/timing and aquatic ecosystems. Evaporative losses from the reservoir.

Source: International Energy Agency (IEA), 2012.

has greater water requirements than cooling towers). Figure 29 shows the different water requirements for various electricity generation processes depending on the type of energy being used as well as the cooling type. Note that "water withdrawn" is the amount of water taken from the water source at the beginning of the process, while "water consumed" is the amount of water used up as part of the process. The difference between these two parameters is the amount of water returned to the water source. Figure 29 highlights how all RE technologies have the potential to generate electricity with greater amounts of water efficiency, as compared to fossil fuel resources. Though there is much variation within each of the values for the water withdrawal and consumption rates of the RE sources, it is clear that they can achieve water efficiencies greater than that achieved by dry cooling with fossil fuel resources (dry cooling uses air instead of water as the cooling medium). The benefit of using RE sources is therefore evident. It is also important to note that water withdrawal and consumption rates tend to be the same for RE sources; all the water they withdraw is consumed and none is returned to the water source. This can be considered advantageous from the perspective that water effluent from power plants usually requires treatment before being returned to the water source to maintain environmental standards. No effluent means minimal potential environmental damage.

Figure 28. Water use for primary energy production



Source: IEA, 2012.

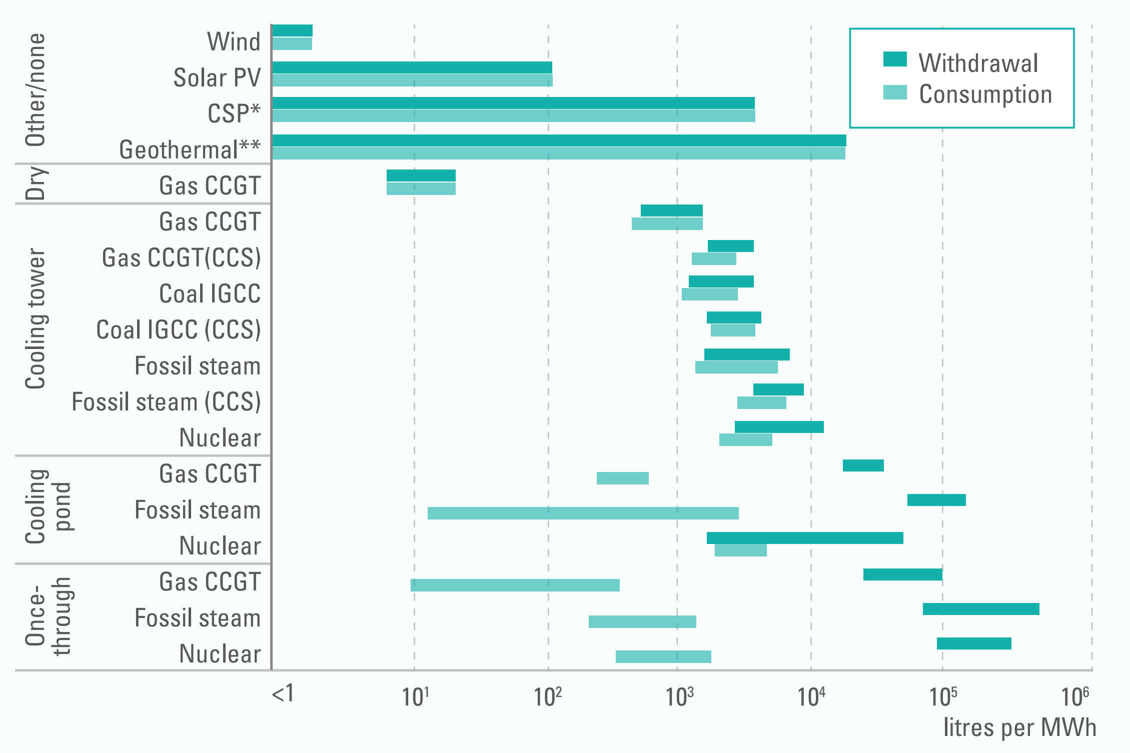
Notes: *The minimum is for primary recovery, the maximum is for secondary recovery;

** The minimum is for in-situ production, the maximum is for surface mining;

*** Includes CO_2 injection, steam injection and alkaline injection and in-situ combustion;

**** Excludes water use for crop residues allocated to food production.

Figure 29. Water use for electricity generation by cooling technology



Source: IEA, 2012.

Notes: * Includes trough, tower and Fresnel technologies using tower, dry and hybrid cooling, and Stirling technology;

** Includes binary, flash and enhanced geothermal system technologies using tower, dry and hybrid cooling.

Key performance indicators for RE technologies

According to IRENA, the indicators used to evaluate RE deployment policies could potentially be categorized as follows: effectiveness, efficiency, equity, and institutional feasibility.[135] Since this toolkit is looking at the water and energy nexus from the technical perspective, the effectiveness category is most relevant and will be discussed in the following paragraphs. Table 10 presents a summary of these different RE effectiveness indicators. It is important to mention that the development of such indicators is an ongoing effort, and so these indicators are continuously being improved as new insights are made.

Effectiveness indicators provide a benchmark for measuring how successfully RE technology has been deployed. Some of the effectiveness indicators, such as installed capacity and electricity generated, are quite simple in nature (i.e. they are easy to employ and are used quite commonly). Such simple indicators may be considered a proxy for effectiveness. But even within these simple indicators, distinctions can be made. For example, considering energy output may be considered better than considering capacity growth as the former provides information about how productive the RE technology has been.[136]

Table 10. Summary of key RE effectiveness indicators

Primary energy Production	Uses
Installed capacity (MW)	Simplest indicator to employ: very low data requirements. Pipeline data may be included. Does not capture operational performance.
Electricity generated (MWh)	Low data requirements. Captures operational performance.
Meeting pre-existing government targets	Assesses link between achievements and targets, but without indication of scale of policy ambition.
European Commission (EC) effectiveness indicator	Measures deployment achieved in a given year as a percentage of remaining unexploited realizable potential to the year 2020. Considerable data and technical capacity requirements to estimate realizable potential. Does not take into account learning rates. Moving base year hinders longitudinal comparison.
Policy impact indicator	Measures deployment (in terms of RE electricity generation) achieved in a given year as a percentage of new RE electricity generation deployment required between 2005 and 2030 to meet IEA WEO 450 projections (projected pathway for stabilizing global carbon dioxide concentrations at 450 parts per million by 2030). National-level IEA WEO 450 projections not available for all non-OECD/BRIC countries, and difficult to disaggregate from regional projections. Use of static base year facilitates longitudinal comparison.
Deployment status indicator	Quantifies maturity of national RE technology markets. Composite indicator combining: RET production as share of consumption; production as share of 2030 realizable potential; installed capacity. Considerable data requirements.

Abbreviation: WEO, World Energy Outlook.
Source: Nicholls and others, 2014.

Other effectiveness indicators, such as the deployment status indicator and the policy impact indicator are more complex. Such complex indicators account for variables like difference in resource potential and progress towards targets, allowing for more comprehensive and specific comparisons between countries. This greater analysis requires more data and data processing which may be difficult to provide for low-income countries.[137] Moreover, though comparing between countries is essential in order to be able to judge relative merit, comparing between countries must be done with care; groups of peer countries should be identified and within these groups comparisons can be made. Nevertheless, it is suggested that the European Commission (EC) effectiveness indicator be used as a primary indicator.[138] Though it is a complex indicator, it is less data-demanding than other complex indicators and may be considered to only slightly exceed simple indicators in this respect.

As per the SE4All initiative, various SDGs have been outlined, and these goals have different targets associated with them, which in turn are associated with different indicators. Goal 7 aims to ensure access to affordable, reliable, sustainable and modern energy for all. The relevant RE target associated with this goal is 7.2 (increase substantially the share of renewable energy in the global energy mix by 2030), and the corresponding indicator for mentoring implementation is 7.b (by 2030 expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries). Another relevant indicator is implicit incentives for low-carbon energy in the electricity sector (measured as $/MWh or $ per ton avoided CO_2). This is referred to as indicator number 52 as part of the indicators mentioned in the Sustainable Development Solutions Network (SDSN) Indicators and Monitoring Framework.[139] The rationale behind this indicator is that it considers the social cost for GHG emissions by requiring government policies applying carbon pricing to be implemented. The effectiveness of carbon pricing in the electricity sector is therefore measured by this indicator as a net cost for society for each unit of GHG abatement induced. Prices on carbon can be explicit or implicit, and by comparing the effective price on carbon by different policies in various countries and sectors, insight can be gained into the viability of different policies to curb emissions. As a result, this indicator estimates GHG abatement costs and the resulting impact on prices without considering societal benefits. The numerical results obtained must be analyzed carefully, since there is no one baseline value for carbon pricing which can comprehensively assess what the diverse set of policies of a certain country are attempting to achieve and at what cost they are attempting to achieve it.[140]

As mentioned, these indicators are still being developed. In their current form, they can only provide limited insight. For example, these indicators do not provide any information about why the deployments of a particular RE technology was successful or how socially acceptable the deployment was perceived to be or what future RE deployment can be expected.[141] To thoroughly interpret the values of a particular indicator for a particular county, a profound understanding of the country is required, along with the analysis of various indicators simultaneously.

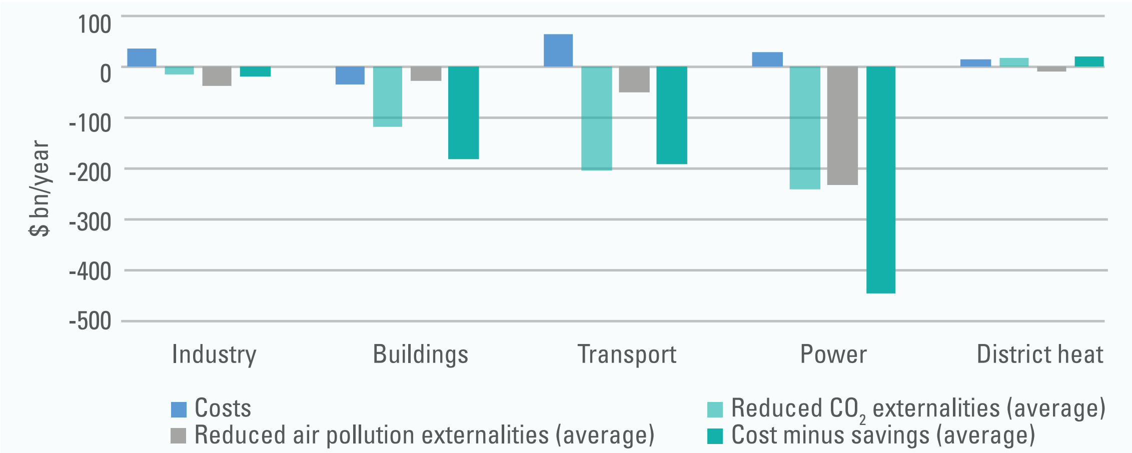
Renewable energy technologies: financial perspective

In this section, the financial perspective of the technologies already discussed in this report will be described in detail. Figure 30 depicts the costs and savings which RE technologies are expected to incur in 2030. Negative costs mean savings and therefore benefits which RE technologies have made possible. It can be seen that for all sectors except district heat, the savings outweigh the costs; this observation is most significant for the power sector. This proves the long-term advantages of the deployment of renewables, and how, though currently costs are one of the main challenges when it comes to using RE, in the long-run this up-front cost will be worth its value many times over.

As part of the wastewater treatment process, AD is used to turn sewage sludge into biogas which can assist in powering the processes taking place at the treatment plant. Table 11 shows the costs incurred when the biogas produced is used to generate electricity. The costs are displayed for a variety of electricity production processes. It can be concluded that the most cost-effective way to generate electricity is using a turbine, but this option is only possible for large WWTPs. Consequently, the lean-burn engine may be considered an option which is both relatively inexpensive and possible for a greater range of plant capacities. The current electricity price in the United States is around $0.12/kWh, which is greater than all the values presented in table 11. This shows the feasibility of using sewage sludge as a source of power in the wastewater treatment industry and how it can lead to significant savings for a WWTP. With respect to Arab countries, in general, waste-to-energy facilities have not been favored, as they tend to be less viable from the financial perspective. However, as fossil fuel reserves decrease, oil prices hover at lower ranges of values, and waste-to-energy technologies improve, production of power from waste such as sewage sludge can be expected to become more feasible. This conclusion is particularly logical when comparing the values in table 11 with the levelized cost of electricity values for different electricity generation technologies in the GCC market. Gas, coal and, to some extent, solar PV, have values similar to those reported in table 11, while other fuels such as oil and liquefied natural gas (LNG) have values that are higher per KWh of electricity generated.[142]

In terms of water heating with the use of solar thermal energy, figure 31 shows how the production costs for such heating processes vary according to the source of energy used to power the heating process. Though this data is not for Arab countries, it still gives an idea of the costs associated with such processes. When comparing between conventional and solar thermal energy sources, it is evident that in some cases, such as those of the southern United

Figure 30. Costs and savings of renewables by sector, 2030



Source: IRENA, 2016a.

Table 11. Estimated cost to generate anaerobic digester gas electricity

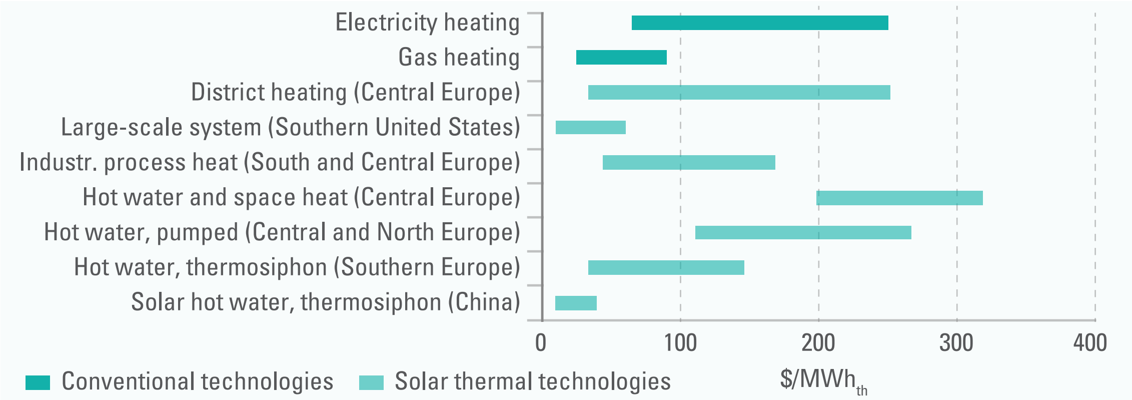
WWTF plant size (MGD)	Corresponding CHP system size (kW)	Estimated cost to generate ($/kWh)				
		Microturbine	Rich-burn engine	Fuel cell	Lean-burn engine	Turbine
1-5	30-130	0.064	0.073	-	-	-
5-10	130-260	0.064	0.060	0.083	-	-
10-20	260-520	0.064	0.060	0.083	0.051	-
20-40	520-1,040	-	-	0.083	0.051	-
40-150	1,040-3,900	-	-	0.083	0.040	-
> 150	> 3,900	-	-	-	0.040	0.032

Abbreviation: MGD, millions of gallons per day.

Source: ERG and RDC, 2011.

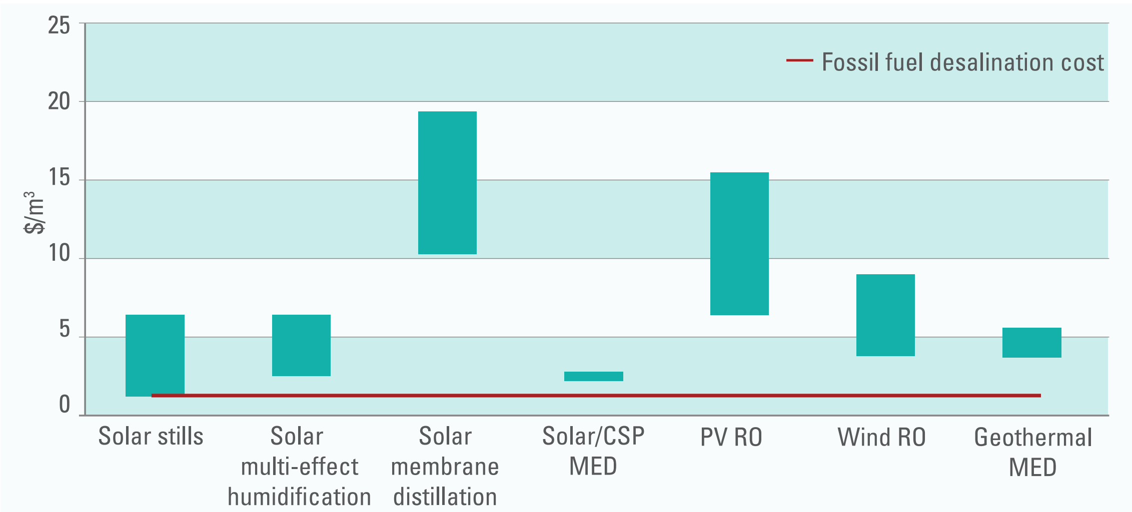
States and China, the costs of solar thermal heating can be lower than the corresponding costs using conventional energy sources. This shows the cost-effectiveness of solar thermal heating operations and is in line with the stage of commercialization of such technology, which has become quite common in many countries, particularly at the residential level. There are multiple success stories having to do with solar water heating in Arab countries; the Prosol program in Tunisia has been described in this report as an example. Other Arab countries doing well in this area are Jordan, Lebanon and Palestine. As of 2010-2012, the installed solar water heating capacity in MENA countries was more than 3,000 MW, and many of those countries have RE targets related to solar water heating in place. These targets are often accompanied by regulatory policies and fiscal and educational incentives.[143]

Figure 31. Solar heat production costs compared with electricity and natural gas-based heating in different regions



Source: Eisentraut and Brown, 2014.

Figure 32. Desalinated water costs for various combinations of desalination processes powered by RE sources



Source: IRENA, 2015a.

The water costs associated with RE powered desalination systems are given in figure 32, which also shows the corresponding costs for desalination powered by fossil fuels. Thus, it can be observed that, with the exception of solar stills powered desalination, none of the RE options have attained the economic viability which conventional energy sources have. Nevertheless, the configurations which seem the most promising are wind RO, geothermal MED, and solar multi-effect humidification. At the same time, the desalination cost is not the

Table 12. Capital costs of two main CSP desalination configuration options

	MED-CSP	RO-CSP + dry cooling
Capital cost-desalination ($/m³)	3,136	1,748-2,425
Capita cost (CSP+PB) ($/m³)	9,125	9,877-10,145
Total investment cost ($/m³)	12,261	11,625-12,570
Breakdown of capital costs for CSP energy (%)		
Solar field	57	54
Thermal storage	21	20
Power plant	18	19
Back-up boiler	4	5
Cooling	0	2

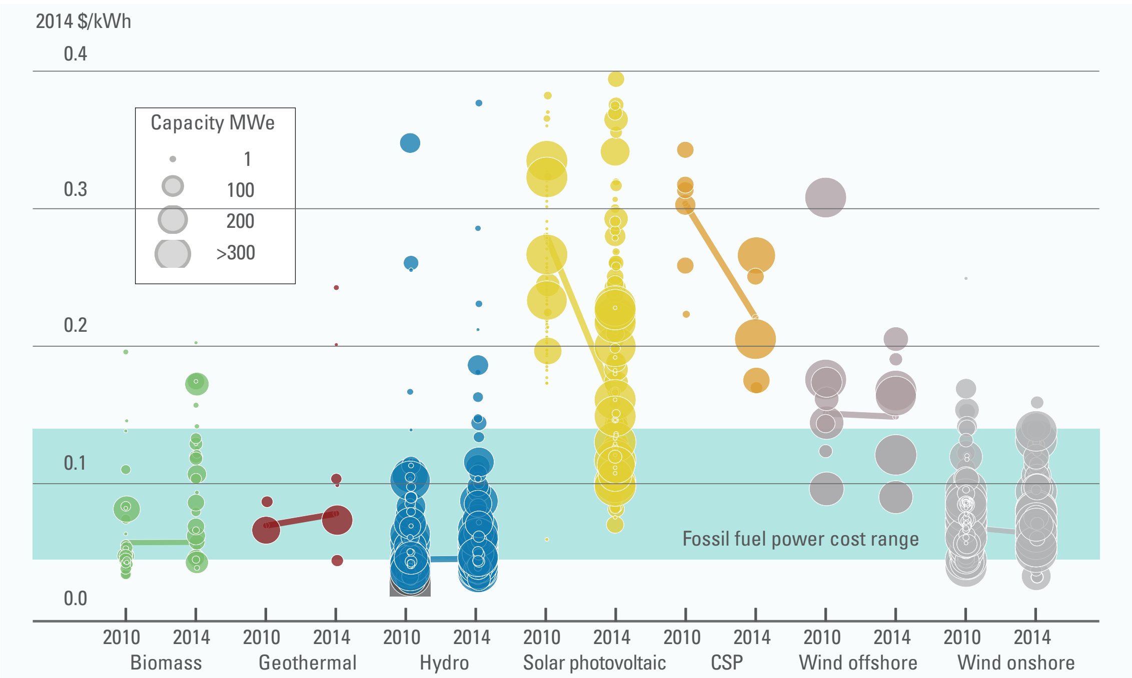
Abbreviation: PB, power block.

Source: World Bank (2012).

Note: Costs are based on the design of a 100,000 m³ per day desalination plant in a hybrid-CSP setup.

Size of the thermal energy storage was twice the solar energy collection capacity assuming, solar energy is available 46% of the year for MED and 54% for RO.

Figure 33. The range of levelized cost of electricity from utility-scale renewable technologies, 2010 and 2014



Source: IRENA, 2015c.

only issue to be considered when deciding on the energy sources of a desalination plant. Many other factors also need to be considered. It can also be pointed out that the design approach for solar desalination plants and fossil-fuel desalination plants is fundamentally different. The design of solar desalination plants focuses on capital costs and the desalination capacity, while in the design of fossil fuels desalination plants, achieving maximum efficiencies in the electricity production process is the main focus.[144] As an example of capital costs for RE powered desalination, table 12 shows the capital costs associated with the two main CSP desalination configuration options. After all, CSP technology is expected to achieve substantial growth in the Arab region. The MED-CSP option appears to be somewhat more costly. The large variation observed for these capital costs for RO technology reflects the wide range of seawater salinity found in the MENA region.

In the application area of electricity production from RE sources, both figure 33 and figure 34 depict information about the cost of electricity production from utility-scale renewable technologies. Figure 33 shows how the electricity cost has changed from 2010 to 2014 on a global scale for different electricity generation capacities. All of these technologies have seen their cost decrease or stay the same; the reduction in cost has been most significant for solar technologies, PV and CSP. All RE technologies, with the exception of CSP, have therefore attained cost values that are comparable with those of fossil fuels. However, as discussed in this report, CSP is one of those technologies with much potential for further development and improvement.

Figure 34. Weighted average cost of electricity by region for utility-scale renewable technologies, compared with fossil fuel power generation costs, 2013/2014

Source: IRENA, 2015c.

In contrast, figure 34 shows how the cost of electricity varies by region. The Middle East is performing similarly to other regions in terms of CSP technology. Such is not the case for PV technology where the Middle East has a relatively high electricity cost. This does not corroborate with the discussion at the beginning of section 3. The discrepancy is most probably due to the fact that figure 34 has 2014 data while the reference mentioned in section 3 discusses values for 2016-2018. This reflects the rapid decrease in PV prices which Arab countries have seen in the past two years. Moreover, the values quoted in section 3 were for specific countries while figure 34 provides average values for the entire Middle East region. An example worth mentioning here is that of Abu Dhabi where, in 2016, offers were received by the Abu Dhabi Water and Electricity Authority that represented the building of the cheapest solar PV power plant on record.[145] The record-low bid was 2.42 cents. cents per kilowatt-hour, made by China's Jinko Solar Holding Co. and Japan's Marubeni Corp. as a joint offer. Indeed, between 2011 and 2016, prices for solar technology decreased by almost 70 per cent.[146]

Conclusion and recommendations

The use of RE sources is an important way to reduce the vulnerability of water and energy resources to the linkages which comprise the water and energy nexus, and this toolkit looks at how this can be facilitated for Arab countries. These countries have high RE resource potential, particularly in terms of solar and wind energy. Prices for onshore wind and utility-scale solar photovoltaic technology are already the lowest in the world for some Arab countries. It is therefore clear that RE technologies are increasingly a feasible option for Arab countries and so, the relatively low rate of growth which the region has seen in this area in the past must be remedied. This toolkit aims to facilitate this process.

This toolkit discusses the different parts of the water sector where RE can be used. For example, as part of wastewater treatment, sewage sludge is produced which can then be a source of energy for wastewater treatment plant operations. Solar water heating is a mature technology, widely implemented in the residential sector; though implementing it on a large scale in industry has proven to be a challenge. Indeed, some of the technologies discussed in this toolkit, such as RE options for the oil and gas sector and the production of bioenergy from industrial wastes, are still in the development or demonstration stages.

Powering desalination with RE is also an option which is increasingly being considered and adopted by Arab countries. Combinations which have already been implemented are PV-RO and wind-RO, though due to the high salinity and temperatures of Gulf waters, using MED is considered to be more efficient and less expensive than using RO. When RE systems are used to power desalination processes and otherwise, the issue of the intermittency of many RE sources should be considered. Thus, some systems have the capability of storing energy while others have hybrid systems which are powered by both renewable and conventional energy sources. With regards to the use of RE to power electricity generation, this report has shown how this is financially feasible for Arab countries while also having benefits that are many times greater than the initial costs of deploying such technology.

For Arab countries, water security due to limited water resources may be considered a more pressing issue than energy security. However, due to the water and energy nexus, even if establishments only focus on increasing their reliance on RE sources, they will also be improving the water security in the region. As an example, this toolkit has shown how RE sources tend to consume less water than conventional energy sources as part of the electricity generation process.

Table A1. Comparison of concentrated solar power systems

Technology	Parabolic trough system	Linear Fresnel system	Solar power tower	Parabolic dish systems
Application	Superheated steam for grid-connected power plants	Saturated and superheated steam for process heat and for grid-connected power plants	Saturated and superheated steam for grid-connected power plants	Stand-alone, small off-grid power systems or clustered to larger grid-connected dish parks
Capacity range (MW)	5-280	5-30	10-370	0.025-0.11
Realized max. capacity single unit (MW)	280	2-30	370	0.11
Capacity installed (MW) [2011 values]	920 (1,600 under construction)	7 (40 under construction)	38 (17 under construction)	No significant commercial deployment (as of January 2013)
Peak solar efficiency (%)	21	15	<20	45-50
Annual solar efficiency (%)	14 (16 projected)	11-13	14-19	25-30
Heat transfer fluid	Synthetic oil, water/steam demonstrated	Water/steam	Air, molten salt, water/steam	N/A
Temperature (°C)	350-550	270-550	250-565	750
Concentration ratio	70-80	60-70	1,000	>1300
Operation mode	Solar or hybrid	Solar or hybrid	Solar or hybrid	Solar or hybrid
Land use factor	0.25-0.35	0.6-0.8	0.2-0.25	
Land use (m^2/MWh/year)	6-8	4-6	8-12	1.85
Estimated investment costs (€/kW)	3,500-6,500	2,500-4,500	4,000-6,000	Early stage of development

Development status	Commercially proven	Recently commercial	Recently commercial	Demonstration
Storage options	Molten salt, concrete, phase change material	Concrete for preheating and superheating, phase change material for evaporation	Molten salt, concrete, ceramics, phase change material	N/A
Reliability	Long-term proven	Recently demonstrated	Recently demonstrated	
Advantages	Long-term proven reliability and durability • Storage options for oil-cooled trough available	Simple structure and easy field construction • Tolerance for slight slopes • Direct steam generation proven	• High temperature allows high efficiency of power cycle • Tolerates non-flat sites • Storage technologies are available, but still not proven in long term	• Very high conversion efficiencies-peak solar to net electric conversion over 30% • Modularity • Most effectively integrates thermal output/storage of several dishes to supply a large power plant • Operational experience of first demonstration projects • Easily manufactured and mass-produced from available parts • No water requirements for cooling the cycle
Disadvantages	Limited temperature of heat transfer fluid hampering efficiency and effectiveness • Complex structure, high precision required during field construction • Requires flat land area	• Storage for direct steam generation (phase change material) in very early stage	• High maintenance and equipment costs	• No large-scale commercial examples • Projected cost goals of mass production still to be proven • Lower dispatchability potential for grid integration • Hybrid receivers still a research and development goal

Sources: Richter,Teske and Short, 2009; Gupta, Gehlot and Gujrathi, 2014; IRENA, 2012; Tyner, and others, 2001; World Bank, 2012.

Table A2. Comparison of principal features of solar thermal storage technologies

Technology	Molten Salt	Concrete	Phase change material	Water/steam	Hot water
Capacity range (MW)	500->3,000	1->3,000	1->3,000	1->200	1->3,000
Realized max. capacity of single unit (MWh)	1,000	2	0.7	50	1,000
Realized max. capacity of single unit (full load hours)	7.7	Not yet applied to CSP plants	Not yet applied to CSP plants	1	Not yet applied to CSP plants
Capacity installed (MWh)	4,100.0	3	0.7	50	20,000 (not for CSP)
Annual efficiency (%)	98	98	98	90	98
Heat transfer fluid	Molten salt	Synthetic oil, water, steam	Water/steam	Water/steam	Water
Temperature range (°C)	290.0-390.0	200-500	Up to 350.0	Up to 550	50-95
Investment costs (€/kWh)	40-60	30-40 (20 projected)	40-50 projected	180	2-5

Advantages	High storage capacity at relatively low cost. Experience in industrial applications. Well suited for synthetic oil heat transfer fluid.	Well suited for synthetic oil heat transfer fluid. Easily available material. Well suited for preheating and superheating in direct steam generating collectors.	Latent heat storage allows for constant temperature at heat transfer. Low material requirements. Well suited for evaporation/condensation process in direct steam generating collectors.	Latent heat storage allows for constant temperature at heat transfer. Experience in industrial applications. Well suited for evaporation/condensation process in direct steam generating collectors.	Very low-cost storage for process heat below 100°C. Experience in industrial applications
Disadvantages	Sensible heat storage requires temperature drop at heat transfer. Molten salt freezes at 230°C.	Not suited for evaporation/ condensation process in direct steam generating collectors. Recent development.	Not suited for preheating and superheating in direct steam generating collectors. Early stage of development.	Not suitable for preheating and superheating	Sensible heat storage requires temperature drop at heat transfer. Not applicable to power generation.

Source: World Bank, 2012.

Endnotes

1. United Nations Economic and Social Commission for Western Asia (ESCWA), 2012.
2. ESCWA, 2016.
3. Bizikova and others, 2013, p.1.
4. World Business Council for Sustainable Development (WBCSD), 2015.
5. European Report on Development, 2012.
6. Turkenburg and others, 2012.
7. Turkenburg and others, 2012.
8. United Nations and World Bank, 2016.
9. International Renewable Energy Agency (IRENA), 2016a.
10. World Bank, 2012.
11. IRENA, 2016b.
12. Amer and others, 2017.
13. Weinberg, 2015.
14. Turkenburg and others, 2012.
15. Argaw, 2003.
16. Turkenburg and others, 2012.
17. Eastern Research Group, Inc. (ERG) and Resource Dynamics Corporation (RDC), 2011.
18. Ibid., p.15.
19. Bachmann, 2015.
20. de Arespacochaga and others, 2015.
21. ERG and RDC, 2011.
22. Argaw, 2003.
23. Ibid.
24. Union of Nova Scotia Municipalities (UNSM) and Verterra Group, 2015.
25. Argaw, 2004, p.13.
26. Argaw, 2003.
27. Vick and Neal, 2012.
28. Global Environmental Finance (GEF) Small Grants Programme, 2003.
29. Abdelhady and others, 2015.
30. Rolland, 2013.
31. Munawwar and Ghedira, 2014.
32. Argaw, 2003.
33. Argaw, 2004.
34. Argaw, 2003.
35. Ibid.
36. Meah, Ula and Barrett, 2008.
37. Turkenburg and others, 2012.
38. Argaw, 2004.
39. Chandel, Nagaraju Naik and Chandel, 2015.
40. Gopal and others, 2013.
41. Argaw, 2003.
42. Gopal and others, 2013.
43. World Bioenergy, 2016.
44. Wida'a, 2015.
45. Lang, 2014.
46. Sudan Tribune, 2013.
47. Wida'a, 2015.
48. Ahmed, 2014.
49. Vick and Neal, 2012.
50. Argaw, 2004.
51. IRENA, 2015a.
52. Turkenburg and others, 2012.
53. Hang, Qu and Zhao, 2012.
54. Khambalkar, Gadge and Karale, 2009.
55. Gastli and Charabi, 2011.
56. IRENA and International Energy Agency's Energy Technology (IEA-ETSAP), 2015.
57. Turkenburg and others, 2012.
58. National Renewable Energy Laboratory, 2003.
59. Menicucci, 2009.
60. Ayompe and others, 2011.
61. Eisentraut and Brown, 2014.
62. IRENA and IEA-ETSAP, 2015.
63. Turkenburg and others, 2012.
64. Ibid.
65. Ibid.
66. Polycarp, Brown and Fu-Bertaux, 2013.
67. Trabacchi, Micale and Frisari, 2012.
68. Ibid.
69. Harrington, 2015.
70. IRENA and IEA-ETSAP, 2012.
71. World Bank, 2012.
72. Ibid.
73. IRENA, 2016c.
74. Subramani and others, 2011.
75. World Bank, 2012.
76. Turkenburg and others, 2012; World Bank, 2012.
77. IRENA and IEA-ETSAP, 2012.
78. World Bank, 2012.
79. Hasnain and Alajlan, 1998.
80. Kalogirou, 2005.
81. IRENA and IEA-ETSAP, 2012.
82. Philipps and others, 2016.
83. Al-Karaghouli and Kazmerski, 2011.
84. Turkenburg and others, 2012.
85. Al-Karaghouli and Kazmerski, 2011.
86. IRENA, 2012.
87. IRENA and IEA-ETSAP, 2012.
88. World Bank, 2012.
89. Dvorak, 2014.
90. Al-Karaghouli and Kazmerski, 2011.
91. IRENA and IEA-ETSAP, 2012.
92. IRENA, 2015c.
93. Al-Karaghouli and Kazmerski, 2011.
94. IRENA and IEA-ETSAP, 2012.
95. Loutatidou and Arafat, 2015.
96. Angenent and others, 2004.
97. Biernat, Malinowski and Gnat, 2013.
98. Absi Halabi, Al-Qattan and Al-Otaibi, 2015.
99. Turkenburg and others, 2012.
100. Ibid.
101. Ibid.
102. Absi Halabi, Al-Qattan and Al-Otaibi, 2015.
103. Eni S.p.A., 2016.
104. Absi Halabi, Al-Qattan and Al-Otaibi, 2015.
105. Graves, 2016.
106. Absi Halabi, Al-Qattan and Al-Otaibi, 2015.
107. Turkenburg and others, 2012.
108. Ibid.
109. Absi Halabi, Al-Qattan and Al-Otaibi, 2015.
110. Ibid.
111. Turkenburg and others, 2012.
112. IRENA, 2015.
113. Poudineh, Sen and Fattouh, 2016.
114. IRENA, 2016b.
115. Philibert, 2015.
116. Turkenburg and others, 2012.
117. Nakhle, 2016.
118. ESCWA, 2015.
119. Campbell, 2010.
120. McNabola and others, 2014.
121. United States Department of Energy, n.d..
122. Potter, 2010.
123. Acker, 2011.
124. Turkenburg and others, 2012.
125. World Bank, 2012.
126. Meisen and Hunter, 2007.
127. IRENA, 2016b.
128. World Bank, 2012.
129. Renewable Energy Policy Network for the 21st Century (REN21), 2013, p. 21.
130. IRENA, 2016b.
131. World Bank, 2012.
132. Böer, 2004.
133. Shabala, 2013.
134. Citation of the "Resource Efficiency Module" of this toolkit.
135. Nicholls and others, 2014.
136. Ibid.
137. Turkenburg and others, 2012.
138. Ibid.
139. Sustainable Development Solutions Network (SDSN), 2016.
140. Ibid.
141. Nicholls and others, 2014.
142. IRENA, 2016c.
143. REN21, 2013.
144. Al-Karaghouli and Kazmerski, 2011.
145. Dipaola, 2016.
146. Ibid.

Bibliography

Abdelhady, Suzan, Domenico Borello, and Simone Santori (2015). Economic Feasibility of Small Wind Turbines for Domestic Consumers in Egypt Based on the New Feed-in Tariff. *Energy Procedia*, vol. 75 (August), pp. 664–670. Available from https://doi.org/10.1016/j.egypro.2015.07.482.

Absi Halabi, Mamun M., Ayman Al-Qattan, and A. Al-Otaibi (2015). Application of solar energy in the oil industry—Current status and future prospects. *Renewable and Sustainable Energy Reviews,* vol. 43 (March), pp. 296–314. Available from https://doi.org/10.1016/j.rser.2014.11.030.

Acker, Thomas L. (2011). *Hydroelectric Industry's Role in Integrating Wind Energy* (T102700-0371). Canada: CEATI International Inc. Available from https://www.ceati.com/freepublications/0371_Web.pdf.

Ahmed, Abdelmoneim Taha (2014). *Biofuel industry in Sudan: Experience and Future Prospects*. Presented at the 2nd Bioenergy Week, Maputo, Mozambique, May. Available from http://www.globalbioenergy.org/fileadmin/user_upload/gbep/docs/2014_events/2nd_Bioenergy_Week_5-9May2014_Maputo/2_-_TAHA_AHMED.pdf.

Al-Karaghouli, Ali A., and L. L. Kazmerski (2011). Renewable Energy Opportunities in Water Desalination. In *Desalination, Trends and Technologies*, Michael Schorr, ed., InTech. Available from http://www.intechopen.com/books/desalination-trends-and-technologies/renewable-energy-opportunities-in-water-desalination.

Alvarado-Revilla, Fabiola (2015). *Desalination Markets 2016: Global Perspective and Opportunities for Growth*. Oxford: Media Analytics.

Amer, Kamel M., and others, eds. (2017). *The Water, Energy, and Food Security Nexus in the Arab Region*. Springer International Publishing AG. Available from https://books.google.ae/books?id=KMWiDQAAQBAJ&pg=PA93&lpg=PA93&dq=traditional+biomass+use+biomass+MENA&source=bl&ots=xA0Nq_mdIF&sig=9zXx6q2cDz3EAwzko-fGRj-5B6g&hl=en&sa=X&ved=0ahUKEwiChcOjz8vRAhXBOxQKHRdbA1sQ6AEINzAF#v=onepage&q&f=false.

Angenent, Largus T., and others, (2004). Production of bioenergy and biochemicals from industrial and agricultural wastewater. *Trends in Biotechnology*, vol. 22, No. 9 (September), pp. 477-485. Available from https://doi.org/10.1016/j.tibtech.2004.07.001.

Argaw, Neway (2003). *Renewable Energy in Water and Wastewater Treatment Applications [Period of Performance: April 1–September 1, 2001]* (NREL/SR-500-30383). National Renewable Energy Laboratory (NREL), June. Available from http://www.nrel.gov/docs/fy03osti/30383.pdf.

Argaw, Neway (2004). *Renewable Energy Water Pumping Systems Handbook [Period of Performance: April 1–September 1, 2001]* (NREL/SR-500-30481). Denver, Colorado: National Renewable Energy Laboratory (NREL), July. Available from http://www.nrel.gov/docs/fy04osti/30481.pdf.

Au-Yeung, Neo (2016). High Power DC Submersible Solar Water Pump for Agricultural. Available from http://suntotalneo.en.ec21.com/High_Power_DC_Submersible_Solar--8960729_8960740.html. Accessed 29 December 2016.

Ayompe, Lacour M., and others (2011). Comparative field performance study of flat plate and heat pipe evacuated tube collectors (ETCs) for domestic water heating systems in a temperate climate. *Energy*, vol. 36, No. 5 (May), pp. 3370-3378. Available from https://doi.org/10.1016/j.energy.2011.03.034.

Bachmann, Nathalie (2015). *Sustainable biogas production in municipal wastewater treatment plants.* IEA Bioenergy. Available from http://www.iea-biogas.net/files/daten-redaktion/download/Technical%20Brochures/Wastewater_biogas_grey_web-1.pdf.

Biernat, Krzysztof, Arthur Malinowski, and Malwina Gnat (2013). The Possibility of Future Biofuels Production Using Waste Carbon Dioxide and Solar Energy. In *Biofuels - Economy, Environment and Sustainability*, Zhen Fang, ed., InTech. Available from http://www.intechopen.com/books/biofuels-economy-environment-and-sustainability/the-possibility-of-future-biofuels-production-using-waste-carbon-dioxide-and-solar-energy.

Bizikova, Livia, and others (2013). *The Water-Energy-Food Security Nexus: Towards a Practical Planning and Decision-Support Framework for Landscape Investment and Risk Management*. International Institute for Sustainable Development (IISD), February. Available from http://www.iisd.org/pdf/2013/wef_nexus_2013.pdf.

Böer, Benno (2004). Halophyte development in the Gulf Arab countries - UNESCO Doha's activities 2001-2003. *Tropical Ecology*, vol. 45, No. 1, pp. 187–189.

Campbell, Richard J. (2010). *Small Hydro and Low-Head Hydro Power - Technologies and Prospects* (CRS Report for Congress No. R41089). Congressional Research Service. Available from http://nepinstitute.org/get/CRS_Reports/CRS_Energy/Renewable_Fuels/Small_hydro_and_Low-head_hydro_power.pdf.

Chandel, S. S., M. Nagaraju Naik, and Rahul Chandel (2015). Review of solar photovoltaic water pumping system technology for irrigation and community drinking water supplies. *Renewable and Sustainable Energy Reviews,* vol. 49 (September), pp. 1084-1099. Available from https://doi.org/10.1016/j.rser.2015.04.083.

Cour des comptes (2014). Le coût de production de l'électricité nucléaire: Actualisation 2014. Communication à la Commission d'Enquête de l'Assemblée Nationale. May. Available from https://www.ccomptes.fr/content/download/68537/1858246/version/2/file/20140527_rapport_cout_production_electricite_nucleaire.pdf.

CSP Today (2016). Projects Tracker Overview. Available from http://tracker.newenergyupdate.com/tracker/projects/table?order=field_pt_country_value&sort=desc&world-region%5B151%5D=151&country%5BMorocco%5D=Morocco&country%5BUAE%5D=UAE&country%5BAlgeria%5D=Algeria&country%5BEgypt%5D=Egypt&country%5BIran%5D=Iran&country%5BIraq%5D=Iraq&country%5BJordan%5D=Jordan&country%5BKuwait%5D=Kuwait&country%5BLebanon%5D=Lebanon&country%5BLibya%5D=Libya&country%5BOman%5D=Oman&country%5BQatar%5D=Qa

tar&country%5BSaudiArabia%5D=SaudiArabia&country%5BTunisia%5D=Tunisia&country%5BYemen%5D=Yemen&reset=Reset. Accessed 3 January 2017.

de Arespacochaga, Nicolas, and others (2015). On-site cogeneration with sewage biogas via high-temperature fuel cells: Benchmarking against other options based on industrial-scale data. *Fuel Processing Technology*, vol.138 (October), pp. 654-662. Available from https://doi.org/10.1016/j.fuproc.2015.07.006.

Dipaola, Anthony (2016). Cheapest Solar on Record Offered as Abu Dhabi Expands Renewables. *Bloomberg.com*, 19 September. Available from https://www.bloomberg.com/news/articles/2016-09-19/cheapest-solar-on-record-said-to-be-offered-for-abu-dhabi.

Dvorak, Paul (2014). Why not more vertical-axis wind turbines? *Windpower Engineering & Development,* 31 October. Available from http://www.windpowerengineering.com/design/vertical-axis-wind-turbines/. Accessed 11 December 2016.

Eastern Research Group, Inc. (ERG), and Resource Dynamics Corporation (RDC) (2011). *Opportunities for Combined Heat and Power at Wastewater Treatment Facilities: Market Analysis and Lessons from the Field.* United States Environmental Protection Agency Combined Heat and Power Partnership, October. Available from http://energy.gov/sites/prod/files/2013/11/f4/epa_wwtf_opportunities.pdf.

Eisentraut, Anselm, and Adam Brown (2014). *Heating Without Global Warming: Market Developments and Policy Considerations for Renewable Heat.* International Energy Agency (IEA). Available from https://www.iea.org/publications/freepublications/publication/FeaturedInsight_HeatingWithoutGlobalWarming_FINAL.pdf.

El-Katiri, Laura (2014). *A Roadmap for Renewable Energy in the Middle East and North Africa.* Oxford Institute for Energy Studies. Available from https://www.oxfordenergy.org/wpcms/wp-content/uploads/2014/01/MEP-6.pdf.

Eni S.p.A. (2016). Eni enters the field of renewable energies in Algeria. 23 September. Available from https://www.eni.com/docs/en_IT/enicom/media/press-release/2016/09/Eni_enters_Algeria_renewables_sector.pdf.

European Report on Development (ERD) (2012). *Confronting Scarcity: Managing water, energy and land for inclusive and sustainable growth*. European Union. Available from http://ec.europa.eu/europeaid/sites/devco/files/consca-report-erd-2011_en.pdf.

Gastli, Adel, and Yassine Charabi (2011). Solar water heating initiative in Oman energy saving and carbon credits. *Renewable and Sustainable Energy Reviews,* vol. 15, No. 4 (May), pp. 1851-1856. Available from https://doi.org/10.1016/j.rser.2010.12.015.

Global Environmental Finance (GEF) Small Grants Programme (2003). Small-Scale Wind Turbines for Water Pumping and Electricity Generation, Egypt. United Nations Development Programme (UNDP). Available from http://www.hy-pa.org/Publications/2005/publications/12-Small-scale%20wind%20turbines%20for%20water%20puming%20and%20electricity%20generation.pdf.

Gopal, C., and others (2013). Renewable energy source water pumping systems—A literature review. *Renewable and Sustainable Energy Reviews,* vol. 25 (September), pp. 351-370. Available from https://doi.org/10.1016/j.rser.2013.04.012.

Graves, LeAnne (2016). Kuwait Oil Company looks to solar to power crude extraction. *The National,* 28 May. Available from http://www.thenational.ae/business/energy/kuwait-oil-company-looks-to-solar-to-power-crude-extraction. Accessed 4 January 2017.

Gude, Veera G., Nagamany Nirmalakhandan, and Shuguang Deng (2010). Renewable and sustainable approaches for desalination. *Renewable and Sustainable Energy Reviews,* vol. 14, No. 9 (December), pp. 2641-2654. Available from https://doi.org/10.1016/j.rser.2010.06.008.

Gupta, Ashok K., Dilip Gehlot, and Ankit S. Gujrathi (2014). Experimental Investigation of Convex Lens Concentrating Solar Power Collector Prototype Performance. *International Journal of Innovation In Engineering Research & Management,* vol. 1, No. 2 (April), pp. 1-4.

Hang, Yin, Ming Qu, and Fu Zhao (2012). Economic and environmental life cycle analysis of solar hot water systems in the United States. *Energy and Buildings*, vol.45 (February), pp. 181-188. Available from https://doi.org/10.1016/j.enbuild.2011.10.057.

Harrington, Kent (2015). Saudi Arabia Creates New Solar-Powered Desalination Technology.16 October. Available from http://www.aiche.org/chenected/2015/10/saudi-arabia-creates-new-solar-powered-desalination-technology. Accessed 11 December 2016.

Hasnain, Syed M., and Saleh A. Alajlan (1998). Coupling of PV-powered RO brackish water desalination plant with solar stills. *Desalination*, vol. 116, No. 1 (1 September), pp. 57-64. Available from https://doi.org/10.1016/S0011-9164(98)00057-5.

International Energy Agency (IEA) (2012). *World Energy Outlook 2012*. Paris, France: International Energy Agency. Available from http://www.iea.org/publications/freepublications/publication/WEO2012_free.pdf.

International Renewable Energy Agency (IRENA) (2012). Concentrating Solar Power. *Renewable Energy Technologies: Cost Analysis Series*, vol. 1: Power Sector, No. 3/5 (June). Available from http://www.irena.org/documentdownloads/publications/re_technologies_cost_analysis-csp.pdf.

International Renewable Energy Agency (IRENA) (2015a). *Renewable Energy in the Water, Energy & Food Nexus.* Abu Dhabi. Available from http://www.irena.org/DocumentDownloads/Publications/IRENA_Water_Energy_Food_Nexus_2015.pdf.

International Renewable Energy Agency (IRENA) (2015b). *Renewable Energy Target Setting*. Abu Dhabi. Available from http://www.irena.org/DocumentDownloads/Publications/IRENA_RE_Target_Setting_2015.pdf.

International Renewable Energy Agency (IRENA) (2015c). *Renewable Power Generation Costs in 2014*. Abu Dhabi. Available from https://www.irena.org/

DocumentDownloads/Publications/IRENA_RE_Power_Costs_2014_report.pdf.

International Renewable Energy Agency (IRENA) (2016a). *REmap: Roadmap for a Renewable Energy Future* (2016 Edition). Abu Dhabi. Available from http://www.irena.org/DocumentDownloads/Publications/IRENA_REmap_2016_edition_report.pdf.

International Renewable Energy Agency (IRENA) (2016b). *Renewable Energy in the Arab Region. Overview of Developments*. Abu Dhabi. Available from http://www.irena.org/DocumentDownloads/Publications/IRENA_Arab_Region_Overview_2016.pdf.

International Renewable Energy Agency (IRENA) (2016c). *Renewable Energy Market Analysis: The GCC Region*. Abu Dhabi. Available from http://www.irena.org/DocumentDownloads/Publications/IRENA_Market_GCC_2016.pdf.

International Renewable Energy Agency (IRENA), and the International Energy Agency's Energy Technology Systems Analysis Programme (IEA-ETSAP) (2012). *Water Desalination Using Renewable Energy* (Technology Brief No. I12). IEA-ETSAP and IRENA . Available from https://www.irena.org/DocumentDownloads/Publications/IRENA-ETSAP%20Tech%20Brief%20I12%20Water-Desalination.pdf.

International Renewable Energy Agency (IRENA), and the International Energy Agency's Energy Technology Systems Analysis Programme (IEA-ETSAP) (2015). *Solar Heat for Industrial Processes* (Technology Brief No. E21). IEA-ETSAP and IRENA. Available from http://www.irena.org/DocumentDownloads/Publications/IRENA_ETSAP_Tech_Brief_E21_Solar_Heat_Industrial_2015.pdf.

Kalogirou, Soteris A. (2005). Seawater desalination using renewable energy sources. *Progress in Energy and Combustion Science,* vol. 31, No. 3, pp. 242-281. Available from https://doi.org/10.1016/j.pecs.2005.03.001.

Khambalkar, Vivek P., Sharashchandra R. Gadge, and Dhiraj S. Karale (2009). Solar water cost and feasibility of solar water heating system. *International Journal of Global Energy Issues*, vol. 31, No. 2, pp. 208-218. Available from https://doi.org/10.1504/IJGEI.2009.023896.

Kim, Jihun, and others (2013). Design Optimization of a Solar-Powered Reverse Osmosis Desalination System for Small Communities. In *Proceedings of IDETC/CIE 2013*. Portland, Oregon, USA: American Society of Mechanical Engineers (ASME). Available from http://www.academia.edu/24544513/Design_Optimization_of_a_Solar-Powered_Reverse_Osmosis_Desalination_System_for_Small_Communities.

Kost, Christoph, and others (2013). *Levelized Cost of Electricity: Renewable Energy Technologies*. Fraunhofer Institut for Solar Energy Systems ISE. Available from https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/Fraunhofer-ISE_LCOE_Renewable_Energy_technologies.pdf.

Lang, Andrew (2014). *Final Report: Bioenergy in Sudan*. Sudan University of Science and Technology, January. Available from http://www.worldbioenergy.org/userfiles/Bioenergy%20in%20Sudan%20final%20report%202014[3].pdf.

Loutatidou, Sawina, and Hassan A. Arafat (2015). Techno-economic analysis of MED and RO desalination powered by low-enthalpy geothermal energy. *Desalination*, vol. 365 (1 June), pp. 277-292. Available from https://doi.org/10.1016/j.desal.2015.03.010.

McNabola, Aonghus, and others (2014). Energy recovery in the water industry using micro-hydropower: an opportunity to improve sustainability. *Water Policy*, vol. 16, No. 1 (February), pp. 168-183. Available from https://doi.org/10.2166/wp.2013.164.

Meah, Kala, Sadrul Ula, and Steven Barrett (2008). Solar photovoltaic water pumping—opportunities and challenges. *Renewable and Sustainable Energy Reviews,* vol. 12, No. 4 (May), pp. 1162-1175. Available from https://doi.org/10.1016/j.rser.2006.10.020.

Meisen, Peter, and Lesley Hunter (2007). Renewable Energy Potential of the Middle East, North Africa vs. The Nuclear Development Option. Global Energy Network Institute (GENI), October. Available from http://www.geni.org/globalenergy/research/middle-east-energy-alternatives/MENA-renewable-vs-nuclear.pdf.

Menicucci, David (2009). *Assembly and Comparison of Available Solar Hot Water System Reliability Databases and Information* (No. SAND2009-2757). United States: Sandia National Laboratories. Available from http://prod.sandia.gov/techlib/access-control.cgi/2009/092757.pdf.

Munawwar, Saima, and Hosni Ghedira (2014). A review of Renewable Energy and Solar Industry Growth in the GCC Region. *Energy Procedia*, vol. 57, pp. 3191-3202. Available from https://doi.org/10.1016/j.egypro.2015.06.069.

Nakhle, Carole (2016). Nuclear Energy's Future in the Middle East and North Africa. 28 January. Available from http://carnegie-mec.org/2016/01/28/nuclear-energy-s-future-in-middle-east-and-north-africa-pub-62562. Accessed 4 January 2017.

National Renewable Energy Laboratory (2003). *Heat Your Water with the Sun* (A Consumer's Guide No. DOE/GO-102003-1824). W ashington, D.C.: United States Department of Energy. Available from http://www.nrel.gov/docs/fy04osti/34279.pdf.

Nicholls, Jack, and others (2014). *Evaluating Renewable Energy Policy: A Review of Criteria and Indicators for Assessment* (IRENA UKERC Policy Paper). Abu Dhabi: IRENA. Available from http://www.irena.org/documentdownloads/publications/evaluating_re_policy.pdf.

Philibert, Cédric (2015). *Renewables in the MENA region*. Presented at the COP21, Paris, France. 5 December. Available from http://www.iea.org/media/workshops/2015/cop21/otherevents/5DecPhilibert.pdf.

Philipps, Simon P., and others (2016). *Current Status of Concentrator Photovoltaic (CPV) Technology* (Version 1.2). Fraunhofer Institute for Solar Energy Systems (ISE) and National Renewable Energy Laboratory (NREL). Available from https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/2016_02_09_CPV_Report_ISE_NREL_Version_1_2.pdf.

Polycarp, Clifford, Louise Brown, and Xing Fu-Bertaux (2013). *Mobilizing Climate Investment: the Role of International Climate Finance in Creating Readiness for Scaled-up Low-carbon Energy*. World Resources Institute. Available from http://www.wri.org/sites/default/files/pdf/mobilizing_climate_investment.pdf.

Potter, Matthew (2010). Micro Hydro. Stanford University, 28 November. Available from http://large.stanford.edu/courses/2010/ph240/potter2/.

Poudineh, Rahmatallah, Anupama Sen, and Bassam Fattouh (2016). *Advancing Renewable Energy in Resource-Rich Economies of the MENA*. The Oxford Institute for Energy Studies. Available from https://www.oxfordenergy.org/wpcms/wp-content/uploads/2016/10/Advancing-Renewable-Energy-in-Resource-Rich-Economies-of-the-MENA-MEP-15.pdf.

Renewable Energy Policy Network for the 21st Century (REN21) (2013). *MENA Renewables Status Report*. Paris: REN21 Secretariat. Available from http://www.ren21.net/Portals/0/documents/activities/Regional%20Reports/MENA_2013_lowres.pdf.

Renewable Energy Policy Network for the 21st Century (REN21) (2016). *Renewables Global Status Report 2016*. Paris: REN21 Secretariat. Available from http://www.ren21.net/wp-content/uploads/2016/10/REN21_GSR2016_FullReport_en_11.pdf.

Renewable Energy Policy Network for the 21st Century (REN21), and Institute for Sustainable Energy Policies (ISEP) (2013). *Renewables Global Futures Report 2013*. Available from http://www.ren21.net/Portals/0/documents/activities/gfr/REN21_GFR_2013.pdf.

Richter, Christoph, Sven Teske, and Rebecca Short (2009). *Concentrating Solar Power Global Outlook 09: WhyRenewable Energy is Hot.* Greenpeace International, SolarPACES, and European Solar Thermal Electricity Association (ESTELA). Available from http://www.greenpeace.org/international/Global/international/planet-2/report/2009/5/concentrating-solar-power-2009.pdf.

Rolland, Simon (2013). Promoting Small Wind in Developing Markets. 1 April. Available from http://www.renewableenergyworld.com/articles/print/volume-16/issue-2/wind-power/promoting-small-wind-in-developing-markets.html. Accessed 7 February 2017.

Servicios Avanzados de Comunicación y Marketing SL (SACM) (2015). CSP World Map. CSPWorld.org. Available from http://cspworld.org/cspworldmap. Accessed 3 January 2017.

Shabala, Sergey (2013). Learning from halophytes: physiological basis and strategies to improve abiotic stress tolerance in crops. *Annals of Botany,* vol. 112, No. 7 (November), pp. 1209-1221. Available from https://doi.org/10.1093/aob/mct205.

Silicon Valley Clean Water (SVCW) (2012). Wastewater Treatment. SVCW. Available from http://www.svcw.org/facilities/sitePages/wastewater%20treatment.aspx. Accessed 29 December 2016.

Subramani, Arun, and others (2011). Energy minimization strategies and renewable energy utilization for desalination: A review. *Water Research,* vol. 45, No. 5 (February), pp. 1907-1920. Available from https://doi.org/10.1016/j.watres.2010.12.032.

Sudan Tribune (2013). KSC introduces biofuel for cars in Sudan for the first time. 20 April. Available from http://www.sudantribune.com/spip.php?article46293. Accessed 18 January 2017.

Sustainable Development Solutions Network (SDSN) (2016). Indicators and a Monitoring Framework. SNDS. Available from http://indicators.report/indicators/i-52/. Accessed 5 January 2017.

Trabacchi, Chiara, Valerio Micale, and Gianleo Frisari (2012). *San Giorgio Group Case Study: Prosol Tunisia.* Climate Policy Initiative (CPI). Available from https://climatepolicyinitiative.org/wp-content/uploads/2012/08/Prosol-Tunisia-SGG-Case-Study.pdf.

Turkenburg, Wim C., and others (2012). Chapter 11 - Renewable Energy. In *Global Energy Assessment: Toward a Sustainable Future*, Johansson, Thomas B., ed., Cambridge University Press, and the International Institute for Applied Systems Analysis (IISA), Laxenburg, Austria, pp. 761-900. Available from http://www.iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/GEA_Chapter11_renewables_lowres.pdf.

Tyner, Craig E., and others (2001). *Concentrating Solar Power in 2001: An IEA/SolarPACES Summary of Present Status and Future Prospects* (SolarPACES Task I: Electric Power Systems). SolarPACES. Available from https://www.ethz.ch/content/dam/ethz/special-interest/mavt/energy-technology/renewable-energy-carriers-dam/documents/Publications/Documents%20for%20Downloading/CSP_2001.pdf.

Union of Nova Scotia Municipalities (UNSM), and Verterra Group (2015). *Wind Energy Fact Sheets for Nova Scotian Municipalities*. Canada: UNSM. Available from http://www.unsm.ca/renewable-energy.htmlUnited Nations Economic and Social Commission for Western Asia (ESCWA) (2012). *Report: Intergovernmental Consultative Meeting on the Water and Energy Nexus in the ESCWA Region - Beirut, 27-28 June 2012*. E/ ESCWA/SDPD/2012/IC.1/2/Report. Beirut: United Nations. Available from https://www.unescwa.org/sites/www.unescwa.org/files/events/files/water_and_energy_nexus_in_escwa_region_report_e.pdf.

United Nations Economic and Social Commission for Western Asia (ESCWA) (2015) *ESCWA Water Development Report 6: The Water, Energy and Food Security Nexus in the Arab Region*. E/ESCWA/SDPD/2015/2. Beirut: United Nations. Available from https://www.unescwa.org/sites/www.unescwa.org/files/publications/files/e_escwa_sdpd_15_2_e_0.pdf.

United Nations Economic and Social Commission for Western Asia (ESCWA) (2016). *Developing the Capacity of ESCWA Member Countries to Address the Water and Energy Nexus for Achieving Sustainable Development Goals: Regional Policy Toolkit.* E/ESCWA/SDPD/2016/Manual. Beirut: United Nations. Available from https://www.unescwa.org/sites/www.unescwa.org/files/events/files/nexus_training_module.pdf.

United Nations World Water Assessment Programme (WWAP) (2014). *The United*

Nations World Water Development Report 2014: Water and Energy, vol. 1. Paris: UNESCO. Available from http://unesdoc.unesco.org/images/0022/002257/225741E.pdf.

United Nations, and World Bank. Sustainable Energy for All: About Us. Available from http://www.se4all.org/about-us. Accessed 2 November 2016.

United States Department of Energy (n.d.). Microhydropower Systems. Available from https://energy.gov/energysaver/microhydropower-systems. Accessed 4 January 2017.

Vick, Brian D., and Byron A. Neal (2012). Analysis of off-grid hybrid wind turbine/solar PV water pumping systems. *Solar Energy,* vol. 86, No. 5 (May), pp. 1197-1207. Available from https://doi.org/10.1016/j.solener.2012.01.012.

Virgili, Francisco, Tom Pankratz, and Global Water Intelligence (GWI) (2016). *IDA Desalination Yearbook 2016-2017.* Oxford, UK: Media Analytics Ltd. Available from https://www.paperturn.com/flipbook/id/ida-yb_free/ida-desalination-yearbook-2016-2017?pid=NzU7549#.

Water in the West (2013). *Water and Energy Nexus: A Literature Review.* Stanford Woods Institute for the Environment, and Bill Lane Center for the American West. Available from http://waterinthewest.stanford.edu/sites/default/files/Water-Energy_Lit_Review.pdf.

Weinberg, Josh (2015). *Making Water-Energy Food Nexus approaches operational to support sustainable urbanization.* Presented at the Sustainable Megacities: Food, Energy, Water and the Built Environment Workshop: Food, Energy, and Water Nexus in Sustainable Cities, Beijing, China, 21 October.

Wida'a, Abdel Azim (2015). *Biofuel Potential for Transport Sector in Sudan.* Presented at the UNCTAD, 17th Africa OILGASMINE, Khartoum, Sudan. November. Available from http://unctad.org/meetings/en/Presentation/17OILGASMINE%20Abdel%20Azim%20Wida%27a%20%20S11.pdf.

World Bank (2012). *Renewable Energy Desalination: An Emerging Solution to Close the Water Gap in the Middle East and North Africa.* Washington, DC: The World Bank. Available from http://elibrary.worldbank.org/doi/book/10.1596/978-0-8213-8838-9.

World Bank (2015). World Development Indicators -World DataBank. Available from http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators. Accessed 24 August 2015.

World Bioenergy (2016). Sudan trying reduce oil dependence with biofuel. Available from https://www.elmia.se/en/worldbioenergy/For-press/news-from-world-bioenergy-not-seen/Sudan-trying-reduce-oil-dependence-with-biofuel-/. Accessed 18 January 2017.

World Business Council for Sustainable Development (WBCSD) (2015). *Co-optimizing Solutions: Water and Energy for Food, Feed and Fiber.* Available from http://www.wbcsd.org/Projects/Climate-Smart-Agriculture/Resources/Co-optimizing-Solutions-water-and-energy-for-food-feed-and-fiber.

Zachary, Justin, and Colleen M. Layman, Bechtel Power Corp. (2010). Adding Desalination to Solar Hybrid and Fossil Plants. *POWER*, 1 May. Available from http://www.powermag.com/adding-desalination-to-solar-hybrid-and-fossil-plants/.

17-00143