Today's and future challenges in applications of renewable energy technologies for desalination

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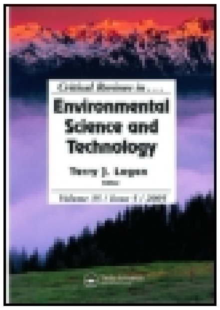

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Today's and Future Challenges in Applications of Renewable Energy Technologies for Desalination

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Today's and Future Challenges in Applications of Renewable Energy Technologies for Desalination

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Recent trends and challenges in applications of renewable energy technologies for water desalination are critically reviewed with an emphasis on environmental concerns and sustainable development. After providing an overview of wind, wave, geothermal and solar renewable energy technologies for fresh water production, hybrid systems are assessed. Then scale-up and economic factors are considered. This is followed with a section on regulatory factors, environmental concerns and globalization, and a final segment on selecting the most suitable renewable energy technology for conventional and emerging desalination processes.

Key words: *challenges, renewable energy technology, desalination, economics, sustainable development, environmental concerns, regulatory factors*

CONTENTS

INTRODUCTION

Adequate and dependable fresh water resources are major issues confronting many nations worldwide (Maila, 2006; Goosen *et al.*, 2011a & 2011b; Huang, 2010; Lund, 2007; Mahmoudi *et al.*, 2010a & 2010b). With the world's energy demand increasing much research has been directed at overcoming these challenges and in particular in using renewable energy to help meet the power needs for water desalination (Huang, 2010; Lund, 2007; Mahmoudi *et al.*, 2010a; Serpen *et al.*, 2010). However, Goosen (2012) and Gottinger and Goosen (2012) argued that while development opens up and advances economies, and creates new wealth, millions are forced to struggle to make meaning of the darker side of development that is not environmentally sustainable. In the past, the world’s ecosystems (i.e. air, land and water) were able to absorb the environmental damage resulting from extensive industrialization and development. Nevertheless, with the rapid increases in global population and industrialization, as well as enhanced demands on natural resources such as fresh water supplies, the earth is no longer able to sustain a healthy and balanced ecosystem (Laboy-Nieves, 2009; Laboy *et al.*, 2009; Mahmoudi *et al.,* 2010a, 2010b; Misra, 2000).

The sustainability of the society in which we live is determined not only by technical and economic progress, but also by environmental management (Abdulla *et al.*, 2009; Gottinger and Goosen, 2012; Laboy *et al.*, 2010; Maila, 2006). Sustainable development using more renewable energy sources, by improving energy efficiency and reducing water demand and waste production is now considered by many as being the model to follow (Goosen *et al.*, 2004; Goosen, *et al.*, 2009a, 2009b; Misra, 2000). Elimelech and Philip (2011), for example, reported on the possible reductions in energy demand by desalination technologies, and the role of innovative technologies in improving the sustainability of desalination as a technological solution to global water shortages (Figure 1). They argued that future research to improve the energy efficiency of desalination should focus on, for example, the pre-treatment and post-treatment stages of seawater reverse osmosis (SWRO) plants. Furthermore, Peñate & García-Rodríguez (2012a) presented a comprehensive review of the main innovations and future trends in the design of SWRO desalination technology with an emphasis on improving process performance and efficiency. They concluded that desalination with renewable energies is an attractive combination that will help to reduce stress on existing water supplies.

The economic potential and environmental benefits of renewable energies, such as geothermal, solar, wave and wind, and their applications to reducing overall energy requirements have been described in a number of recent articles (Cataldi, *et al.*, 1999; Huang, 2010; Goosen *et al.*, 2011b; Lund, 2007; Mahmoudi *et al.*, 2010a; Serpen *et al.*, 2010; Stefansson, 2005). Chronicled accounts show uses of, for example, geothermal water by Romans, Japanese, Turks, Icelanders, Central Europeans and the Maori of New Zealand for bathing, cooking and space heating (Lund, 2007). As another early example, ancient Greeks were the earliest to use passive solar design in their homes; as early as 400BC whole Greek cities were built in this way (Butti and Perlin, 1980; Leipoldt, 2011) The Romans later improved on these designs by using glass for windows, in this manner trapping solar heat. The first glasshouses (i.e. pre-curser to modern day greenhouses) were created by them to produce the correct growing environment for exotic plants and seeds that they brought to Rome from different parts of their vast empire. The Romans even passed a bylaw that it was an offence to obscure a fellow citizen's access to sunlight.

There are broadly contradictory opinions on the extent of ultimately recoverable fossil fuel reserves, and the extent to which unconventional resources can be tapped. In discussing hydrogen's role in an uncertain energy future Moriarty and Honnery (2009) argued that energy use over the next few decades faces deep uncertainties. While the potential for renewable energy (RE) sources, such as wind and solar is far greater, they face orders of magnitude scale-up in order to be major energy suppliers. Moriarty and Honnery (2009) predicted that a low energy future is the likely outcome. As shown in Table 1 the present global energy system is dominated by fossil fuels. Renewable energy sources have consistently accounted for only 13% of the total energy use over the past 40 years. A crucial query is for how long can this last without running into restraints in the form of limited reserves of fossil fuels, or severe environmental problems from their combustion, including not only global climate change from CO_2 and methane emissions, but also air pollution.

Combining renewable energy sources with desalination systems has abundant potential for water scarce regions such as MENA (i.e. Middle East and North Africa). (Goosen *et al*, 2010, 2011b; Goosen and Shayya, 1999; Khamis, 2009; Mahmoudi *et al*., 2008, 2010b; Misra, 2010; Serpen *et al*., 2010; Stock Trading, 2010; Tester *et. al*., 2007). As an example, a paper by Subiela and Penate (2011) describes the experience of desalting with solar PV energy in Morocco with the Adira project and discusses not only the technical aspects of implementing this kind of hybrid project, but also its economic, environmental and social aspects. Papapetrou *et al.* (2009) noted that the decreasing cost of renewable energy equipment, and experience from hybrid renewable energy desalination implementation is driving the cost down. At the same time, the cost of conventional water supply is increasing, especially in isolated sites where water needs to be transported by ships or trucks. Therefore renewable energy desalination is becoming competitive.

Renewable energy-driven desalination systems can be separated into two classifications. The first includes distillation processes (e.g. multi-stage flash (MSF), multiple-effect distillation (MED), thermal-vapour compression (TVC), humidification-dehumidification (HD)) driven by heat produced directly by the renewable energy system while the second includes membrane (e.g. reverse osmosis (RO), electrodialisys (ED)) and distillation processes (mechanical vapor compression (MVC)) driven by electricity or mechanical energy produced by renewable energy sources. Furthermore, hybrid systems also show great promise with, for example, geothermal brine being used directly in membrane distillation technology to feed a solar still (Houcine, *et al.*, 1999; Bouchekima, 2003). It can be argued that the most promising and current features related to membrane distillation (MD) are in the use of seawater and/or waste heat recovery systems (e.g. residual industrial vapour) for stand-alone systems for remote areas (Gemma Raley, *et al.*, 2012; Koschikowski, *et al.*, 2009). Solar-driven humidification–dehumidification desalination for small-scale decentralized water production has also been reported by Narayan et al. (2010) and even more than a decade ago by Bourouni et al. (1999a, 1999b, and 2001).

Small and medium water treatment plants can be connected to a wind turbine or a photovoltaic system in stand alone applications. For stand-alone applications it is important to have energy storage which is the main reason on the limits in size of the plants (Papapetrou *et al.,* 2009). To partially solve this problem, wind turbines as well as the desalination system can be connected to a grid system (Eltawil *et al*., 2009). The Kwinana Desalination Plant, for example, located south of Perth in Western Australia, has an installed capacity of 140 megalitres of drinking water per day, supplying the Perth metropolitan area (BlurbWire 2010). Electricity for the plant is generated by the 80 MW Emu Downs Wind Farm located in the state's Midwest region. However, many questions remain over scale-up problems and economic viability of renewable energy technology for freshwater production.

The aim of the current study was to provide a critical review of recent trends and challenges in water desalination using renewable energy resources with an emphasis on environmental concerns and sustainable development. After providing an overview of wind, wave, geothermal and solar renewable energy technologies for fresh water production, hybrid systems were assessed. Then scale-up and economic factors were considered. This was followed with a section on regulatory factors, environmental concerns and globalization, and a final segment on selecting the most suitable renewable energy technology for conventional and emerging desalination processes.

WIND POWER AND FRESH WATER PRODUCTION

Kalogirou (2005) in a meticulous evaluation of renewable energy sources for desalination reported that purely on a theoretical basis, and disregarding the mismatch between supply and demand, the world's wind energy could supply an amount of electrical energy equal to the present world electricity demand. Wind is generated by atmospheric pressure differences, driven by solar power. Of the total 173,000 TW (i.e. 1 TW = 10^{12} W) of solar power reaching the earth, about 1200 TW (0.7%) is used to drive the atmospheric pressure system (Soerensen, 1979). This power generates a kinetic energy reservoir of 750 EJ (i.e. 1 EJ = 10^{18} J) with a turnover time of 7.4 days. This conversion process mainly takes place in the upper layers of the atmosphere, at around 12 km height (where the 'jet streams' occur). If it is assumed that about 1% of the kinetic power is available in the lowest strata of the atmosphere, the world wind potential is of the order of 10 TW, which is more than sufficient to supply the world's current electricity requirements.

Peñate *et al.* (2011) assessed appropriate designs for seawater reverse osmosis desalination (SWRO) driven by off-grid wind energy systems. The authors argued that only mature and efficient technologies are suitable for medium or large scale desalination. A scheme based on gradual capacity with nominal production of 1000 m^3/d was compared to a conventional fixed capacity desalination plant. The intermittent nature of wind resources is a major drawback. However, the gradual capacity desalination plant was able to adjust or fit to the available wind energy and thus to maximize the annual water production. The authors also noted that the use of wind energy to supply a stand-alone SWRO desalination system, adapted to medium or large water demands, makes it necessary to take into account water storage as the key to a workable system. This stored water must meet the water demand in periods of lack of wind resources or serious breakdowns of the system.

Isolated regions with prospective wind energy resources such as islands can employ wind energy systems to power seawater desalination for freshwater production (Koschikowski and

Heijman, 2008; Kalogirou, 2005). The advantage of such systems is a reduced water production cost compared to the costs of transporting the water to the islands or to using conventional fuels as power source. In particular, small decentralised water treatment plants combined with an independent wind energy convertor system (WECs) (Figure 2a) show great potential for transforming sea water or brackish water into pure drinking water (Koschikowski and Heijman, 2008).

Diverse approaches for wind desalination systems are possible (Koschikowski and Heijman, 2008; Kalogirou, 2005). Firstly, both the wind turbines as well as the desalination system can be connected to a grid system. In this case, the optimal sizes of the wind turbine system and the desalination system as well as avoided fuel costs are of interest. The second option is based on a more or less direct coupling of the wind turbine(s) and the desalination system. In this case, the desalination system is affected by power variations and interruptions caused by the power source (wind). These power variations, however, have an adverse effect on the performance and component life of desalination equipment. Recently, numerous medium and large scale water treatment and desalination plants have been partially or excusively powered with renewable energy mainly wind turbines, PV (photovoltaic) cells or both (Carta *et al.*, 2003a, 2003b, 2004; Subiela *et al.*, 2004). The energy demand of, for example, the Sureste SWRO plant located in Gran Canaria, Canary Islands, of a capacity of 25,000 m^3/d is provided by a combination of PV cells (rooftop) with the rest from the grid which consist of an energy mix including wind energy (Figure 2b) (Sadhwani & Veza, 2008; IDA Conference, 2008).

An energy yield and economic analysis was performed by Dehmas *et al.*, (2011) of a hypothetical wind farm consisting of 5 wind turbines of 2MW each. It was found that wind energy can successfully power a SWRO desalination plant in their case study region in Ténès situated in northern Algeria on the Mediterranean coast. Analysis results showed that wind power could provide a viable substitute to diesel oil for irrigation pumps and electricity generation.

The Kwinana Desalination Plant, located south of Perth in Western Australia, is one example where a grid connected wind power and reverse osmosis (RO) desalination plant have been successfully combined (Figure 3). The plant can produce nearly 140 megalitres of drinking water per day (BlurbWire 2010). Electricity for the plant is generated by the 80 MW Emu Downs Wind Farm located in the state's Midwest region. The RO plant was the first of its kind in Australia and covers several acres in an industrial park. Operating pressures varied between 10 and 25 bars for brackish water and 50–80 bars for seawater (Eltawil *et al.*, 2009).

Wind power turbines are generally large structures (e.g. 100 ft high or greater) that generate large amounts of power (in the megawatt range). When considering applications in the area of desalination it is important to remember that such structures face limitations in distribution and deployment including environmental concerns (e.g. noise and size may affect wildlife in the area where wind turbines are located). There is also the need to locate wind farms in remote areas away from public infrastructures (Fein and Merritt, 2011). Research is underway on micro/nano wind gathering devices of less than an inch that can be mounted on rollable or stacked sheets for easy installation (Fein and Merritt, 2011). Small wind turbines power generation systems can be installed in residential homes and business and may or may not be connected to an existing electrical grid. However, it remains to be seen whether such micro/nano wind gathering devices can be deployed in a cost effective way, especially in the area of desalination.

OCEAN WAVE, TIDAL AND HYDROSTATIC POWER FOR DESALINATION

Countries with large populations and long ocean shorelines have great potential in generating energy which can be used for desalination. Wang *et al.*, (2011), for example, reviewed the distribution of resources and the technology status of tidal, wave, marine current, ocean thermal and salinity gradient energy in China. The authors concluded that the country's ocean energy resources are quite rich and their distribution fits well with the energy demands of the country's coastal regions which tend to be highly populated and industrialized. A future challenge will be how to apply this renewable energy for desalination for fresh water production for its extremely large population. From the technical maturity point of view, tidal power generation technology was found to be the most mature. China has faced great pressures to meet rapidly expanding energy needs as a result of rapid economic growth over the past decade. However, this rapid growth has resulted in significant air, water and soil pollution which is affecting the health of its citizens.

Over the past decade China's share of global energy use has swelled significantly so that currently it is to over 15% (Wang *et al.,* 2011). This state is now the world's second-largest energy consumer. The total energy consumption of China in 2009, for example, reached the equivalent of 3.10 billion tonnes of coal, with an increase of 124% from 2000. Renewable ocean energy technology may help to solve this energy problem. The country, for example, has developed numerous ocean renewable energy projects with some going back nearly three decades. For example, The Jiangxia pilot tidal power plant (Fig. 4 LHS) is one of three plants in China. The power plant was claimed to be the third largest tidal power station in the world, after the La Rance tidal power plant in France and the Annapolis tidal generating station in Canada (Xie et al., 2009). According to the latest figures, total power output of the Jiangxia pilot tidal power plant is 1.62 x 10^8 kWh per year. The Ocean Technology Institute, now known as National Ocean Technology Centre (NOTC), set up a 100 kW pendulum wave power plant (as shown in Fig. 4 Middle) in Daguan Island in Shandong. As a final example, in 2006 the North Eastern Normal University (NENU) in Changchun in Jilin Province developed a 1 kW floating horizontal axis turbine to harness surface tidal currents. In 2008 an improved 2 kW version of the device was tested in the coastal area of Qingdao (Fig. 4 RHS) (Zhang, 2009). The question now is how can China utilize these renewable energy sources for desalination?

Jayashankar *et al.* (2009) reported that near-shore bottom-standing oscillating water column (OWC) wave energy plants in Japan and India have been available for about a decade. Historically the weakest link in the conversion efficiency of OWC based wave energy plants built so far has been the bidirectional turbine. This is a similar problem to that observed with the floating horizontal axis turbine described previously by Zhang, 2009 (Fig. 4RHS). We can speculate that the OWC system may be a suitable energy source for a stand alone or autonomous RO desalination plant as described by Foley and Whittaker (2009).

One of the earlier studies on conversion of wave energy into electrical energy resulted in a device called Salter's Duck or officially referred to as the Edinburgh Duck (Figure5) (Thorpe 1999, Salter *et al.*, 2011). The concept is similar to a water turbine combined with an electrical generator as occurs with hydroelectric turbines. Flowing water is converted to mechanical energy which causes a generator to rotate, producing electricity. In small scale controlled tests, the Duck's curved cam-like body could stop 90% of wave motion and could convert 90% of that to electricity giving 81% efficiency. The original device was anchored to the sea floor using cables. A modified Duck system was employed in a vapour compression desalination process (Salter *et* *al.*, 2011). Although an interesting concept and system, it remains to be seen whether scale-up problems can be overcome.

Davies (2005) also reported on the potential of linking ocean-wave energy to desalination. They found that along arid, sunny coastlines, an efficient wave-powered desalination plant could provide water to irrigate a strip of land 0.8 km wide if the waves are 1 m high, increasing to 5 km with waves 2 m high. Wave energy accessibilities were compared to water shortages for a number of arid nations for which statistics were available. According to Davies (2005) wave-powered desalination could provide 16% of the required fresh water for Morocco and 600% for Somalia. The later suggests a great deal of available wave energy along the coast of East Africa, where Somalia is located. In a related study, Magagna and Muller (2009) described the growth of a stand-alone, off-grid RO desalination system powered by wave energy. The system consisted of two main parts; a high pressure pump (Wave Catcher) that allows generation of a high pressure head from low head differences, and a wave driven pump to supply the necessary head to the Wave Catcher. The high pressure pump could produce 6 MPa of pressure which is necessary to drive a RO membrane for desalination of water. It can be argued that wave energy technology is still at the prototype stage, since there is no standard technology. Wave energy also has intermittent behaviour problems similar to wind energy.

A techno-economic model of an independent wave-powered desalination plant was developed by Foley and Whittaker (2009). They showed that freshwater could be produced for as little as \$0.75/m^3. The modelled plant consisted of what was called an Oyster wave energy converter (Cameron *et al.*, 2010), conventional RO membranes and a pressure exchanger–intensifier for energy recovery. In their paper however, Foley and Whittaker (2009) indicated that a several technological barriers must be overcome if wave-powered desalination is to be exploited effectivelly. The first of these barriers is the development of the energy recovery technology. We can speculate that the energy recovery devices that are commercially available in RO may be modified for use in wave-powered systems. Likewise, the operation of the proposed technology is very similar to other technologies such as the Clark pump (i.e. recovers mechanical energy from concentrate flow and returns it directly to the feed flow; see Manolakos *et al.*, 2008). The second barrier is the development of a suitable filtering and pre-treatment technology that can be deployed with the wave energy converter and operated without servicing or significant maintenance for extended periods of time. Lastly, the acceptable operation of the RO membranes under the variable feed conditions provided by the wave energy converter needs to be established (Goosen et al., 2011a).

Most of the work on wave energy conversion has focused on electricity production (Davies, 2005); any such converter could, in principle, be coupled to an electrically-driven desalination plant, either with or without connection to the local electricity grid. Worldwide exploitable of wave energy resources is estimated to be 2 TW, so it is a promising option for electricity generation. Thus, there is a great potential in coupling wave power with seawater reverse osmosis (Chapa *et al.,* 2007) (Figure 6). Wave-powered desalination offers an environmentally sensitive solution for areas where there is a shortage of water and sufficiently energetic waves, such as occurs of the East African.

Charlier and Finki (2009) in a recent book on the tidal power of oceans recommended small-scale projects for harnessing the ocean's tidal energy for applications in desalination. Since this is a relatively new area smaller projects would be a lower risk economically. They went on to explain that the environmental benefits such as a reduction in pollution through cleaner air would have to be balanced against the negative aesthetic (i.e. visual) effects. In a related study, Davis (1997) identified a large number of tidal sites in the world's ocean's which can provide a significant, viable and cost effective source of reliable energy.

In an associated study, the potential exploitation of the hydrostatic pressure of seawater at a sufficient operative depth was considered by several investigators in the 1960s with a view to increasing energy efficiency of the then developing RO industrial desalination technology (Drude, 1967; Glueckstern, 1982). More recently, several configurations were proposed for freshwater production from seawater using RO and hydrostatic pressure: submarine, underground and ground-based (Reali *et al.*, (1997). In conventional surface-based industrial desalination plants applying RO technology, the freshwater flow at the membrane outlet is approximately 20–35% of the inlet seawater flow, depending on membrane type and characteristics and feed water salinity. The resulting brine is disposed off in the sea. While RO installations generate the required pressure with high-pressure pumps, the submarine approach uses seawater hydrostatic pressure. The desalinated water, produced at about atmospheric pressure and collected in a submarine tank at the same working depth, is pumped to the sea surface. It was shown that this approach saves about 50% of the electricity consumption with respect to an efficient conventional RO plant (about 2–2.5 kWh/m^3) since only the outlet desalinated water is pumped instead of the inlet seawater, thus reducing the pumping flow rate by 55–80% (Pacenti *et al.*, 1999). Another advantage of this configuration is to avoid the pre-treatment of the inlet seawater, therefore saving costs for chemicals and equipment (Charcosset, 2009).

Folley *et al.* (2008) and Whittaker *et al.* (2007) reported on the potential of an independent wave-powered desalination system combined with an RO plant utilising a pressure exchanger-intensifier for energy recovery. A key component of the system is a wave energy converter called Oyster (Figure 7). Oyster is essentially a wave powered hydroelectric plant located at a nominal water depth of 12 m which in many locations is relatively close to the shoreline. The system comprises a buoyant flap, 18 m wide and 10 m high, hinged at its base to a sub-frame which is pinned to the sea bed using tensioned anchors. The surge component in the waves forces the flap to oscillate which in turn compresses and extends two hydraulic cylinders mounted between the flap and the sub-frame which pumps water at high pressure through a pipeline back to the beach (Figure 7). On the shore is a modified hydro-electric plant consisting of a Pelton wheel turbine (i.e. extracts energy from the impulse or momentum of moving water) driving a variable speed electrical generator coupled to a flywheel. Folley *et al.* (2008) went on to argue that a directly-fed independent wave-powered desalination would appear to offer a promising potential for the coupling of renewable energy sources with desalination technology. Nevertheless, in order to make wave-powered desalination a reality, additional effort is necessary to design and develop the pressure exchanger-intensifier suitable for wave-powered desalination, together with tackling the challenges associated with RO membrane durability under variable feed conditions, feed water pre-treatment and system reliability for a remote location

GEOTHERMAL DESALINATION

Among renewable energies, geothermal production is the third highest. It is behind hydro, but before solar and wind. In the case of Iceland, 86% of space heating and 16% of electricity are supplied by geothermal energy (Dorn, 2008, White and Williams, 1975; Wright, 1998). Geothermal reservoirs can produce steam and hot water which can be used for heat and electricity generation. Thus, there is a potential use for thermal (e.g. multi effect distillation (MED), multistage flash (MSF), membrane distillation (MD), vapour compression (VC)) and membrane (e.g. reverse osmosis (RO)) desalination processes.

When using geothermal energy to power systems such as desalination plants we avoid the need for thermal storage. In addition, the energy output of this supply is generally stable compared to other renewable resources such as solar, wave and wind power (Bourouni and Chaibi, 2005). Kalogirou (2005) has shown that the ground temperature below a certain depth remains relatively constant throughout the year. Popiel *et al.* (2001) reported that one can distinguish three ground zones; surface, shallow and deep, with geothermal energy sources being classified in terms of their measured temperatures as low (<100°C), medium (100–150°C) and high temperature (>150°C), respectively.

Geothermal wells deeper than 100 m can reasonably be used to power desalination plants (Kalogirou, 2005). We can also envisage the utilization of geothermal power directly as a stream power in thermal desalination plants. Furthermore, with the recent progress in MD technology, the utilization of direct geothermal brine with temperature up to 60°C has become a promising solution (Kalogirou, 2005; Fridleifsson et al., 2008; Houcine, *et al.*, 1999). It should be noted, however, that MD can operate at higher temperatures (80ºC or higher). The performance is highly reduced for lower temperatures (Maab *et al.*, 2012; Francis *et al.*, 2012). Fridleifsson *et al.* (2008) reported that electricity is produced by geothermal means in 24 countries, five of which obtained up to 22% of their needs from this source. Furthermore, direct application of geothermal energy for heating and bathing has been reported by 72 countries. By the end of 2004, the worldwide use of geothermal energy was 57 TWh/yr of electricity and 76 TWh/yr for direct use. Fridleifsson *et al.* (2008) goes on to argue that it is considered possible to increase the installed world geothermal electricity capacity from the current 10 GW to 70 GW with present technology, and to 140 GW with enhanced technology.

An ambitious program was established by the Algerian government in 1988 with the aim to expand the utilization of geothermal heated greenhouses in regions affected by frost (Fekraoui and Kedaid, 2005). Unfortunately, this program was hampered by security concerns (Fekraoui and Kedaid, 2005). Mahmoudi *et al*. (2010) has noted that due to the world economic crisis and the decreasing oil and gas reserves, decision makers in arid countries such as Algeria, need to review their policies regarding the promotion of renewable energies. Algeria is an oil and gas producer; hence decision makers believed that encouraging the use of renewable energies can affect the country's oil exports (Mahmoudi *et al*., 2009b).

Mahmoudi *et al*., (2010b) in a recent report proposed the application of geothermal sources to power a brackish water greenhouse desalination system for the development of arid and relatively cold regions of Algeria (Figure 8). Geothermal resources can be used to heat the greenhouses and to provide freshwater needed for irrigation of the crops cultivated inside the greenhouses. The Geothermal Energy Center’s director Hal Gurgenci at University of Queensland in Australia noted that geothermal-powered desalination systems could be a boon for small towns facing water shortages (Wash Technology, 2009). He went on to state that the greenhouse-geothermal energy system described by Mahmoudi et al., (2010b) is a clever combination where desalination is coupled with an agricultural function which is both cost-efficient and environmentally-friendly.

APPLICATIONS OF SOLAR ENERGY FOR WATER DESALINATION

Mekhilef *et al.*, (2011) in a review on solar energy use in industries noted that a study on the world energy consumption released by International Energy Agency (IEA) predicted that by 2050, solar array installations will supply around 45% of the energy demand in the world. However, this prediction is in contrast to a report by Moriarty and Honnery, (2009) (Table 1) mentioned earlier that shows renewable energy sources have consistently accounted for only 13% of the total energy use over the past 40 years. We can therefore argue that the IEA estimate may be on the high side. The review by Mekhilef *et al*., (2011) was aimed at assessing solar energy systems utilization in industrial applications. In particular they looked at those applications which are more compatible for integration with solar energy system technologies such as solar water heating, space heating and cooling, solar refrigeration using adsorption/desorption, desalination, and thermal power systems. Solar air conditioning can be done, for instance, through a solar open-loop using desiccants, or a solar closed-loop using absorption and adsorption cooling (Figure 9). Solar air conditioning is expected to play an increasing role in new building design.

The combination of renewable energy with desalination schemes holds immense potential for improving drinkable water supplies in arid regions (Mahmoudi *et al*., 2008, 2009a, 2009b, 2010b; Papapetrou *et. al*., 2005). Desalination by way of solar energy is a suitable alternative to small scale conventional methods to providing freshwater, especially for remote and rural areas where small quantities of water for human consumption are needed (Al-Hallaj *et al*., 1998). Attention has been directed towards improving the efficiencies of the solar energy conversions, desalination technologies and their optimal coupling to make them economically viable for small and medium scale applications. Solar energy can be used directly as thermal or it can be converted to electrical energy to drive RO units. Electrical energy can be produced from solar energy directly by photovoltaic (PV) conversion or via a solar thermal power plant.

Solar stills, which have been in use for several decades, come in a variety of options (Goosen *et al*., 2000; Rodriquez *et al*, 1996; Fath, 1998). The simple solar still (Figure 10A) is a small production system yielding on average 2-5 L/day. It can be used wherever freshwater demand is low and land is inexpensive. Many modifications to improve the performance of the solar stills have been made including incorporating a number of effects to recover the latent heat of condensation (Figure 10B) (Al-Hallaj *et al*., 1998). In an effort to improve productivity, Kalidasa Murugavel and Srithar (2011) did a performance study on basin type double slope solar still with different wick materials and minimum mass of water. It was found that the theoretical production rate using a proposed model were close to the experimental. Nevertheless we can argue that simple solar still systems are not economically viable for large-scale applications. Furthermore, while a system may be technically very efficient it may not be economic (i.e., the cost of water production may be too high) (Kalidasa Murugavel and Srithar, 2011). Therefore, both efficiency and economics need to be considered when choosing a desalination system. In a related study, an extensive review of solar stills was carried out Velmurugan & Srithar (2011). They reported for example on how a mini solar pond was integrated with single basin solar still. The mini solar pond supplied hot water to the solar still thus augmenting the evaporation rate of the saline water in the still and increasing its productivity by 28%**.** However, the paper failed to recommend a specific type of solar still. The study may be useful for those researchers seeking to improve existing stills. It has been reported that, compared with other solar desalination technologies, solar ponds, even though they are limited to small-scale applications, provide the most convenient and least expensive option for heat storage for daily and seasonal cycles (Kalogirou, 2005).

Solar collectors are usually classified according to the temperature level reached by the thermal fluid in the collectors (Kalogirou, 2005). Low temperature collectors provide low-grade heat, only a few degrees above ambient air temperature and use unglazed flat plate collectors. This low-grade heat is not useful to serve as a heat source for conventional distillation processes (Fahrenbruch and Bube, 1983; Kalogirou, 2005). Medium temperature collectors provide heat of more than 43˚C and include glazed flat plate collectors as well as vacuum tube collectors using air or liquid as the heat transfer medium. They can be used to provide heat for thermal desalination processes by indirect heating with a heat exchanger. High temperature collectors include parabolic troughs or dishes or central receiver systems. They typically concentrate the incoming solar radiation onto a focal point, from which a receiver collects the energy using a heat transfer fluid. The high temperature energy can be used as a thermal energy source in thermal desalination processes or can be used to generate electricity using a steam turbine. Sun tracking is required to ensure that the collector is always kept in the focus of the reflector for improving the efficiency.

Long term energy storage is a major problem for renewable energy applications. One solution to this problem is the use of solar ponds (Figure11). A salt concentration gradient in the pond helps in storing the energy. Whereas the top temperature is close to ambient, a temperature of 90 °C can be reached at the bottom of the pond where the salt concentration is highest (Figure 11b). The temperature difference between the top and bottom layer of the pond is large enough to run a desalination unit, or to drive the vapour generator of an organic Rankine cycle engine (Peñate & García-Rodríguez, 2012b; Saleh et al., 2011; Wright, 1982). The Rankine cycle converts heat into work. This cycle generates about 80% of all electric power used throughout the world including virtually all solar thermal, biomass, coal and nuclear power plants. Saleh *et al.*, (2011) investigated a solar pond that had been constructed near the Dead Sea and that was coupled with a flash desalination plant. By using a simulation model the authors showed that a 3000 m^2 solar pond installed near the Dead Sea site would be able to provide an annual average production rate of 4.3 L min^{-1} distilled water compared with 3.3 L min^{-1} that would be produced by a comparable solar pond with the same surface area in El Paso, Texas in the USA (Lu *et al.* 2001). The increase was assumed to be due to the higher heat capacity storage of the solar pond at the Dead Sea site.

If high temperature collectors or solar ponds are used for electricity generation, a desalination unit, such as a multistage flash system (MSF), can be attached to utilize the reject heat from the electricity production process. Since, the conventional MSF process is not able to operate with a variable heat source, an adapted MSF system called ‘Autoflash’ was developed which can be connected to a solar pond (Szacsvay *et al.*, 1999). Examples of different plants coupling a solar pond to an MSF process include: Margarita de Savoya, Italy: Plant capacity 50–60 m^3/day; Islands of Cape Verde: Atlantis ‘Autoflash’, plant capacity 300 m^3/day; Tunisia: a small prototype at the laboratoire of thermique Industrielle; a solar pond of 1500 m^2 drives an MSF system with capacity of 0.2 m^3/day; and El Paso, Texas: plant capacity 19 m^3/day (Lu *et al.*, 2000).

Solar photovoltaic (PV) systems directly convert sunlight into electricity by solar cells (Kalogirou, 2005). PV is a mature technology with life expectancy of 20 to 30 years. In small and medium-sized systems the grid is used as a back-up source of energy, (any excess power from the PV system is fed into the grid). In the case of large centralized plants, the entire output is fed directly into the grid. Hybrid arrangements, on the other hand, are autonomous systems consisting of PV arrays in combination with other energy sources, for example in combination with a diesel generator or another renewable energy source (e.g. wind). Hybrid systems are discussed in more detail in the next section.

There are mainly two PV driven membrane processes, reverse osmosis (RO) and electrodialysis (ED). From a technical point of view, PV as well as RO and ED are mature and commercially available technologies. The feasibility of PV-powered RO or ED systems, as valid options for desalination at remote sites, has also been proven (Peñate, et al., 2012c; Subiela et al., 2009; Papapetrou et al., 2009; Childs *et al.*, 1999). The main problem in the past with these technologies has been the high cost and, for the time being, the availability of PV cells. However, PV panels have reduced in cost in the last few years (e.g. currently 3-4 USD/W installed, down from 8 USD/W in 2006) (Peñate, et al., 2012c; Subiela et al., 2009).

Burgess and Lovegrove (2005) compared the application of solar thermal power desalination coupled to membrane versus conventional distillation technology. They reported that a number of experimental and prototype solar desalination systems have been constructed, where the desalination technology has been designed specifically for use in conjunction with solar thermal collectors, either static or tracking. To date such systems are either of very low capacity, and intended for applications such as small communities in remote regions, or else remain unproven on a larger scale. Schwarzer *et al* (2001) described a simple system which has flat plate collectors (using oil as a heat transfer fluid) coupled to desalination "towers" in which water evaporates in successive stages at different heights (similar to the multi effect still shown in Figure 10B). The condensation of vapour in one stage occurs at the underside of the next stage, transferring heat and increasing the gain output ratio. A very similar system (not mentioned by Schwarzer), called a "stacked plate still", was described by Fernandez (1990). It is important to remember that a clear distinction should be made between systems where the RO is coupled directly with solar thermal energy and those where electricity is produced by solar thermal energy and then this electricity is used to run the RO unit.

A company based in California has developed an RO based desalination system which is specifically tailored to solar thermal input (Childs *et al*., 1999). A patented direct drive engine (DDE) converts heat to the hydraulic power required by RO. Desalinated water production using the DDE was projected to be more than 3 times greater (for an identical dish collector) than that which would be obtained by RO driven by a dish-Stirling electricity generation system or PV power. Burgess and Lovegrove (2005) noted that the project remains at the pilot stage with the DDE not commercially available. We can speculate that it has perhaps become less attractive due to the advances in conventional RO.

A number of solar desalination pilot plants have been installed and most have been operating successfully with very little maintenance (Reddy and Ghaffour, 2007). Operational data and experience from these demonstration plants can be utilized to achieve higher reliability and cost minimization. Indirect collection systems for these plants comprise solar collectors that produce thermal, or electrical, or shaft energy. These types of energy produced by the collector systems can be used to run conventional desalination processes such RO, ED, MSF, multi-effect distillation (MED), thermal vapor compression (TVC), mechanical vapor compression (MVC), humidification/ dehumidification (HD) systems and other promising processes which are under development such as membrane distillation (MD) and adsorption desalination (AD). However, factors that need to be considered when making a choice of which combination system to choose include product water quality, feedwater quality, size of the unit, power requirements, economics, and operation and maintenance. More than 80% of the relatively small solar desalination capacity, for example, is produced by RO and MED from mostly demonstration plants (Reddy and Ghaffour, 2007).

A fully automated solar-driven AD prototype system was recently commissioned at the King Abdullah University of Science and Technology (KAUST) in Saudi Arabia (Figure12) (Ng *et al*., 2012). It had a nominal capacity of 3 m^3 per ton of adsorbent (silica gel) per day, and was powered fully by solar energy using an array of 485 m^2 thermal collectors. In addition, the AD prototype could generate cooling suitable for air conditioning at a nominal capacity of 10 Rtons. Rtons stands for refrigeration tons (i.e. 1 Rton = 3.52 kW) and is a technical term used by cooling engineers. The new technology produces distillate water and cold water simultaneously, and can be seasonally adjusted to favor either cooling or potable water production which makes it particularly attractive in arid and semi-arid regions. Besides electricity efficient, the AD cycle is inherently low in maintenance by design because it has almost no major moving components. An estimation of CO_2 emission of the AD cycle yielded 0.64 Kg/m^3 which is the least polluting.

In comparison, the emissions from conventional cycles are in excess of 5 to 12 folds higher than the AD cycle.

Mehrgoo and Amidpour (2011) performed a modeling design study of a humidification-dehumidification (HD) desalination process with a closed air cycle and water heating in order to maximize the fresh water production rate per unit of volumetric flow. The paper may be of use for those requiring modeling equations for process design of solar desalination systems. In a related study, a demonstration-scale solar HD seawater greenhouse pilot plant was constructed in Oman in the Arabian Gulf in 2003 (Goosen *et al.,* 2003; Mahmoudi *et al.,* 2008). Goosen *et al.* (2003) determined the influence of desalination process parameters that would enhance freshwater production for the growth of crops in the greenhouse (Figure 8).

Finally, it is important to note here that there are still several limitations in the use of solar desalination. Firstly, at present solar desalination does not appear to be a viable option for very large scale applications, either technically or economically. However, it can be used for small/medium scale applications for supplying water in remote locations where there is no electric grid connection. Secondly, energy storage is a major concern since solar energy is available only during day time and its intensity changes from morning to evening. In contrast the energy requirements of any desalination process are constant and continuous and the efficiency of any desalination process is low if operated at variable load; variable operation even affects the plant operating life (Goosen *et al.,* 2012; Mahmoudi et al., 2009b; Ghaffour, 2009). An energy storage system or an alternative back-up source of energy is therefore required to run the desalination plant continuously at constant load. Finally, available conventional desalination processes may not be suitable, technically and economically, for operating with solar energy in remote locations since the operation and maintenance of these technologies require skilled operators (Mahmoudi *et al.*, 2009b; Ghaffour, 2009).

HYBRID SYSTEMS

A major challenge facing renewable energy systems such as wave, solar and wind is the variability of energy supply over time. Solar radiation, for instance, fluctuates and is dependent on environmental conditions. Therefore, combining photovoltaic (PV) energy generation with other renewable resources such as wave energy in a hybrid power system can reduce the supply interruption since strong waves frequently occurred during cloudy days or at night time. Hybrid systems are also preferred for remote and isolated sites that are far away from conventional power systems. El-Sayed and Sharaf (2011) presented a hybrid renewable energy utilisation scheme employing a combination of PV and wave energy converters (Figure13). The hybrid system was digitally simulated and validated using Matlab/ Simulink/ Sim-Power software. The study scheme comprised in addition to a PV array, a wave energy permanent magnet linear generator (PMLG). The PMLG generator converted the wave energy into linear motion from the wave excitation force (Figure13). The relative motion between the permanent magnets and the coils generated electrical energy (Leijon, 2005; Greaves et al., 2009). We can speculate that this type of hybrid system will ensure a more stable and uninterrupted supply of electrical energy.

Trieb *et al.* (2002) almost a decade ago proposed a Euro-Mediterranean power pool interconnecting the most productive sites for renewable electricity generation in the north and south of Europe based on solar, wind, hydro and geothermal energy (Figure14). This power supply could be used for freshwater production as well as other commercial applications. Trieb *et al.* (2002) argued that the exploitation of the tremendous solar energy potential in North Africa quickly comes to its limits if it is restricted to national boundaries. Although the North African countries have vast resources of solar radiation and also land to place the necessary solar collector fields, their technological and financial resources are limited, and the local electricity demand is relatively small. The opposite is true for Europe (Figure14, left). In order to exploit the renewable energy potential of both regions in an efficient and economic way, an interconnection of the electricity grids was proposed to allow for the transmission of solar electricity between North Africa and Europe (Figure 14, *right*). The synergies of such a scheme would not only reduce considerably the cost of solar electricity in Europe, but also would create an additional income for the North African countries, enabling them to finance and develop their renewable energy resources for local use and for export.

Bourouni *et al* (2011) in a recommended paper reported on a design and optimization study of desalination RO plants driven by various types of renewable energies systems (Table 2, Figure15). The authors also reported on the corresponding costs. As shown in Table 3, the cost of desalinated water depends on several factors including plant capacity, renewable energy/RO system design, feed water quality, and site location. The particular focus by Bourouni *et al* (2011) was on hybrid systems consisting of solar PV, and wind energy systems, batteries for energy storage, and application in RO water desalination. The optimization of the hybrid systems was done by using Genetic Algorithms. This allowed for the generation of several possible solutions for coupling small RO unit to renewable energy systems.

Karellas et al., (2011) performed a technical and economic study of an autonomous (i.e. stand alone) hybrid desalination system located on Chalki Island in Greece. An economic comparison was made to the transport of fresh water to the island by ships. Their hybrid system consisted of a solar thermal collector field in combination with a heat exchanger and an Organic Rankine Cycle to drive a RO process. In an Organic Rankine cycle (ORC) the low-temperature heat recovered from an organic, high molecular weight fluid is converted into useful work with the aid of a turbine. The authors concluded that the stand alone hybrid renewable energy desalination technology can deliver potable water at a cost of 10.17 €/m^3 (i.e. 13.2 \$ US/m^3) while currently fresh water is transported to the case study (i.e. an island) site at a cost of 8.35 €/m^3 (i.e. 10.9 \$ US/m^3). However, the renewable energy desalination system incorporates environmental and transportation advantages, since pollution caused by the ships, as well as delivery delays are no longer factors to be considered. The project described by Karellas et al., (2011) is a good example of the dilemma faced in the application of renewable energy technology; the renewable energy desalination system works, there is no consumption of fossil fuels, and environmental pollution is greatly reduced. However, generally speaking, the cost of the produced potable water is still higher than transporting fresh water to the island from the mainland, at least in this example. We can argue that this problem will resolve itself with time as transportations costs go up and the costs of hybrid renewable energy-OR systems go down.

Kaldellis et al. (2004) examined the economic viability of several hybrid desalination plant configurations based on the available renewable energy sources (i.e. wind and solar) using an integrated cost-benefit analysis. Their results support the utilization of renewable energy sources-based desalination plants as the most promising and sustainable method to satisfy the fresh, potable water demands of the small- to medium-sized islands at a minimal cost. The environmental and macro-economic benefits were also recognized.

In a related study, Parissis et al. (2011) presented a proposal for a wind energy and hydrogen storage power system for Corvo Island in the Azores. This small Portuguese island is exclusively dependent on diesel fuel. Imported fuel dependency and security of supply are of particular concern since frequently there are transport problems due to severe weather conditions. The proposed wind energy and hydrogen storage power system introduced by Parissis et al. (2011) for Corvo included the introduction of hydrogen as a means of storage and wind energy as an additional electricity production source in order to replace to a great extent conventional fuel. An analysis of the proposed system indicated a significant reduction (43%) in the power generation cost. In addition, 80% of the electricity needs of the island would be covered by renewable energy, thus decreasing the island's heavy dependency on imported fuel, reducing harmful emissions and enhancing the supply security. The last issue in particular is vital when one takes into account the long distance of this island from larger islands and continental Portugal. The scheme was also assessed in terms of its environmental and social implications. A cost-benefit analysis was performed and the results indicated that an 80% penetration of wind energy into the power system of Corvo Island coupled with the introduction of hydrogen energy storage was profitable both from the perspectives of the investor and the society.

Ipsakis et al. (2009) has also proposed a small to medium scale stand-alone hybrid power system based on a PV array and wind generators that stores the excessive energy from renewable energy sources in the form of hydrogen via water electrolysis. Their aim was to use the power system in a polymer electrolyte membrane (PEM) fuel cell planned for operation at Neo Olvio of Xanthi in Greece. We can argue that this small to medium scale system has potential applications in providing, for example, electrical energy for running RO units for seawater and brackish water desalination in remote arid, sunny and windy locations.

In two interesting studies Jacobson et al. (2011) and Cao et al. (2009) reported on salt removal in a continuously operated up flow microbial desalination cell (MDC) with an air cathode and a cation-exchange membrane. When current is produced through anode bacterial oxidation and cathode reduction, anions migrate into the anode chamber and cations transport into the cathode chamber. As a result, salts are ‘‘relocated” into the wastewater stream and salt concentration in seawater can be greatly reduced. MDCs hold great promise for drinking water production because of potential energy savings during the desalination process. However, it should be noted that the experiments reported by Jacobson et al. (2011) were run with 0.5 L tubular bioreactors. It remains to be seen how this system will function on a larger scale.

Lastly, Gude et al., (2010) in an excellent paper critically reviewed sustainable practices and innovative desalination technologies for water reuse and energy recovery (i.e. staging, waste heat utilization, hybridization). They noted that these approaches have the potential to reduce the stress on existing water and energy sources with a minimal impact on the environment. It was suggested that an all-inclusive approach of coupling renewable energy sources with technologies for recovery, reuse, and recycle of both energy and water can meet the world’s energy and water needs. In particular high capital costs for renewable energy sources for small-scale applications suggested that a hybrid energy source comprising both grid-powered energy and renewable energy will reduce the desalination costs in view of the present economics of energy.

Finally, the choice of desalination method affects significantly the water desalination cost. Under special conditions hybrid systems such as solar and wind can offer increased and more stable production of freshwater.

SCALE-UP AND ECONOMIC CONSIDERATIONS

Factors Affecting Scale-Up and Cost Efficiency

Many factors enter into the capital and operating costs for desalination: capacity and type of plants, plant location, quality of feed water, labor, energy, financing, concentrate disposal, and plant reliability (USBR, 2003). For example, the cost of desalted seawater is about 3 to 5 times the cost of desalting brackish water from the same size plant, due primarily to the higher salt content of the former (USBR, 2003; Reif, 2008). In any state or district, the economics of using desalination is not just the number of dollars per cubic meter of freshwater produced, but the cost of desalted water versus the other alternatives (e.g. superior water management by reducing consumption and improving water transportation). In many arid areas, the cost of alternative sources of water (i.e. groundwater, lakes and rivers) is already very high and often above the cost of desalting. Any economic evaluation of the total cost of water delivered to a customer must take account of all the costs involved. This includes the costs for environmental protection (such as brine or concentrate disposal), and losses in the storage and distribution system.

The capital and operating costs for desalination plants have tended to decrease over the years due primary to improvements in technical efficiency (Peñate & García-Rodríguez, 2012a; Reif, 2008). At the same time that desalting costs have been decreasing, the price of obtaining and treating water from conventional sources has tended to increase because of the increased levels of treatment being required to meet more stringent water quality standards as well as due to continuous pollution of available water resources. This rise in cost for conventionally treated water also is the result of an increased demand for water, leading to the need to develop more expensive conventional supplies, since the readily accessible water sources have already been used up.

The energy consumption for diverse desalination schemes is presented in Table 4. Distillation technologies (i.e. MSF and MED) need thermal and electrical energy while membrane processes (i.e. SWRO and BWRO) in large commercial plants need only electrical energy. However, both are energy intensive accounting for up to 50% of the operating cost of each process (Mahmoudi *et al*., 2009b; Ghaffour, 2009). Details of desalination costing and energy requirement for each type of water desalting sy3stem were reported by Reddy and Ghaffour (2007). The amount of desalinated water produced by different desalination processes per square meter of solar collector area required is given in Table 5. This shows that the small-scale simple solar still is the least efficient at 4-5 L/day/m^2. The cost of a polycrystalline silicon PV cells unit surface is 5 to 6 times more expensive than that of solar thermal collector surface used for other processes (Mahmoudi *et al*., 2009b; Ghaffour, 2009) (Table 5). Therefore we can argue that this is one drawback to scale up of PV systems.

VARI-RO direct drive technologies (Childs and Dabiri, 2000; Childs *et al*. 1999) and solar powered Rankine cycle (Garcia- Rodriguez and Blanco-Galvez, 2007) have been proposed for producing shaft energy from solar thermal energy to drive RO pumps for improving the efficiency of complete process. Efficiencies of 24% and 30% have been achieved with monocrystalline and polycrystalline silicon and Gallium Arsenide (GaAs) and its alloys, respectively (Subiela *et al*., 2007; Garcia-Rodriguez, 2002).

Ghaffour *et al.* (2011) in a review of 17 solar desalination projects sponsored by MEDRC (Middle East Desalination Research Center) reported that the success in implementing solar technologies in desalination at a commercial scale depends on improvements to convert solar energy into electrical and/or thermal energies economically. They argued that the wider use of solar technologies in desalination will eventually increase the demand on these technologies, making it possible to go for mass production of photovoltaic (PV) cells, collectors and solar thermal power plants. This, along with improvements in efficiency, would ultimately lead to a reduction in the costs of these technologies. For example, organic dye based solar cells are being researched along with incorporation of nanotubes in solar PV cells for better transport efficiency of photons to the collector surface (Green *et al*., 2012; Law *et al*., 2005; Mayer *et al*., 2007). These new advancements are expected to enhance the efficiency of solar PV cells, which currently have less than 15% efficiency. For example, multijunction cells with efficiencies of over 40% have been reported by Green *et al*., (2012). In a related review study, Ghermandi and Messalem (2009) investigated the current developments in the field of solar-powered RO desalination on the basis of the analysis of 79 experimental and design units worldwide. They concluded that PV powered RO desalination is mature for commercial implementation. Although no standard design approach has been developed, the technical feasibility of different design concepts was demonstrated in a relatively large number of case studies. Systems that directly couple the PV modules to variable speed DC pump motors seemed to have the highest potential for energy efficient and cost-effective small-scale PV–RO desalination. Some concern was expressed about the long-term performance and reliability of such systems.

A thorough analysis of the economic, regulatory and technical implications of large-scale solar power deployment was made by Merrick (2010). He reported that despite its current high cost relative to other technology options, a combination of costs reductions and policy support measures could lead to increasing use and application of solar power technologies. He noted that concern about climate change is a potential reason why large-scale solar power deployment may occur. Development of the renewable energy sector has the potential to create new industries and associated jobs. If large-scale transformation of the world’s electricity systems is to happen, it will likely occur with a combination of renewable energy sources such as wind, wave, solar and geothermal. For large-scale solar power deployment to occur other factors will come into play; transmission infrastructure will be required, electrical energy will be in demand when the sun is not shining, power quality will need to be maintained, other forms of electricity generation will be displaced, and regulatory policies may help or hinder an efficient transformation.

Another important factor is efficient power management strategy (PMSs) for integrated stand-alone power systems. This was assessed by Ipsakis *et al*. (2009) on the ability of such systems to meet the power load requirements through effective utilization of the electrolyzer and fuel cell under variable renewable energy generation (i.e. solar and wind). The key bottle necks or decision factors in the power management strategies were found to be the level of the power provided by the renewable energy sources and the state of charge of the accumulator (i.e. storage system).

The potential of solar-driven humidification–dehumidification (HD) desalination for small-scale decentralized water production has been reviewed in detail by Narayan *et al.* (2010). It was found that among all HD systems, the multi-effect closed air open water (CAOW) water-heated system is the most energy efficient. For this system, the cost of water production was about US$ 3–7/m^3 (ven though this is higher than that for RO systems working at similarly small capacities (5–100 m^3/day), the HD system has advantages for small-scale decentralized water production. These advantages include much simpler brine pre-treatment and disposal requirements and simplified operation and maintenance. However, it remains to be seen whether or not HD systems can be scalled-up successfully.

Concentrated solar power (CSP) is one of the more promising renewable energy technologies. Viebahn et al., (2011) argued that in order to assess the sustainability and scale-up of this technology, an overall or integrated view is necessary: what are the drivers of CSP? Why should CSP be brought forward as soon as possible? Which individual technologies within CSP could develop in the long term? How much capacity could be installed and how much electricity could be generated over the next decades, at what economic and ecological cost? The paper by Viebahn et al. (2011) attempted to answer some of these concerns. An integrated technology assessment showed that CSP plants could play a promising role in Africa and Europe, helping them to reach their climate protection goals.

One more key aspect in renewable energy implementation at large-scale is the footprint requirements. In a report by Denholm and Margolis (2008), the overall average per-capita solar PV electric footprint for the United States, defined as the land area required to supply all end-use electricity from solar PV, was found to be about 181 m^2 per person, with a state- and scenariodependant range going up to over 450 m^2 per person. This is a significant footprint constraint and it can be argued that existing utilities/plants may find it difficult to implement renewable energy resources due to the large footprint requirement.

Desalination using renewable energy sources such as solar, geothermal, wind and wave consist essentially of a combination of two separate and distinct technologies: energy production and water desalination. The challenge lies in finding an optimal design for combining the two through a system-oriented approach (Mathioulakis et al, 2007). Although solar energy, for instance, is abundant and free, the hardware for using the energy economically, for capturing it in an efficient way, converting it to useful forms, and storing it is not free of charge (Gude and Nirmalakhandan, 2010). We can argue that it is not possible to reduce the cost of desalination using solar energy to a comparable range with conventional desalination at least in the near future. Currently, solar energy desalination will probably find only remote location applications where there is no electrical grid connection.

For indirect applications, additional equipment is required to convert renewable energy to thermal or shaft work or electrical energy. At the same time the conversion efficiencies are low (Gude and Nirmalakhandan, 2010). This contributes to the increase in the capital cost. Also, electrical power is subsidized in many countries where there is lack of freshwater, such as in the Arabian Gulf. Furthermore, solar and wind energies are not continuous sources of energy. But the operation of desalination processes for technical and economic reasons require continuous operation. This necessitates additional equipment to store thermal and electrical energy generated by, for example, solar and wind energies which contributes to an increase in the investment cost of desalination and water treatment plants. Presently, high temperature solar collector systems offer the lowest-cost solar electricity for large-scale power generation; 10 megawatt-electric and above. They cost about $2–3 per watt, which results in a cost of solar power of US$ 0.1–0.20 per kWh. Hybrid systems that combine large concentrating solar power plants with natural gas combined cycle or coal plants can reduce costs to US$ 1.5 per watt and reduce the cost of solar power to below US$ 0.08 per kWh.

The combination of solar power with additional power sources, as noted by Ghermandi and Messalem (2009), may be beneficial both in small and large-scale desalination. In small-scale systems, PV panels may combine favorably with wind turbines, achieving lower overall costs where the complementary aspects of the two renewable sources can be exploited. In large-scale systems, CSP and fuel co-firing of desalination plants can help to bestow stability on desalination unit operation during night-time or periods of low sunshine. In both small and large-scale systems, connection to the electrical grid for combined power and water generation will promote stable operation of the system. Ghermandi and Messalem (2009) concluded that state-of-the-art solar-RO desalination is cost-competitive with other water supply sources only in context of remote regions.

Delucchi and Jacobson (2011) estimated conventional electricity transmission costs (Table 6). They reported that the more that the dispersed wind and solar generating sites were interconnected, the less the variability in output of the whole connected scheme. A system of interconnections between widely dispersed generators and load centers has been called a ‘‘supergrid.’’ The configuration and length of transmission lines in a supergrid will depend on the balance between the cost of adding more transmission lines and the benefit of reducing system output variability as a result of connecting more dispersed generation sites. The optimal transmission length in a supergrid is unknown. Delucchi and Jacobson (2011) speculated that the average transmission distances from generators to load centers in a supergrid will be longer than the average transmission distance in current systems. They noted that the cost of this additional transmission distance is an added cost of ensuring that wind, wave and solar power generation always matches demand.

In a related case study, Palermo (2009) conducted a net present value analysis of installing a solar power generation system on turkey ranches in California in the USA. The research although not directly connected to desalination does provide useful information regarding a solar system’s power production capacity, investment cost, maintenance requirements, amount of energy saved, useful life of equipment, and tax incentives for a company. The investment cost of the system included the price of the equipment and installation service. He noted that many of the system costs may be offset by rebates, tax credits and grants from various government agencies. These must also be included in the financial analysis as they can greatly affect the financial viability of the project. The system was projected to have a useful life of 30 years. Palermo (2009) commented that the use of solar energy also gave the company an advantage over the competition when used as a marketing tool due to the use of green technology. It was recommended that future research should focus on emerging technologies, enhanced rebate opportunities and evaluating different sized systems.

DeCanio and Fremstad (2011) reasoned that solar power is the ultimate technology for energy supply because of its abundance, even though currently it is one of the more expensive of the alternate energy sources. Table 7 gives a range of estimates of the cost of electricity from a variety of studies. The highest average value is from solar PV at 491 $/MWh (see bottom of

Table 7). DeCanio and Fremstad (2011) noted that there is every expectation that solar costs will decrease over time with research and experience. Water desalination cost literature has also been reviewed and assessed by Karagiannis and Soldatos (2008). They reported that desalination cost has decreased over the last years due to technical improvements in a world of increasing fossil fuel prices. For conventional systems the relative cost for seawater desalination ranged from $0.6/m^3 to more than $4/m^3, depending on the capacity of the plant, while for brackish water desalination the cost was almost half, due presumably to lower salt concentrations in the feed water, materials used, size of the installation, and cost of the membranes. When renewable energy sources were used the cost was much higher, and in some cases could even reach $20/m^3, due to expensive energy supply systems. However, Karagiannis and Soldatos (2008) argued that this cost is counter balanced by the environmental benefits.

In an excellent study, Papapetrou *et al.*, (2010) described a roadmap for the development of desalination powered by renewable energy (Table 8). The project called Promotion of Renewable Energy for Water production through Desalination (ProDes) brought together 14 leading European organisations in order to support the market development of renewable energy desalination in Southern Europe. The roadmap was developed within the ProDes project (Prodes, 2010) with input from various key actors from industry and academia. This roadmap was intended to assist in coordinating and guiding the renewable energy-desalination community in overcoming the barriers they are currently facing. The study identified the main targets, and the resources and activities required to follow-up on strategies in the technological, economical, and institutional and social areas (Table 8). The key recommendations were to formalise the renewable energy (RE) desalination community into a body that would represent the sector and would lobby for its interests. This body was mentioned as the "RE–Desalination Association" and the target was to have it established before 2012 and to include at least 20 members. The other activities identified as priorities included: target a 3–5 % share of the new installations in the global desalination market by 2016; define the R&D priorities that will benefit the entire sector and promote these priorities to bodies that fund R&D, targeting R&D worth more than 100 million Euro in the period 2014 to 2020; support the wider establishment of RE–desalination education and training activities with the aim of reaching 2,000 students and 500 professionals per year within Europe by 2015; coordinate the development of a comprehensive market analysis on a country by country basis, covering the four most promising markets by 2014; develop and promote appropriate legal structures and policies on a country by country basis, starting with the four most promising markets by 2015; and finally raise awareness about the technology and demonstrate its market potential

Market Potential, Process Selection and Risk Managment

Ghermandi and Messalem (2009) addressed market concerns by providing an extensive assessment of the experience gathered from solar-powered reverse osmosis (RO) desalination. The prospects for commercial penetration and for further development of the principal technological solutions were identified and discussed. They concluded that concentrating solar power (CSP) and RO desalination are the most promising fields of development for medium and large-scale solar desalination. Ghermandi and Messalem (2009) went on to report that solar RO desalination is cost-competitive with other water supply sources only in remote regions where grid electricity is not available and freshwater demand is met by water imports or small-scale fuel-driven desalination plants. In this market, the share of PV–RO and hybrid PV–RO desalination plants will likely increase in the near future. They noted that an infiltration of solar RO desalination in other markets seems unlikely in the short-term. According to the authors, the rapid advancement of both CSP and PV solar technologies offers the best outlook for the wider implementation of these potentially sustainable water supply technologies.

Three international desalination markets have been studied for export opportunities for European Union (EU) technology developers (Ghermandi and Messalem, 2009; Prodes 2010; Papapetrou et al., 2010) (Table 8). The markets analysed were the Middle East and North Africa (MENA) region, with a profile on Morocco; the Oceania region, with a profile on Australia; and South Africa. Each report provided details on the economic and governmental structures, the power sector, renewable energy legislation, the water sector, recent investment and a summary of the renewable desalination market potential. The results of the Prodes project in particular indicated a lack of comprehensive market analysis as to the size, locations and segments of the market (Prodes 2010). This makes it difficult to assess the risk and investors are reluctant to invest. It was recommended that a more detailed and reliable market analysis was required (Table 8).

Oceania is a very diverse region containing highly developed countries such as Australia as well as the less developed Pacific Island nations (Ghermandi and Messalem, 2009). There is a high demand for desalination projects in the region which is supported politically due to concerns regarding the impact of climate change (Prodes 2010). A consequence of this political support is that there are a large number of sources of potential funding for renewable energy desalination projects, which are in many cases supported by the government. In South Africa, on the other hand, there is at present less enthusiasm for renewable energy desalination projects due to the perceived high project costs (Prodes 2011). In addition, the region suffers from a significant shortage of skilled personnel, at both the technical and managerial levels, which creates challenges for the successful completion of new projects. As a final point, the MENA contains many states where the cultural and political systems are very different from those in Europe. This can generate trouble when trying to initiate renewable energy desalination projects in the region (Prodes 2011). Furthermore, many countries in the area have vast reserves of oil and gas and are currently heavily dependent on this energy source. This means that in many countries there is limited support for renewable energy and research in this area is underfunded. The MENA region, though, has large renewable energy resources, primarily solar and wind energy that could be exploited to power desalination projects. Consequently, the region is ideally suited for the development of renewable energy desalination projects where there is political will.

Delucchi and Jacobson (2011) reported on the feasibility of providing all energy for all purposes in all regions of the world using wind, water and solar (WWS) power. They concluded that a large-scale wind, water, and solar energy system can reliably supply all of the world’s energy needs, with significant benefit to climate, air quality, water quality, ecological systems, and energy security, at reasonable cost. To accomplish this, about 4 million 5-MW wind turbines, 90 thousand 300-MW solar PV plus CSP plants, 1.9 billion 3 kW solar PV rooftop systems, and lesser amounts of geothermal, tidal, wave, and hydroelectric plants are required. Delucchi and Jacobson (2011) went on to conclude that the private cost of generating electricity from onshore wind power is less than the private cost of conventional, fossil-fuel generation, and is likely to be even lower in the future. The world's wind resources are huge. But as wind becomes a larger fraction of electricity generation, grid integration must be resolved, particularly to smooth fluctuations in wind power output. Adding energy storage or back-up has been proposed as a solution by Kempton and Dhanju (2006) but dedicated storage or back-up adds capital cost to wind power. Their article proposes vehicle-to-grid power (V2G) as a storage resource for large-scale wind power (Figure16).

Kempton and Dhanju (2006) explained that the complete transformation of the energy sector would not be the first large-scale project undertaken in US or world history. During World War II, the US transformed motor vehicle production facilities to produce over 300,000 aircraft, and the rest of the world was able to produce an additional 486,000 aircraft. To improve the efficiency and reliability of a wind, water and solar (WWS) power infrastructure, advance planning is needed. Ideally, good renewable energy sites would be identified in advance and sites would be developed simultaneously with an updated interconnected transmission system. The obstacles to realizing this transformation of the energy sector are primarily social and political, not technological.

When considering which renewable energy desalination system to select, stand-alone electric generation hybrid systems are generally more suitable than systems that only have one energy source for the supply of electricity to off-grid applications, especially in remote areas with difficult access. However, the design, control, and optimization of hybrid systems are usually very complex tasks. Bernal-Agustin and Dufo-Lopez, (2009) in a thorough review of the literature determined that the most common systems are those consisting of a PV generator and/or wind turbines and/or diesel generator, with energy storage in lead-acid batteries. Bernal-

Agustin and Dufo-Lopez, (2009) argued that energy storage in hydrogen, although technically viable, has a drawback in terms of its low efficiency in the electricity–hydrogen–electricity conversion process. Economically it cannot compete with battery storage at the present time.

Reif (2008) performed a profitability analysis and risk management of geothermal projects being implemented in Bavaria Germany. Reif's study concluded that the sensitive response of the project‘s rate of return to changes in the parameters of their computer simulations made it clear that geothermal projects are financially risky. For instance, every project faced the usual business risks, such as budget over-runs, increases in interest rates, and delays. Project management was used to limit these risks. It was recommended that the initiators of a plan must run profitability simulations in order to analyze varying scenarios before implementing the project. Results need to be updated as a project progresses. Reif (2008) argued that reserves must always be planned for in the financing. In addition, business risks could also be limited by suitable structuring of the contracts with the partners in the project (e.g. drilling companies, power-plant supplier, and civil-engineering companies).

Lerner *et al.* (2009) in assessing risks discussed how and why accurate wind forecasting is a necessary ingredient for the continued growth and penetration of wind power on a global scale. They noted the critical need for proper collaboration in planning the distribution and size of wind projects, and the electricity transmission grid from the municipal to international scale. Site characteristics such as accessibility during construction, the distance to transmission and load can determine if a site is ideal for development. Project location is therefore the single most important, controllable factor in determining the economic viability of a wind energy project. Lerner *et al.* (2009) recommended that computer simulations of the dynamics of the atmosphere (e.g. numerical weather prediction models or NWP) can also provide vital information on the wind resources at a site.

Promotion of Renewable Energy Policy and Reduction in Reliance on Conventional Power Generation

Frondel *et al*. (2010) critically reviewed the centerpiece of a government sponsorship of renewable energy projects in Germany called the Renewable Energy Sources Act (EEG); focusing on its costs and the associated implications for job creation and climate protection. Government sponsorship of renewable energy projects in this European country is often cited as a model to be imitated in other states, being based on energy and environmental laws that go back nearly two decades (Frondel *et al.*, 2010). Frondel *et al*. (2010) argued that German renewable energy policy has failed to harness the market incentives needed to ensure a viable and cost-effective introduction of renewable energies into the country’s energy portfolio. They went on to explain that the government’s support mechanisms have in many respects underminded and subverted market incentives, resulting in massive expenditures that show little long-term promise for stimulating the economy, protecting the environment, or increasing energy security.

On the positive side, Germany has more than doubled its renewable electricity production since 2000 and has already significantly exceeded its minimum target of 12.5% for renewable energy usage (i.e. wind, biomass and others in Figure17) as a percentage of total energy usage set for 2010. This increase came at the expense of conventional electricity production, whereby nuclear power experienced the largest relative loss between 2000 and 2008 dropping from 30.2%

to 23.3%, respectively. Currently, wind power is the most important of the supported renewable energy technologies: In 2008, the estimated share of wind power in Germany's electricity production amounted to 6.3% (Figure17), followed by biomass-based electricity generation and water power, whose shares were around 3.6% and 3.1%, respectively. In contrast, the amount of electricity produced through solar PV was negligible: Its share was as low as 0.6% in 2008.

In their article, Frondel *et al*. (2010) maintain that Germany's principal mechanism of supporting renewable technologies through feed-in tariffs (FIT), in fact, imposes high costs without any of the alleged positive impacts on emissions reductions, employment, energy security, or technological innovation. A feed-in tarrif is a policy mechanism designed to accelerate investment in renewable energy technologies. It achieves this by offering long-term contracts to renewable energy producers, typically based on the cost of generation of each different technology. Technologies like wind power, for instance, are awarded a lower per-kWh price, while technologies like solar-PV and tidal power are offered a higher price, reflecting their higher costs. Frondel *et al*. (2010) explained that it is most likely that whatever jobs are created by renewable energy promotion would vanish as soon as government support is terminated. Rather than promoting energy security, the need for backup power from fossil fuels means that renewables increase Germany's dependence on gas imports, most of which come from Russia. The system of feed-in tariffs may also stifle competition among renewable energy producers and may create unwanted incentives to force a company to lock into existing technologies.

As other European governments imitate Germany by enhancing their promotion of renewables, policy makers should scrutinize the logic of supporting energy sources that cannot compete in the market in the absence of government assistance. Nonetheless, government intervention can serve to support renewable energy technologies through other mechanisms that harness market incentives such as funding for research and development (R&D), which may compensate for under-investment from the private sector.

Consider now the controversy surrounding conventional energy production using for instance nuclear technology. The feasibility of integrated nuclear desalination plants has been proven with over 150 reactor-years of experience, chiefly in Kazakhstan, India and Japan (Kadyrzhanov *et al.*, 2007; Khamis, 2009; Misra, 2010; Stock Trading, 2010). However, Jacobson and Delucchi (2011) argued that nuclear energy should not be considered as a long-term global energy source. The growth of nuclear energy has historically increased the ability of nations to obtain or enrich uranium for nuclear weapons and a large-scale worldwide increase in nuclear energy facilities would aggravate this dilemma, putting the world at greater risk of a nuclear incident. The historic link between energy facilities and weapons is evidenced by the development or attempted development of weapons capabilities secretly in nuclear energy facilities in Pakistan, India (Federation of American Scientists, 2010), Iran (Adamantiades and Kessides, 2009), and North Korea. Kessides (2010) asserted that a vigorous global expansion of civilian nuclear power will significantly increase proliferation. Similarly, Miller and Sagan (2009) reported that some new entrants to nuclear power will probably emerge in the coming decades. In Japan, some ten desalination facilities linked to pressurised water reactors operating for electricity production have yielded 1000-3000 m^3/day each of potable water, and over 100 reactor-years of experience have accrued. However, the recent earthquake and tsunami catastrophe in Japan (i.e. 2011) and its effects on their nuclear reactors have shown the susceptibility of this technology and the need for better safeguards.

REGULATORY FACTORS, ENVIRONMENTAL CONCERNS AND GLOBALIZATION

Policy and Legal Considerations

Zang *et al.* (2009) discussed the opportunities and challenges for renewable energy policy in one of the most rapidly developing countries in the world, China (PRC). In 2005, the PRC Law of Renewable Energy was passed. Over the past three decades China's renewable energy policy has only been partially successful in allowing for the sustainable economic growth of the country. Zhang *et al.* (2009) recommended several areas for improvement: enhanced research and development with an emphasis on domestic manufacturing of renewable energy equipment; better development of process management to ensure that policies are fully implemented; and the need to set up a market investment and financing system that will allow for bank loans to entrepreneurs. They concluded that industrialized development of renewable energy is a longlasting and complicated process, which requires not only policy support from the state but also breakthroughs and development in techniques and markets; persistent support in terms of policy should be offered; continuous technology breakthroughs are needed, and markets need to be cultivated.

A recent European Union (EU) Commission proposal for promoting the supply of power from renewable energy sources was based on a pan-European, harmonised tradable green certificate (TGC) scheme. Jacobsson *et al.* (2009) reasoned, on the basis of a multi-disciplinary analysis, that a pan-EU TGC system is not the way forward for Europe. They noted that it is vital that the majority of member states avoid implementation of such policy designs put forward by a coalition of vested interests. Instead they should look at the available evidence and design policies that stand a better chance of meeting the criteria of effectiveness, efficiency and equity.

In particular Jacobsson *et al*. (2009) went on to explain that the policies must enable the EU to meet the innovation/industrialisation challenge. Only then can the ability to implement an industrial revolution in energy systems be developed in a way that meets the needs of the member countries. The EU major power companies cannot be expected to lead this revolution. In addition to an ambitious and imaginative energy efficiency policy, they argued that a renewables policy must be designed to open up and secure attractive investment conditions for entrepreneurs for a broad range of technologies. Jacobsson *et al*. (2009) noted that in a market economy, the prospect of economic rents is a necessary and appropriate incentive for encouraging entrepreneurship. Economic rents refer to the difference between the raw costs of everything needed to produce the goods or service and the price. However, rents should be channelled to risk taking innovators/ entrepreneurs and should not be confused with the excess profits captured by incumbents free-riding on badly designed regulations. Only in this way, will Europe have a chance of meeting the challenge of climate change and of ensuring an economically healthy industrialisation of new technologies. Jacobsson *et al*. (2009) concluded that a trading system must be designed in a way so that it does not lead to economic inefficiencies. They went on to explain that the challenge for policy is to design frameworks that allow for a full use of the resource base, acknowledge the institutional diversity in the EU and, most importantly, make it possible for the member states to address the innovation/industrialisation challenge.

The general conclusions reached by Jacobsson et al. (2009) where supported by another study reported by Papapetrou *et al.,* (2010) on the development of desalination powered by renewable energy. It was reported that there is a negative perception of desalination by the population (Prodes, 2010; Papapetrou *et al.,* 2010) (Table 8). Renewable energy desalination

(RE-D) is a new technology and is typically small-scale. This results in opposition of local communities to installation of RE-D. In addition the new technology is not commissioned because water authorities prefer familiar technologies and want to keep centralized control. The strategies for solving these problems, recommended by Papapetrou *et al*., (2010) included supporting the development and implementation of a long-term and consistent communication strategy by the renewable energy desalination community, and facilitating organization of seminars, debates and other events related to renewable energy desalination involving engineers and decision makers from large institutions responsible for water and energy in the target countries.

In a related study, Tonn *et al* (2010) explored the question: is it possible for the United States to meet its energy needs sustainably without fossil fuels and corn ethanol? It can be argued that energy is one of the most pressing policy issues facing the United States today. The authors presented a scenario depicting life in the United States in the year 2050. The scenario was designed to achieve energy sustainability: fossil fuels and corn ethanol were replaced by other sustainable and inexhaustible energy sources. The scenario described the disappearance of the suburbs, replaced by a mix of high density urban centers and low density eco-communities. A suite of advanced technologies and significant social changes underpinned the situation. Analysis of the energy implications inherent in the scenario suggested that total United States energy consumption would be around 100 quads in 2050, approximately the same as in the year 2010 despite a forecasted population increase of 130 million. A quad is a unit of energy equal to 10^{15} BTU, or 1.055×10^{18} joules (equivalent to 8 billion gallons of gasoline). The establishment of renewable energy portfolio standards or regulations in the U.S. has forced water utilities to implement renewable energy technologies. We can argue that the increased creation of such portfolios in the MENA (i.e. Middle East North Africa) region will result in better implementation of renewable energy resources.

Tonn *et al*. (2010) went on to develop a tool for constructing future energy portfolios. This tool was used to construct a US national energy portfolio for the year 2050 that is consistent with the situation offered above. The approach consisted of defining a 2050 base case; distilling the key energy-related assumptions from the scenario (Table 9); operationalizing the assumptions for input into the instrument; and iterating among assumptions to produce a national energy portfolio. They concluded that the scenario appears plausible. Technology currently exists to support the energy system transformation. Social trends and trends in the built environment also appear favorable with respect to the scenario. It does not assume a major, voluntary de-materialization of the economy or lifestyles. This and the renewable energy aspects of the state of affairs would appear to be publicly acceptable and affordable. The authors explained that supplementary examination is needed to more accurately establish monetary costs to society and to build a well-organized and evenhanded collection of policies to encourage this future vision.

In a related regulatory and policy area, Johnstone *et al*. (2010a, 2010b) examined the effect of environmental policies on technological innovation in the specific case of renewable energy. The analysis was conducted using patent data on a panel of 25 countries over the period 1978–2003. They found that public policy plays a significant role in determining patent applications. Different types of policy instruments were effective for different renewable energy sources. For example, broad-based policies, such as tradable energy certificates, were more likely to induce innovation on technologies that are close to competitive with fossil fuels. Johnstone *et al.*, (2010a, 2010b) argued that more targeted subsidies, such as feed-in tariffs, are needed to induce innovation on more costly energy technologies, such as solar power. There was a high growth in ocean energy patenting recently. However, there appeared to have been little growth in innovation levels in the area of geothermal and biomass/waste-to-energy since the 1970s. Empirical results generated by Johnstone *et al*., (2010a, 2010b) indicated that public policy has had a very significant influence on the development of new technologies in the area of renewable energy. The passage of the Kyoto Protocol, for example, had a positive and significant impact on patent activity with respect to wind and solar power, as well as renewable energy patents overall. In addition, public expenditures on research and development (R&D) have had a positive and significant effect on innovation with respect to wind and solar power in all of their models, as well as with geothermal and ocean sources in some of their models.

The Environment and Sustainability

As mentioned in the section on promotion of renewable energy policy and reduction in reliance on conventional power generation, government sponsorship of renewable energy projects in Germany is often menioned as a model to be imitated, being based on environmental laws (e.g. Renewable Energy Sources Act) that go back nearly twenty years (Frondel et al., 2010). Frondel et al. (2010) argued that the government’s support mechanisms have essentially failed as a result of massive expenditures that showed little long-term promise for stimulating the economy, protecting the environment, or increasing energy security. Frondel et al. (2010) explained that it is most likely that whatever jobs are created by renewable energy promotion would vanish as soon as government support is terminated. Rather than promoting energy security or sustainability, there is still the need for backup power from fossil fuels.

Desalination of sea and brackish water requires large quantities of energy which normally results in a significant environmental impact if fossil fuels are used (e.g. CO_2 and SO_2 emissions, thermal pollution of seawater). The operating cost of different desalination techniques is also very closely linked to the price of energy as noted in the section on cost efficiency. This makes the use of renewable energies associated with the growth of desalination technologies very attractive. Let us take a closer look at the environmental impacts that must be considered during utilization of geothermal resources as outlined by Fridleifsson *et al*. (2008), Kagel *et al*. (2005), Lund (2007) and Rybach (2007). These include emission of harmful gases, noise pollution, water use and quality, land use, and impact on natural phenomena, as well as on wildlife and vegetation. The environmental advantages of renewable energy can be seen when comparing, for instance, a coal-fired power plant to a geothermal power plant; the former produces about 25 times as much carbon dioxide (CO_2) and sulfur dioxide (SO_2) emissions per MWh (i.e. 994 kg vs. up to 40 kg for CO_2, 4.71 kg vs. up to 0.16 kg for SO_2, respectively) (Lund, 2007; Fridleifsson *et al*., 2008). However, in a geothermal power plant hydrogen sulfide (H_2S) also needs to be routinely treated and converted to elemental sulfur since about 0.08 kg H_2S may be produced per MWh electricity generated. We can argue that this is still much better than oil-fired power plants and natural gas fired plants which produce 814 kg and 550 kg of H_2S per MWh, respectively.

The ready availability of inexpensive oil and natural gas reserves in such areas of the world as the Arabian Gulf may reduce the need for using renewable energy for desalination. However, looking at this more closely we see that this is non-sustainable since fossil fuels are non-renewable, and with a continually growing population there is an ever increasing demand on the use of fossil fuels for desalination. Take Saudi Arabia as a specific example; in 2008 total petroleum (i.e. oil and gas) production was 10.8 million bbl/d with internal oil consumption at 2.4 million bbl/d (i.e. about 25% of the total production) (U. S. Energy Information Administration, 2010a, 2010b). Most of the internal consumption was used for electricity generation and water desalination. The population is expected to increase from 30 million in 2010 to approximately 100 million by 2050 (U.S. Census Bureau, 2004). It has been estimated that by then 50% of the fossil fuel production will be used internally in the country for seawater desalination in order to provide freshwater for the people. This will reduce the state's income, increase pollution and is clearly non-sustainable. There are also concerns about the resulting political instability which could arise due to these effects (Cristo and Kovalcik, 2008). A possible solution to the environmental and sustainability problems is the increased use of renewable energy as well as conventional nuclear energy sources for desalination (Fridleifsson *et al.*, 2008; Lund 2006, 2007; Stock Trading, 2010). However, the former has scale-up problems and the latter has serious safety concerns.

Delucchi and Jacobson (2011) explained that there is a need to eliminate subsidies for fossil-fuel energy systems or taxing fossil-fuel production and use to reflect the costs of environmental damage. An example of the latter is carbon taxes that represent the expected cost of climate change due to CO_2 emissions (Table 9). Regarding environmental damages, it is estimated that the external costs of air pollution and climate change from coal and natural-gas electricity generation in the US range from \$0.0019/kWh to \$0.12/kWh for 2005 emissions, and from \$0.01 to \$0.16/kWh for 2030 emissions (Table 10). Only the upper end of the 2005 range, which is driven by assumed high climate-change damages, can begin to compensate for the more than

$0.10/kWh higher current private cost of solar PVs and tidal power (Table 10). Assuming that it is politically not feasible to add to fossil-fuel generation carbon taxes that would more than double the price of electricity, eliminating subsidies and charging environmental damage taxes cannot by themselves make the currently most expensive wind, wave and solar energy options economical**.**

Hegedus and Luque (2011) assessed the achievements and challenges of solar electricity from photovoltaics (PV). They argued that there is sufficient land, raw materials, safety protocols, capital, technological knowledge and social support to allow PV to provide over 12% of the world's electrical needs by 2030. However, new ways of energy storage would need to be found. They noted that the present PV development has been made possible by public support, driven by public opinion, which has led to governments spending substantial money to subsidize PV. The authors predicted that PV will continue to grow at a fast pace towards the 12% goal by 2030. However, strong political support will be necessary. Hegedus and Luque (2011) claimed that the promise of significant growth in employment, due to raw materials processing, module manufacturing, installation, and non-PV system components, is becoming a major driving force behind that political support.

Sustainable Growth and Globalization

As has been discussed in this paper, desalination using conventional energy sources based on limited fossil fuels is non-sustainable. In addition, as outlined in the section on the environment and sustainability, there is the problem of water, soil and air pollution due to extensive industrialization and rapid global population growth (Misra, 2000). While energy for water desalination in resource rich countries is not a major concern, it is important to remember that the poorer developing world generally does not have energy resources, with extreme poverty still affecting the lives of one out of every five persons (Sharma, 2007). Perhaps, the development of inexpensive renewable energy technology based on solar, wind or wave energy may one day help to alleviate this problem. In addition, soil and water resources degradation from erosion, overuse and poor irrigation practices continue to harm agricultural lands and usable groundwater, jeopardizing production. Alamar and Murali (2009) noted that for sustainable development to be meaningful, over-consumption has to be brought under control. An increase in the use of renewable energy sources will partially help to achieve this goal by reducing reliance, for example, on limited fossil fuels.

To find an acceptable balance, Omer (2007) described the links between resources and productivity as well as indicators for sustainable consumption and production (Figure18). Sustainable development has three constituents: social, economic and environmental (Misra, 2000). The problem is that these are not always compatible. For example, burning coal in power plants will give lots of energy for industry (i.e. economic benefits). However, the power stations will increase environmental pollution which in turn increases human health problems. In addition, in a free market economy, the private-sector may not bother to conserve nature. For the sake of profit, it may destroy forests, overuse mineral resources, or pollute air and water. Related reports by Goosen *et al*., (2004, 2009a, 2009b) explained that a major concern is the location of a significant fraction of the world's desalination capacity in coastal areas of oil producing countries, such as in the Arabian Gulf (Al-Sajwani, 1998). What happens to the desalination capacity if the seawater becomes polluted or if there are regional wars?

Sustainability therefore requires a rare balance between three sets of goals (i.e. social, economic and environmental). One way to help achieve this balance is through education for sustainable development, including the use of renewable energy technology. This should be obligatory for all people (e.g. decision makers, students, industrial workers), as this represents the primary vehicle available for catalyzing cultural changes (Ferrer and Álvarez, 2003). Furthermore, in the case of companies, how do we make sustainability a commitment rather than just a compliance cost? Building sustainable firms and organisations requires a commitment to people's development.

Finally, in developing countries, diseases related to poor water quality and inappropriate wastewater disposal account for illness and loss of productivity equivalent to 2% of Gross Domestic Product (GDP) (UNDP, 2006). Inversely, poor countries which invest in having better access to water and supply and sanitation, have a better economy. The relationship between economic development, environmental management and human health is therefore a complicated process, affecting both the quality and sustainability of the society in which we live. There is a rising comprehension that there should be an increased use of renewable energy technology for industrial and domestic applications. This will aid in solving some of the major environmental and sustainability problems facing the developing as well as developed regions of the world.

SELECTING THE MOST SUITABLE TECHNOLOGY FOR CONVENTIONAL & EMERGING DESALINATION PROCESSES

What tools are available for helping to decide on which renewable energy systems are most suitable? A paper by Baños et al. (2011), presented a review of the current state of the art in computational optimization methods applied to renewable and sustainable energy, offering a clear vision of the latest research advances in this field. Their review of over 200 papers provided an overview of the latest research developments in the use of optimization algorithms for design, planning and control problems in the field of renewable and sustainable energy. One of their main conclusions was that the use of heuristic (e.g. trial and error) approaches, multi-objective optimization and parallel processing are promising research areas in the field of renewable and sustainable energy. In a related study, Bourouni *et al* (2011) in a recommended paper reported on a design and optimization of desalination RO plants driven by renewable energies. RO desalination units can be coupled with different types of renewable energy systems (Figure 15). The authors summarized several studies which were presented with various possible combinations (Table 2). They also reported on the corresponding costs (Table 3). The optimization of hybrid systems was done by using Genetic Algorithms similar to the work by Baños et al. (2011).

The program of Bourouni *et al* (2011) calculated the optimal configuration of the system after determining several possible combinations. This optimal configuration was described very precisely: the number and type of membranes in the RO installation, backup system, HP pumps, number and type of PV panels, number and type of turbines, number and type of batteries, different costs, and finally the number of running hours of each component in the system. The final goal was to minimize the total water cost (Capital cost plus Operational costs). Their model was validated using a case study of a PV/RO unit, installed in Ksar Ghilène a village in southern Tunisia by the Technological Institute of Canary Islands (ITC) in 2006. The case study results, based on the estimation of the value of kWh/m^3 water produced, recommended a wind/RO configuration. The development of a tool by Bourouni *et al* (2011) to integrate all parameters involved and compare between the possible scenarios is very important since it allows for the generation of several possible solutions for coupling small RO unit to renewable energy systems.

As argued earlier, Subramani et al. (2011) also concluded that while technology advances are important, economic and political factors are often critical to large-scale deployment of renewable energy. Innovative technologies such as forward osmosis and ion concentration polarization show promise but long-term operational data are lacking. In particular they noted that the selection of appropriate renewable energy resources depends on factors such as plant size, feed water salinity, plant location, availability of grid electricity, technical infrastructure, and the availability of local renewable energy resources, and storage options. In a similar study, Kalogirou (2005) reviewed a number of pilot systems erected in various parts of the world. Kalogirou (2005) maintained that the most popular combination of technologies is multiple effect boiling (MEB) with thermal collectors and RO with PV. PV is particularly good for small applications in sunny areas. For large units, wind energy was reported to be more attractive as it requires less space than solar collectors.

Bensebaa (2010) investigated the best options for thermal and PV based large scale solar power plants. To compete with traditional sources of power generation, he argued that solar technologies need to be able to provide electric power to respond to demand during peak hours. In spite of their high capital cost, adding energy storage was considered a better long term solution than hybrid solar systems for large scale power plants. This is in contrast to the results of Kaldellis *et al.* (2004) who favoured hybrid desalination plant configurations based on the available renewable energy sources (i.e. wind and solar) using an integrated cost-benefit analysis. In the case of Bensebaa (2010) a comparison between the two solar options was also provided that included energy storage. Although electricity storage is more expensive than thermal storage, PV power remains a competitive option. Operation and maintenance (O&M) expenses in the solar thermal plant were about ten times higher than PV, an important factor resulting in higher energy cost. Based on data from proven commercial technologies, the study showed that PV holds a slight advantage even when energy storage is included.

Bensebaa (2010) went on to explain that other factors that should also be considered when comparing different solar power options include land requirements; annual power efficiency and required distance between two parallel strings of module/trough to avoid shading; larger distances are required in the case of parabolic troughs to allow trucks to move freely for regular water cleaning. According to the author the greatest challenge with solar thermal is water requirement. A 50 MW plant for example requires around 850,000 m^3 of water annually (Hosseinia *et al*., 2005). There are very few areas in the world with high direct radiation that are also endowed with enough renewable water resources. On the other hand, solar thermal provides relatively better potential for green house gas (GHG) mitigation. When compared to coal and natural gas solar options allow significant GHG mitigation. Although CO_2 emission reduction is significant, Bensebaa (2010) found that its impact on the financial comparison between solar thermal and solar PV is minimal.

Forsberg (2009) discussed sustainability by combining nuclear, fossil, and renewable energy sources. The energy industries face two sustainability challenges: the need to avoid climate change and the need to replace traditional crude oil as the basis of the world's transportation system. Forsberg (2009) argued that fundamental changes in the world's energy system will be required to meet these challenges. This may require tight coupling of different energy sources (nuclear, fossil, and renewable) to produce liquid fuels for transportation, match electricity production to electricity demand, and meet other energy needs. This implies a shift in which different energy sources are integrated together (i.e. hybrid systems), rather than being considered separate entities that compete.

Eltawil *et al.* (2009) performed a review of renewable energy technologies integrated with desalination systems. They reported that in spite of intensive research worldwide, the actual penetration of renewable energy powered desalination installations is still low. See also Table 1 which shows that renewable energies have accounted for only 13% of the world's total energy production over the past 40 years (Moriarty and Honnery, 2009). The most mature technologies for renewable energy application in desalination are wind and PV driven membrane processes and direct and indirect solar distillation. Environmental issues are associated with brine concentrate disposal, energy consumption and associated greenhouse gas production. On the other hand, social issues may include the public acceptance of using recycled water for domestic dual-pipe systems, industrial and agricultural purposes.

The suitability of a given renewable energy source for powering a desalting process depends on both the requirements of such process and the form of energy that can be obtained from a given source. Different combinations between renewable energy sources and desalination technologies are possible (Figure 15). Furthermore, many low-density population areas require not only freshwater availability, but in most of the cases an electrical grid connection. For these regions Mathioulakis *et al.* (2007) noted that the real problem is the optimum economic design and evaluation of combined plants in order to be economically viable for remote or arid regions.

Conversion of renewable energies requires high investment cost. According to the authors, the technology is not yet mature enough to be exploited through large-scale applications.

Eltawil *et al.* (2009) and Mathioulakis *et al.* (2007) described that renewable energies and desalination plants are different technologies, which can be combined in various ways depending on several input parameters (Figure15, Table 11). Photovoltaic (PV) is considered a good solution for small applications in sunny areas. For larger units, Mathioulakis *et al.* (2007) suggested that wind energy may be more attractive since it does not require much ground. This solution is often the best case for islands where flat ground is limited but there is a good wind source. In choosing the best system, the general tendency is to combine thermal energy technologies (i.e. solar thermal and geothermal energy) with thermal desalination processes and electromechanical energy technologies with desalination processes requiring mechanical or electrical power. The following combinations are commonly used: PV or wind-power with RO, ED or VC; and solar thermal or geothermal energy with distillations processes.

As a final example, Greenlee *et al*. (2009) reported that the unit operating cost for RO coupled with renewable energy is higher than for typical RO plants. Communities that would typically benefit from coupled renewable energy-RO systems are located in rural areas, where financial resources and system maintenance personnel are limited. They argued that factors including capital cost, sustainable technology, technical operation, social acceptance, and energy resource availability, have contributed to the slow growth of the renewable energy-RO market. This is similar to the results of Mathioulakis *et al*. (2007). While the basic operating principles remain the same for all RO applications, individualized applications have developed, based on feed water quality. The two key types of feed water, seawater and brackish water have unique features that require explicit parameter modification and system design. Seawater RO recovery is chiefly limited by osmotic pressure increase and organic material fouling; system design typically consists of chemical and filtration pretreatment and one RO stage. On the other hand, brackish water RO membrane systems characteristically consist of two RO stages in series; key issues include salt precipitation and concentrate management. While both seawater and brackish water RO have been sufficiently developed to be used in large scale commercial plants, several significant challenges to the RO field remain. Further improvements are needed in membrane technology, energy use, and concentrate treatment, which will allow a wider application of RO to inland and rural communities.

CONCLUDING REMARKS

Renewable energy technologies are rapidly emerging with the promise of economic and environmental viability for desalination. There is a need to accelerate the development and scale-up of novel water production systems from renewable energies. These technologies will help to minimize environmental problems. Our investigation has shown that even though there are concerns that government policy may undermine market incentives, there is great potential for the use of renewable energy in many parts of the world. Solar, wind, wave and geothermal sources can provide a viable source of energy to power both seawater and brackish water desalination plants.

Recent trends have show improvements in technical efficiency, which should ultimately help to reduce the costs of these technologies. The decreasing cost of renewable energy equipment, and experience from hybrid renewable energy desalination implementation are also driving the cost down. Photo voltaic (PV) panels, for example, have reduced in price in the last few years. At the same time, the cost of conventional water supplies is increasing, especially in isolated sites. Therefore renewable energy desalination is becoming competitive. One worrisome trend, noted in this study, is that renewable energy sources have consistently accounted for only 13% of the total energy use over the past 40 years.

When considering which renewable energy desalination system to select, stand-alone electric generation hybrid systems are generally more suitable than systems that only have one energy source for the supply of electricity to off-grid applications, especially in remote areas with difficult access. During the last few years, reverse osmosis has become the optimal choice in even larger units. Under special conditions hybrid systems such as solar and wind can offer increased and more stable production of freshwater. The utilization of conventional energy sources and desalination technologies, notably in conjunction with cogeneration plants, still appears to be more cost effective than solutions based on only renewable energies and, thus, is generally the first choice.

Major challenges identified in this study are the necessity to formalise the renewable energy desalination community into organizations that would represent the sector and would lobby for their interests; the need to target atleast a 5 % share of new installations in the global desalination market over the next decade; the requisite to support the wider establishment of renewable energy desalination education and training activities for students, professionals and decision makers including raising awareness about the technology, the environmental benefits and demonstrating its market potential; the responsibility to coordinate the development of a comprehensive market analysis on a country by country basis; and the need to develop and promote appropriate legal structures and policies on a regional basis.

In order to aid commercialization, different types of governmental policy instruments (e.g. tax breaks; low interest loans) can be effective for different renewable energy sources. However, broad-based policies, such as tradable energy certificates, are more likely to induce innovation on technologies that are close to competitive with fossil fuels. There is also a need to eliminate subsidies for fossil-fuel energy systems or taxing fossil-fuel production and use to reflect the costs of environmental damage. Another major barrier is that in some instances government renewable energy policy may undermine and subvert market incentives, resulting in massive expenditures that show little long-term promise for stimulating the economy, protecting the environment, or increasing energy security. It is possible that whatever jobs are created by renewable energy promotion may vanish as soon as government support is terminated.

In closing, the successful application of renewable technology requires an understanding of sustainable development which includes finding a balance between three sets of goals; social, economic and environmental. One way to help achieve this balance is to educate people as this represents the primary vehicle available for catalyzing cultural changes. This is critical for long term economic and social sustainability. This is the main challenge facing us.

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Table 1. Global primary energy use in exajoules (EJ), 1970-2006 (adapted from Moriarty and Honnery, 2009). In describing national or global energy budgets, it is common practice to use large-scale units based upon the joule; 1 EJ = 10^{18} J.

Energy source	**1970**	**1980**	**1990**	**2000**	**2006**
Fossil fuels					
Coal	64.2	75.7	93.7	98.2	129.4
Oil	94.4	124.6	136.2	148.9	162.9
Natural gas	38.1	54.9	75.0	91.8	107.8
Total Fossil fuels	***196.7***	***255.1***	***305.0***	***339.0***	***400.1***
Nuclear	0.7	6.7	19.0	24.5	26.6
Renewable	29.4	37.6	48.5	55.6	66.2
All energy	***216.8***	***299.5***	***372.4***	***419.0***	***492.9***
Renewable (%)	***13.6***	***12.6***	***13.0***	***13.3***	***13.4***

Table 2. Coupling of Renewable Energy Systems with Reverse Osmosis Desalination (adapted from Bourouni *et al*., 2011; Peñate *et al.*, 2012a)

	REFERENCE	STAND-ALONE SYSTEMS									NON STAND-ALONE SYSTEMS			
		Simple without batteries COUPLING			Simple with batteries			Hybrid						
		PV/RO	Wind/RO	Diesel/RO	PV/Batteries/RO	Wind/Batteries/RO	PV/Diesel/RO	PV/Wind/Diesel/RO	PV/Wind/Batteries/RO	PV/Grid/RO	Wind/Grid/RO	PV/Wind/Grid/RO	PV/Wind/Diesel/RO	PV/Wind/Diesel/Grid/RO
EXPERIMENTAL	Joyce et al.(2001)	■												
	Thomson (2003)	■												
	Pestana et al.(2004)		■											
	Carta et al. (2003)		■											
	Koklas & Papathanassiou (2006)		■											
	Liu et al. (2002)		■											
	Miranda (2003)		■											
	Masson et al. (2005)				■									
	Abdallah et al. (2005)				■									
	Sardi & Beer (1996)				■									

	Maurel (1991)				■								
	Kehal (1991)				■								
	Tzen & Morris (2003)					■							
	Weiner et al. (2001)							■					
	Kershman et al. (2002)										■		
	Peñate *et al.*, 2012a	■	■						■	■	■		
MODELING & DESIGN	Helal et al.(2008)	■		■			■						
	Thomson (2003)	■											
	Tzen et al. (1998)				■								
	Voivontas et al. (2001)				■	■		■	■	■			
	Setiawan et al. (2009)							■	■				
	Tzen et al. (2004)									■			
	Mohamed & Papadakis (2004)									■			
	Hochnut (1997)											■	
	Rheinlander et al. (2003)												■

Table 3. Water cost for desalination by Renewable Energies (adapted from Bourouni *et al*., 2011; Papapetrou et al., 2010)

Combination	**Water**	**Plant Capacity (m^3/d)**	**Water Cost (US$/$m^3$)**	**Reference**
PV/BAT/RO	Seawater	12	27	Sardi & Beer (1996)
	Seawater	120	7.4	
	Brackish	250	6.7	Maurel (1991)
PV/RO	Seawater	1.5	2.95	Thomson (2003)
	Seawater	< 100	12-16	Papapetrou et al. 2010
	Brackish	< 100	7-9	
WIND/BAT/RO	Brackish r	250	2.7	Tzen & Morris (2003)
WIND/GRID/RO	Seawater	300	1.8	Kershman et al. (2002)
WIND/RO	Brackish	< 100	4-7	Papapetrou et al. 2010
	Seawater	< 100	7-9	
	Seawater	1,000	2-5	
PV/GRID/RO	Seawater	300	1.9	Kershman et al. (2002

Table 4. Energy consumption (using waste heat in thermal processes) in large desalination processes. (Mahmoudi *et al*., 2009b; Ghaffour, 2009).

Process	**Thermal energy** (kWh/m^3)	**Electrical energy** (kWh/m^3)	**Total energy** (kWh/m^3)	**Product water quality** (ppm)
MSF	7.5 - 12	2.5 – 3.5	10 – 15.5	5 - 30
MED	4 - 8	1.5 - 3	5.5 - 11	
SWRO	-	3 - 6	3 - 6	100 - 500
BWRO	-	0.5 – 2.5	0.5 – 2.5	

Table 5. Productivity of different desalination processes per square meter of solar collector area (Childs and Dabiri, 2000; Childs *et al*., 1999).

Desalination process	**Water produced per solar collector surface area** (L/day/m^2)
Simple solar still	4-5
H/D process–Medium T solar thermal collector	12
MSF, MED with thermal storage – Medium T solar thermal collector	40
SWRO-PV	200
VARI-RO DDE – Dish Sterling solar collector (Only in concept stage)	1200

Table 6. Approximate fully annualized generation and conventional transmission costs for wind, wave and solar power (adapted from Delucchi and Jacobson, 2011).

Energy technology	**Annualized cost (2007 $/kWh-delivered)**	
	Present (2005–2010)	Future (2020+)
Wind onshore	$0.04–0.07	≤ $0.04
Wind offshore	$0.10–0.17	$0.08–0.13
Wave	≥$0.11	$0.04
Geothermal	$0.04–0.07	$0.04–0.07
Hydroelectric	$0.04	$0.04
Concentrated solar power (CSP)	$0.11–0.15	$0.08
Solar photovoltaic (PV)	>$0.20	$0.10
Tidal	>$0.11	$0.05–0.07
Conventional (mainlyfossil) generation in US	$0.07	$0.08

Table 7. Estimates of Levelized Cost ($/MWh) of Electricity by Source (adapted from DeCanio and Fremstad, 2011).

Study Reference	**Measure**	**Coal**	**Nuclear**	**Wind**	**Geo-thermal**	**Solar PV**	**Solar Thermal**
U.S. Energy Information Administration, 2010a, 2010b	$2008 per MWh, 2016	100.4	119	149.3	115.7	396.1	265.6
RETI Stakeholder Steering Committee, 2010	Levelized cost ranges in $/MWh			90-130	100-160	250-350	240-290
Lazard ltd., 2009	Levelized cost ranges in $/MWh	78-144	107-138	84-140	85-120	212-296	199-325
Borenstein, 2008	$/MWh, annual real interest rate from 1-7%					337-565	
Renewables 2010 Global Status Report	Typical energy cost, $/MWh			50-90 (Onshore) 100-140 (Offshore)			
Benson and	$/MWh	43		75		280	200

Orr, 2008	(2007$)						
Greenpeace Int., SolarPACES, and ESTELA,2010	$/MWh at sites with very good solar radiation						150
IEA/NEA 2005	$/MWH, see IEA/NEA 2010 for details	28-75 (pulverized)	33-74	50-156 (Onshore) 71-134 (Offshore)		226-2031	292
European Commission 2008	$/MWh, see IEA/NEA 2010 for details	52-65 (pulverized)	65-110	97-142 (Onshore) 110-181 (Offshore)		674-1140	220-324
EPRI 2008	$/MWh, see IEA/NEA 2010 for details	64 (pulverized)	73	91			175
IEA/NEA 2010	$/MWh	54-120 (r = 5%) 67-142 (r =	29-82 (r = 5%) 42-137 (r = 10%)	48-163 (onsh. r = 5%) 101-188 (offsh. r=10%)		215-333 (high load) 600 (low load)	136-243

		10%)					
Average	**$/MWh**	**79**	**84**	**112**	**99**	**491**	**225**

Table 8. The main barriers, their effects and the way forward in the development of desalination powered by renewable energy (adapted from Papapetrou *et al.,* 2010).

BARRIER	EFFECT	STRATEGY
TECHNOLOGICAL		
Most RE-D[1] are not developed as a single system but are combinations of components developed independently	→ Poor reliability → Increased water cost	• Promote cooperation between companies from the energy sector, water sector and other specialists to achieve fully functional integrated products • Promote cooperation within the RE - desalination field for achieving R&D results that will benefit the whole sector • Support development of standardized, reliable and robust systems offering competitive performance guarantees
Desalination development focuses on ever larger systems	→ Lack of components appropriate for small scale desalination plants, typical of many RE -D combinations	• R&D of components suitable for the smooth and efficient coupling of the existing desalination and renewable energy technologies • Support development of elements that will make RE -desalination robust for long stand-alone operation in harsh environments
Current desalination technology has been designed for use with a constant	→ Increased capital and maintenance costs	• Support development of components and control systems that allow desalination technologies to deal better with variable energy input, hybrid systems and energy

energy supply, however most RE provide variable energy supply		storage to reduce variability • Support development of co-generation systems that produce water and power
ECONOMICAL		
Lack of comprehensive market analysis as to the size, locations and segments of the market	→ It is difficult to assess the risk and investors are reluctant to invest	• Support development of detailed and reliable market analysis
SME s lack the financial resources and local know-how to enter distant markets	→ Difficulty to access some of the most promising niche markets	• Cooperation with agencies from EU countries in the target markets for organising trade missions • Facilitate collection and dissemination of relevant experiences and information in the RE -desalination community
The pricing structures and the subsidies of water supply create unfair competition	→ Investment in RE -D remains unprofitable even where it offers better value than the current solutions	• Promote pricing structures and subsidy allocations that let the market choose the most efficient solution and encourage efficiency in the use of the water, while ensuring global access to safe water • Campaign for inclusion of RE for desalination in national schemes that support RE electricity generation
Lack of identified niche markets with the ability to pay for the full cost of the systems, which would demonstrate the technology	→ No cash is generated that could be used for further product development, reducing the costs and improving the	• Identify niche markets and use existing support programs in combination with financing schemes to help users that are willing and able to pay for the technology

attracting additional customers	performance	
INSTITUTIONAL AND SOCIAL		
Negative perception of desalination by the population	→ Opposition of local communities to installation	• Support development and implementation of a long-term and consistent communication strategy by the RE –desalination community
RE-D is a new technology and is typically small-scale, suitable for community-led water provision	→ RE-D is not commissioned because water authorities prefer familiar technologies and want to keep centralized control	• Facilitate organization of seminars, debates and other events related to RE -desalination involving engineers and decision makers from large institutions responsible for water and energy in the target countries
Bureaucratic structures not tailored for independent water production; separation of energy and water policies	→ The cost and effort required to deal with the bureaucracy does not favour small companies	• Promote simpler and straightforward processes to obtain a license for independent water production • Lobby for greater cooperation between the power and water branches in governmental and non-governmental institutions
Lack of training and infrastructure	→ Reduced plant availability → Lack of personnel for operation and maintenance	• Support education and training at all levels
Cultural gap between project developers and the end-users	→ Projects fail for non-technological reasons like	• Encourage adequate consideration of socio-cultural factors and establishment of communication channels with the end-users

conflict about control

RE-D[1] = renewable energy driven desalination

Table 9. Scenario design and supporting technological and social change assumptions. (Tonn *et al*., 2010).

Scenario Design Assumptions	**Technology and Social Change Assumptions**
Liquid Petroleum, Coal, Natural Gas production/ consumption in the US are eliminated by 2050.	Electricity transmission losses will decrease by 25% by 2050 due to advancements in high temperaturesuperconducting lines and smart grid designs.
By 2050, approximately 50% of the population will live in super-urban high density areas and 50% will live in low-density, semi-self sufficient areas.	Transportation energy efficiency will increase by 40% by 2050 due to more efficient vehicles, and reductions in trip demand and trip length due to life style and land use changes.
Transportation energy consumption by 2050 will be 70% electricity and 30% biofuels.	Energy consumption in the residential, commercial and industrial sectors will decrease by 25% by 2050 due to improvements in energy efficiency.
Energy consumed by the US petroleum industry will fall to zero by 2050.	Energy consumption in the pulp and paper sector will decrease by another 20% by 2050 due to decreased demands for paper and packaging
Nuclear power production to ~26 quads by 2050.	Energy consumption in the food sector will decrease by another 20% by 2050 due to more local production.
Wind power production to ~17 quads by 2050	Energy consumption in the commercial sector will decrease by another 20% by 2050 due to decrease

	need for commercial space
Geothermal power production to ~5 quads by 2050.	Energy consumption in the residential sector will decrease by another 20% by 2050 due to a decrease in the average size of homes and an increase in average household size (which will increase by 20%)
Solar power production to ~36 quads by 2050.	Requisite advances will be made in electric battery technologies, power storage technologies, and smart grid technologies.
Unconventional Hydro to ~3 quads by 2050.	
Increase in biofuels production, multiple sectors, to ~17 quads by 2050.	

Table 10. Environmental external costs of electricity generation in the US (year 2007 US cents/kWh).(adapted from Delucchi and Jacobson, 2011).

	Air pollution 2005			**Air pollution 2030**	**Climate change (2005/2030)**		
	5th%	Mean	95th %	Mean	Low	Mid	High
Coal	0.19	3.2	12.0	1.7	1.0/1.6	3.0/4.8	10/16
Natural gas	0.0	0.16	0.55	0.13	0.5/0.8	1.5/2.4	5.0/8.0
Wind, water and solar power	0.0	0.0	0.0	0.0	0	0	≈0

Table 11. Recommended renewable energy-desalination combinations (Mathioulakis *et al*., 2007).

Feed water quality	**Product water**	**RE resource available**	**System size**			**Suitable combination**
			Small (1-50 m^{3}d^{-1})	**Medium** (>50 m^{3}d^{-1})	**Large** (>>50 m^{3}d^{-1})	
Brackish water	Distillate	Solar	X			Solar distillation
	Potable	Solar	X			PV-RO
	Potable	Solar	X			PV-ED
	Potable	Wind	X	X		Wind-RO
	Potable	Wind	X	X		Wind-ED
Seawater	Distillate	Solar	X			Solar distillation
	Distillate	Solar		X	X	Solar thermal-MED
	Distillate	Solar			X	Solar thermal-MED
	Potable	Solar	X			PV-RO
	Potable	Solar	X			PV-ED
	Potable	Wind	X	X		Wind-RO
	Potable	Wind	X	X		Wind-ED
	Potable	Wind		X	X	Wind-MVC

Potable	Geothermal	X	X	Geothermal-MED
Potable	Geothermal		X	Geothermal-MED

PV= photovoltaic, RO= reverse osmosis, ED= electrodialysis, MED= multi effect distillation,
MVC= mechanical vapour compressor

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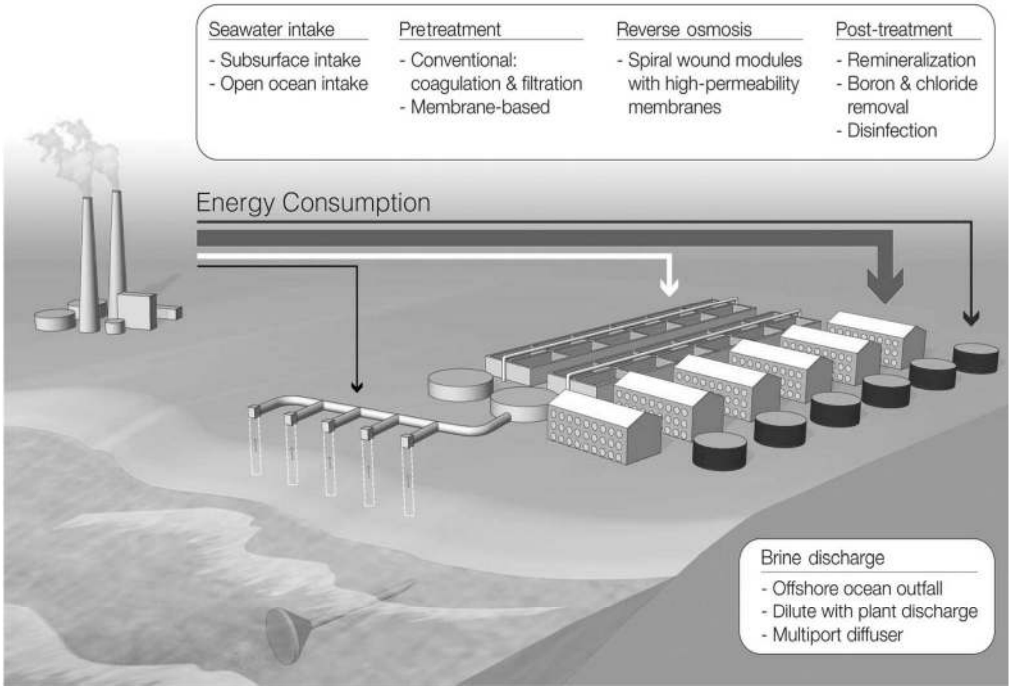

Figure 1. Energy consumption in a seawater reverse osmosis (SWRO) desalination plant. Conceptual drawing showing the various stages; seawater intake (lower black line), pretreatment (white line), reverse osmosis (thick dark grey line), post-treatment (upper black line), and brine discharge—and their interactions with the environment. The thickness of the arrows for the energy consumption represents the relative amount of energy consumed at the various stages (Elimelech & Philip, 2011).

Figure 2a. (Left) Wind Farm (Kalogirous, 2005); 2b (Right) Wind turbines and PV cells of Sureste SWRO plant (Sadhwani, 2008; IDA Conference, 2008).

Figure 3. The Kwinana Seawater Reverse Osmosis Desalination (SWRO) Plant and Wind Farm in Perth, Western Australia. 3a (*Upper Left*) The SWRO Plant seaside location in Pert; 3b (*Upper Right*) The Emu Downs Wind Farm consisting of 48 Vestas wind turbines each with 1.65 MW generating capacity; 3c (*Lower*) The desalination plant, with 12 SWRO trains with a capacity of 160 megalitres per day and six BWRO trains delivering a final product of 144 megalitres per day. (Pankratz, 2008).

Figure 4.. *LHS*: Jiangxia pilot tidal plant (Photo by Zhou Xuejun). *Middle*: The pendulum-type wave energy conversion device in Daguan Island (100 kW, 2000, NOTC). *RHS*:2 kW device for surface tidal current (2009, NENU) (Wang et al., 2011)

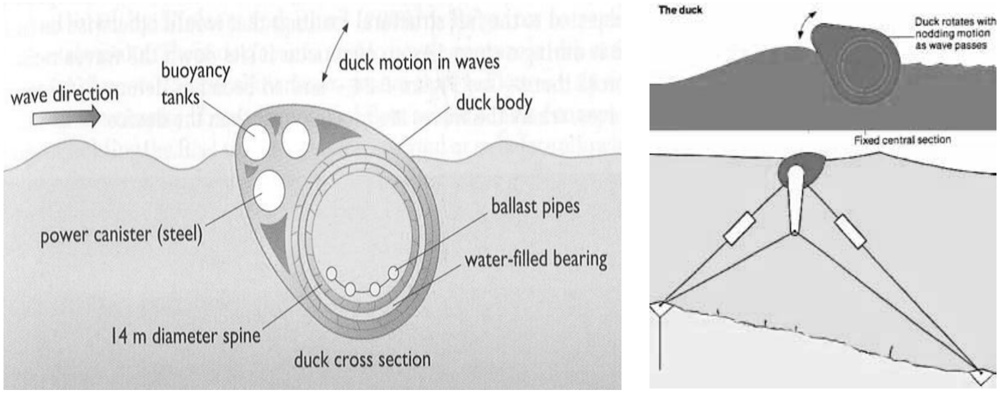

Figure 5. The wave device incorporates an electricity generating system based on a pendulum connected to a generator (RHS). Flowing water (i.e. ocean wave) is converted to mechanical energy which causes a generator to rotate producing electricity As the Salter Duck "bobs" up and down on the waves, the pendulum swings forwards and backwards generating electricity. (Thorpe, 1999).

Figure 6. Wave Energy. The Aquabuoy 2.0 is a large 3 meter wide buoy tied to a 70-foot-long shaft. By bobbing up and down, the water is rushed into an acceleration tube, which in turn causes a piston to move. This moving of the piston causes a steel reinforced rubber hose to stretch, making it act as a pump. The water is then pumped into a turbine which in turns powers a generator. The electricity generated is brought to shore via a standard submarine cable. The system is modular, which means that it can be expanded as necessary (Chapa, 2007).

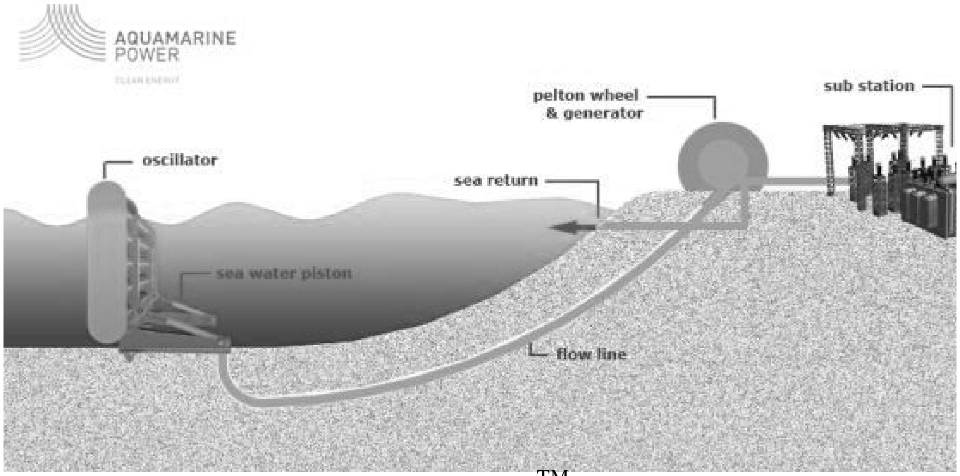

Figure 7. General arrangements of Oyster^{TM} Whittaker *et al.* (2007).

Figure 8. The Seawater Greenhouse at Al-Hail, Muscat, Oman (Mahmoudi *et al*., 2008; Sablani *et al*., 2003; Paton & Davies, 1996; Davies & Paton, 2005).

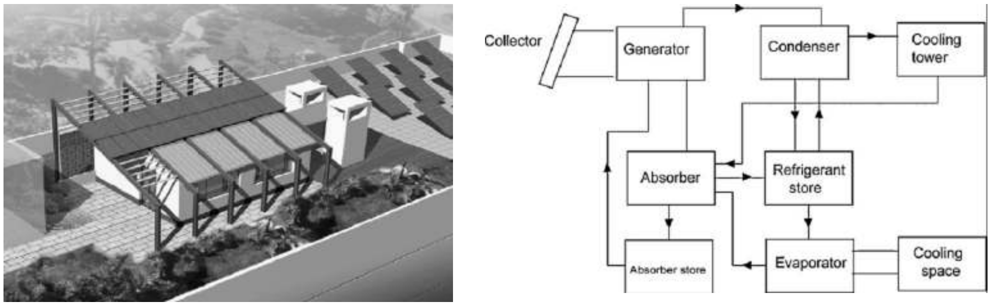

Figure 9. LHS Solar air conditioning system installed on the rooftop of a building located in China (Li *et al*., 2007; Mekhilef *et al*., 2011). RHS Block diagram of a typical solar cooling system with refrigerant storage (Sumathy *et al*., 2003; Mekhilef *et al*., 2011).

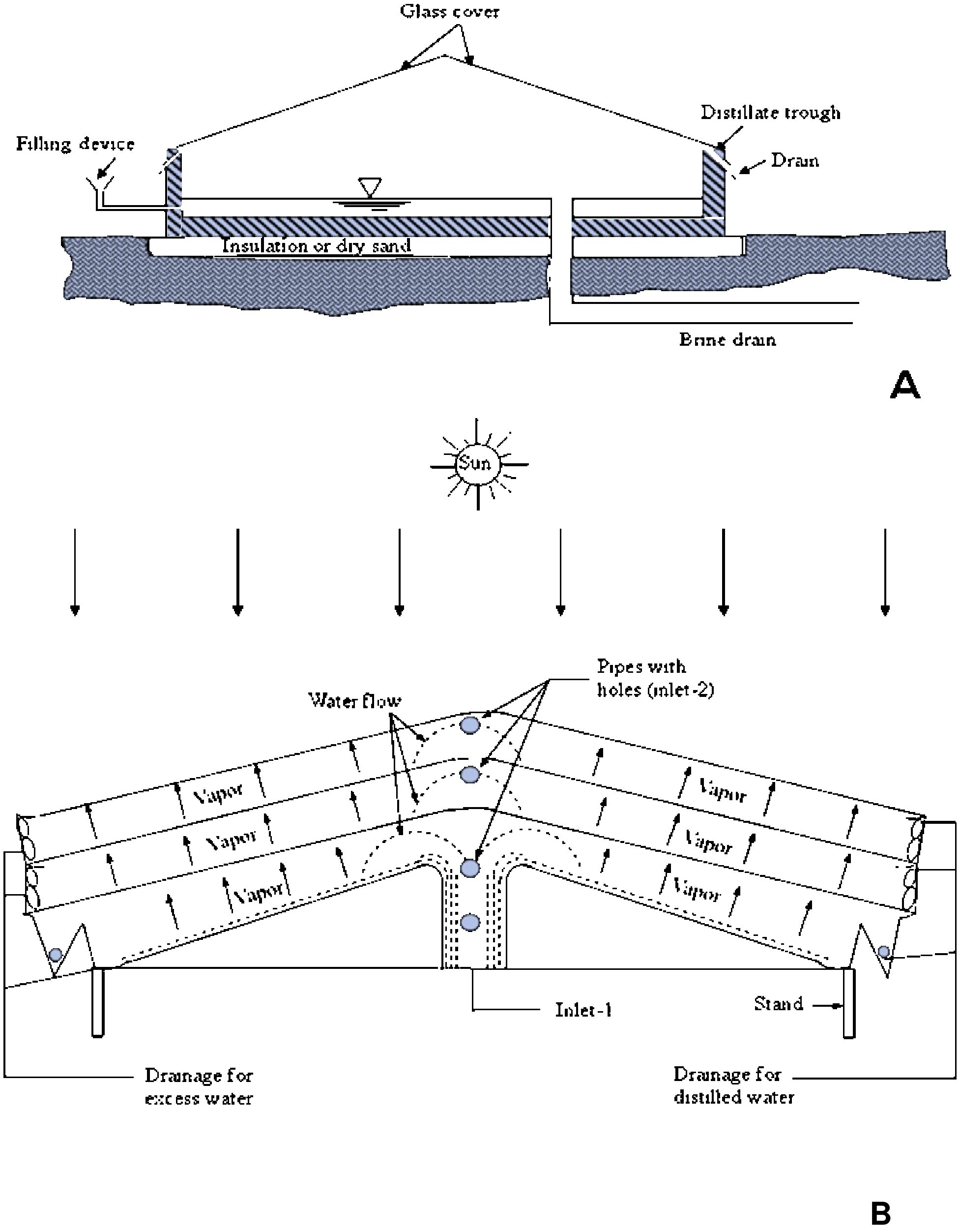

Figure 10. Solar desalination systems (Goosen *et al*., 2000; adapted from Fath, 1998). A. Single-effect basin still. B. Typical multi-effect multi-wick solar still.

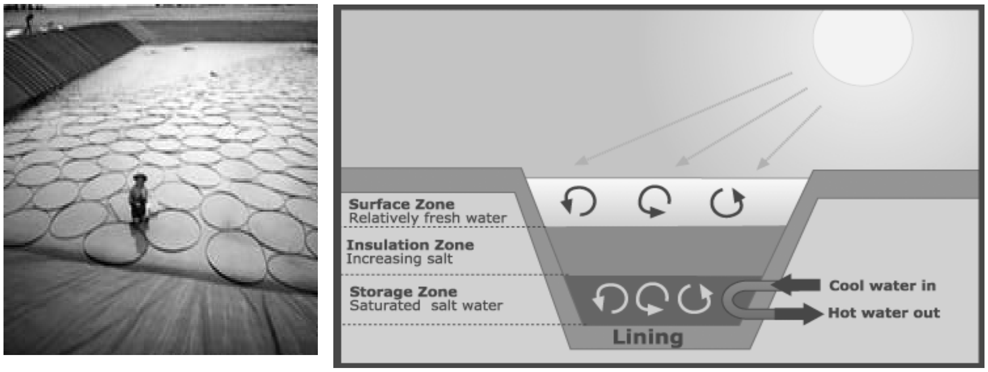

Figure 11a. (*Left*) Solar pond for heating purpose demonstration in Australia (http://www.aph.gov.au/library/pubs/bn/sci/RenewableEnergy_4.jpg). 11b. (*Right*) Solar Ponds Schematic The salt content of the pond increases from top to bottom. Water in the storage zone is extremely salty. As solar radiation is absorbed the water in the gradient zone cannot rise, because the surface-zone water above it contains less salt and therefore is less dense. Similarly, cooler water cannot sink, because the water below it has a higher salt content and is denser. Hot water in the storage zone is piped to, for example, a boiler where it is heated further to produce steam, which drives a turbine. (Wright, 1982; and Energy Education, 2011).

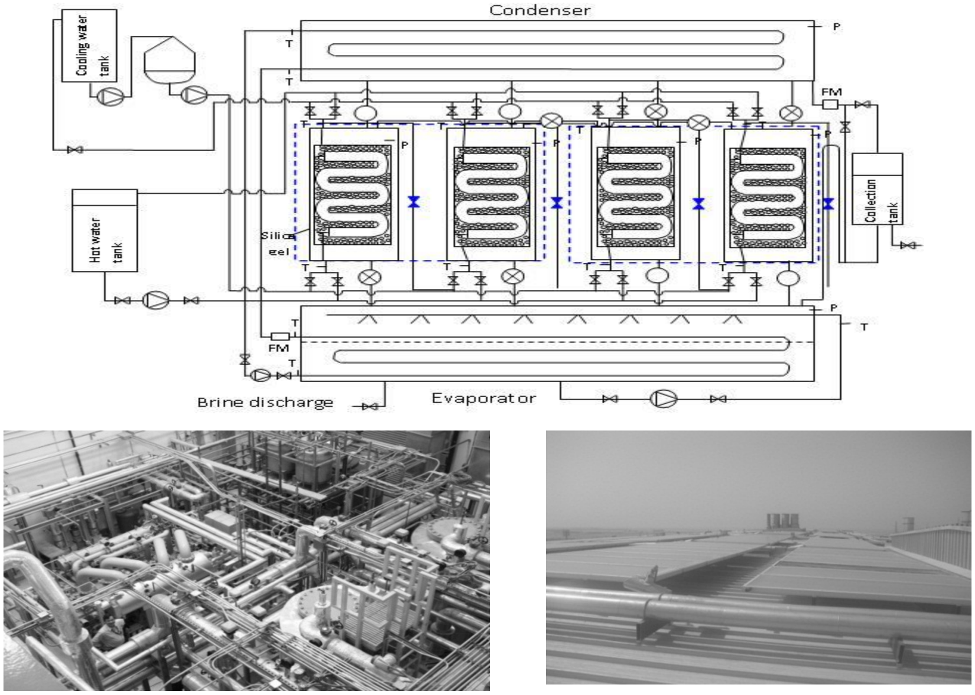

Figure 12. *Upper:* A schematic of the major components of an adsorption desalination (AD) cycle. *Lower LHS*: Adsorption desalination with cooling prototype system at KAUST in Saudi Arabia. *Lower RHS*: Solar flat-plate collector system at KAUST, Saudi Arabia (Ng *et al*., 2011).

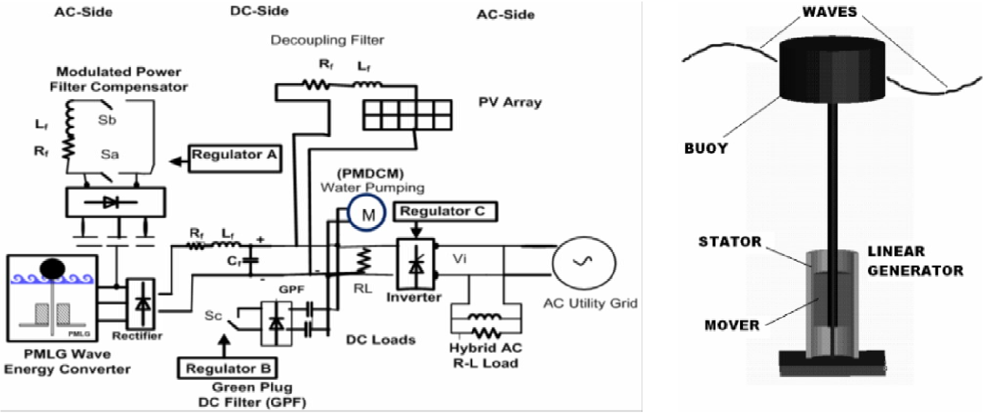

Figure 13. *LHS:* Hybrid photovoltaic/wave energy permanent magnet linear generator (PMLG) utilisation scheme. *RHS:* Wave energy converter. A floating buoy-permanent magnet linear generator (PMLG) converts wave energy to electrical energy (El-Sayed and Sharaf, 2011; Leijon, 2005; Greaves et al., 2009).

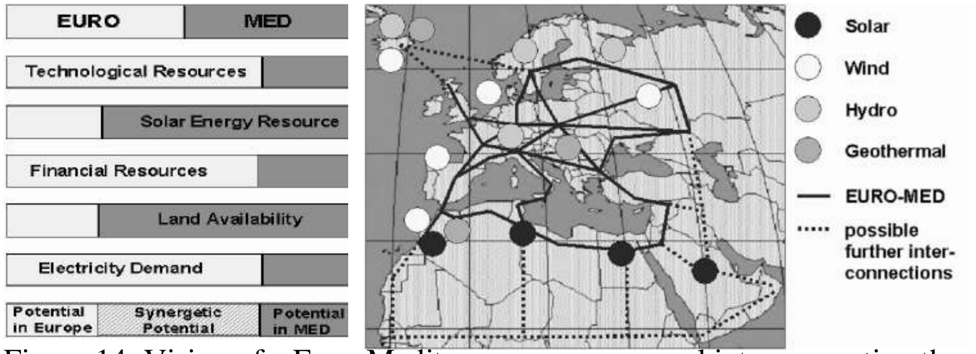

Figure 14. Vision of a Euro-Mediterranean power pool interconnecting the most productive sites for renewable electricity generation in the north and south of Europe. Such an international alliance will activate the large synergetic renewable energy potential of both regions, which otherwise could not be exploited to the same extend because of national limitations (Trieb *et al*., 2002).

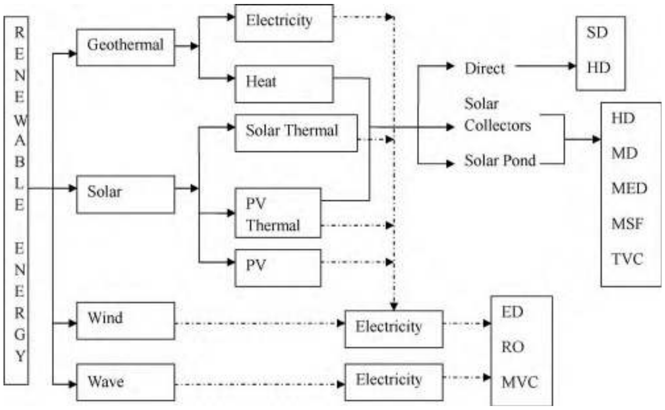

Figure15. Possible combinations of renewable energy sources with desalination processes (Gude *et al*., 2010; Bourouni *et al*., 2011). SD = solar distillation, HD = humidification-dehumidification, MD = membrane distillation, MED= multi effect distillation, MSF = multi stage flash, TVC = thermal vapour compression, PV= photovoltaic, RO= reverse osmosis, ED= electrodialysis, MVC= mechanical vapour compressor

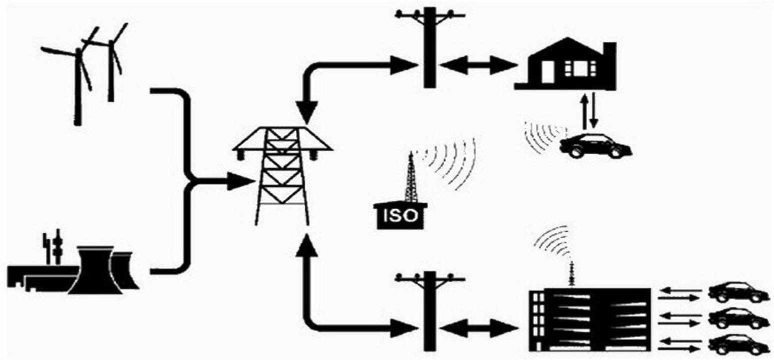

Figure 16. Concept of vehicle-to-grid power (V2G) as a storage resource for large-scale wind power (Kempton and Dhanju, 2006).

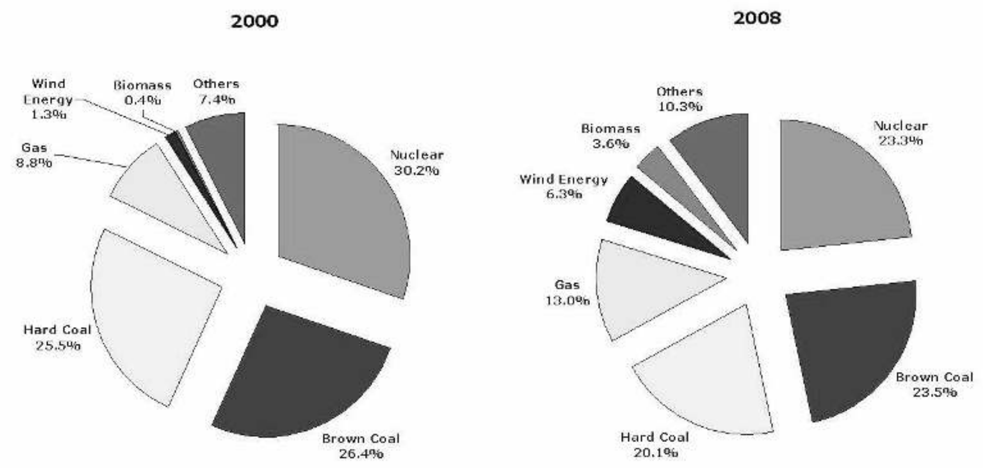

Figure 17. Gross Electricity Production in Germany in 2000 and 2008 (Frondel *et al.*, 2010).

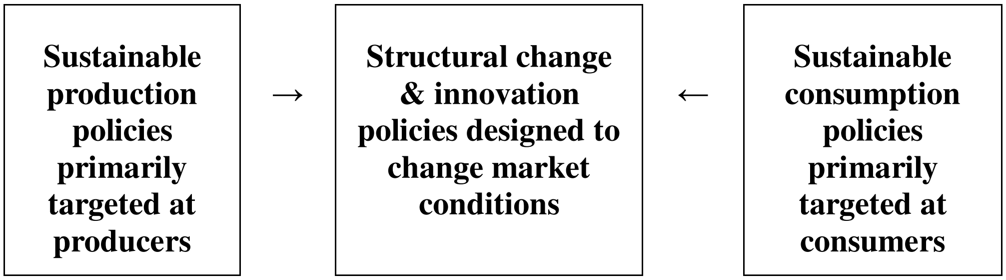

Figure 18. Link between resources and productivity (adapted from Omer, 2007)