CAN DESALINIZATION ALLEVIATE GLOBAL WATER SCARCITY? DEVELOPING SCENARIOS FOR SIMULATION MODELING

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Abstract

Freshwater scarcity is likely to increase in the future. Tapping into alternative water supply sources such as sea water desalination is normally a matter of technology development and cost. While existing desalination technologies remain energy intensive and require high capital investment, they are constantly developing. A similar parallel trend is observed in renewable clean energy sources. With the improved technologies, economy of scale and a shift towards the use of renewable energy, the desalination may become globally more affordable. This study attempts to formulate possible scenarios of these technological developments and examine their global and regional implications. The study uses learning curves to analyze the future trends in desalination and renewable energy, which are then interpreted in terms of specific parameters and integrated into a global economic model – Water, Agriculture, Technology, Environment and Resource Simulation Model (WATERSIM). It explores and illustrates the impacts of government policies for desalination and renewable energy technologies on water availability for agriculture up to 2050.

Introduction

The issue of global water scarcity is continuously discussed in science literature and top international policy gatherings. It can be quantitatively expressed in terms of various indices including use-to-availability ratio, number of people competing for the same resource in a given area, per-capita water availability, water stress indicator etc. Regardless of quantitative measures used, there is an overall consensus that water scarcity is progressing and will continue to increase due to population growth, increase in demand for food, and climate change (Seckler et al., 1998; Falkenmark and Rockstorm, 2004; CAWMA, 2007; Rockstorm et al. 2009). International Water Management Institute (IWMI) defines water scarcity in terms of access to water, and categorizes it as "economic" or "physical" (CAWMA, 2007). Areas of little or no water scarcity are those where less than 25% of river flows are withdrawn for different uses. Economic water scarcity occurs in conditions of the lack of investments in water infrastructure or lack of human capacity, which limit access to water even if water is physically available. In such areas, less than 25% of water resources are withdrawn, but malnutrition exists. Physical water scarcity, on the other hand, occurs in river basin where most (e.g. 75%) of water resources are already allocated and new/growing demands are impossible to satisfy. A global distribution of physical and economic water scarcity (Fig. 1) suggests that most of Africa, western part of South America, and some section of South East Asia are economically water scarce. Physical water scarcity is typical for western parts of the US, Mexico, northern Africa, Middle East, Southern Africa, and North China. Smakhtin et al. (2004) suggested yet another way of looking at water scarcity globally that "reserves" environmental water requirements and hence reduces the water available for other sectors thus effectively increasing water stress levels in various river basins and countries (Fig. 2). The study used the hydrological and water use data from the global WATERGAP model (Döll and Siebert, 2002) having a spatial resolution of 0.5° and a temporal resolution of 1 month. In both approaches to water scarcity, it was defined with reference to river flow only. Opportunities for alleviating water scarcity may exist if rain, as a larger source of water is taken into account (Rost et al., 2008; Hoff et al., 2009; Siebert and Döll, 2010), and yet these are most likely limited due to the inherent difficulties associated with capturing and managing this source.

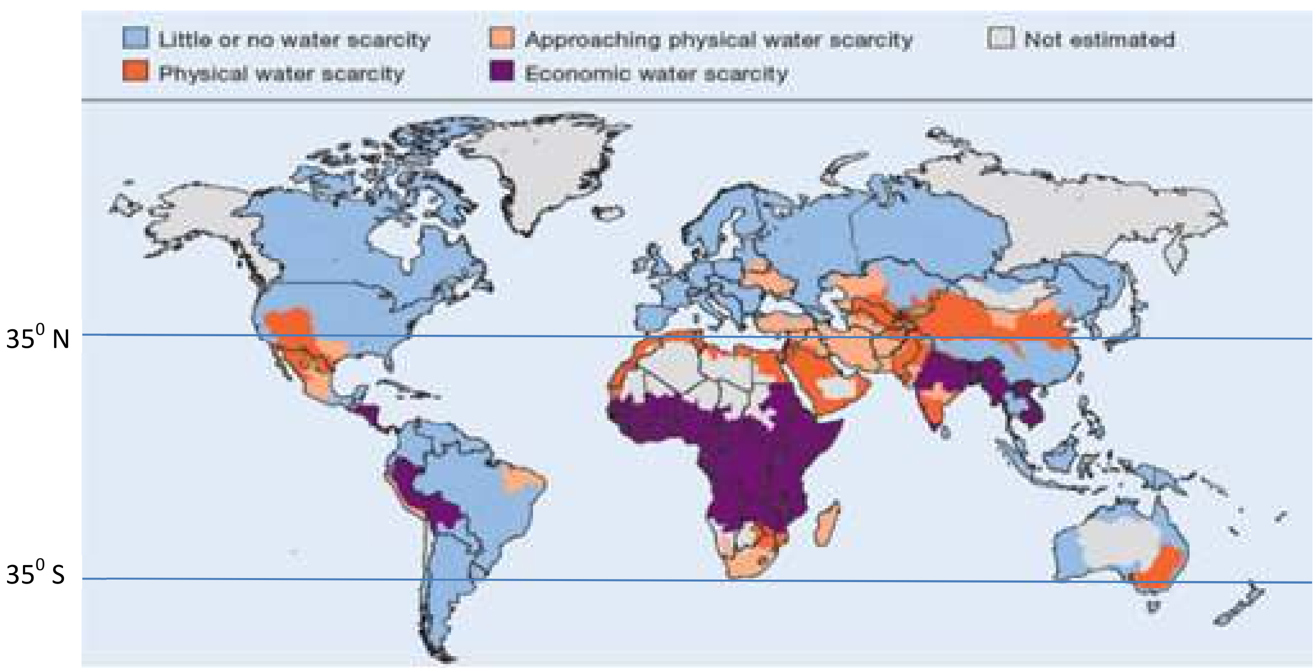

Figure 1: Global water scarcity map

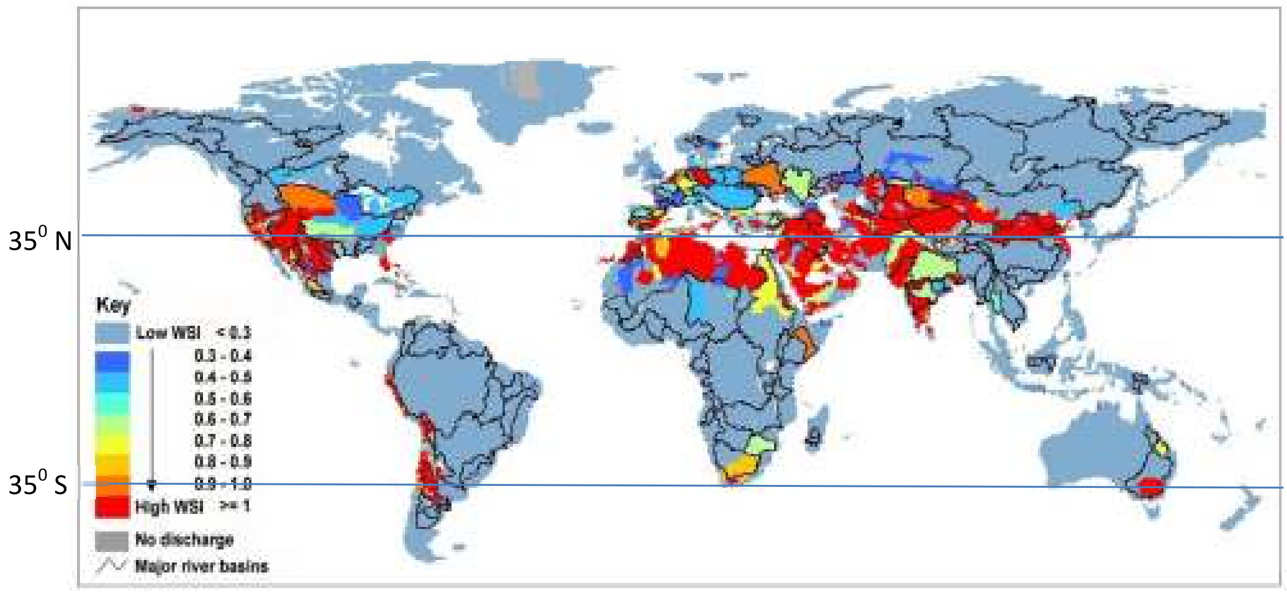

Figure 2: Global environmental water scarcity map

There are, of course, various ways of alleviating water scarcity, including developing water resources through inter-basin transfers, flow regulation, tapping into groundwater, water productivity improvement, demand management, recycling, etc. Yet, in many regions of the world, as evident from Fig. 2, there are hardly many "conventional" options left to improve water availability/supply. Conventional sources and measures have their limits. What is often missing in the debate on how to save the world from "looming water scarcity crisis" is the due attention to the fact that we have the unlimited potential source of water, but it is beyond the "freshwater box". Every hydrology text book contains the basic estimates of global water sources. Freshwater (inclusive of fresh groundwater, water in ice caps and glaciers and rivers and lakes) constitutes only 3% of the total. The rest is water in the ocean. Most of human water supply currently comes from rivers (which themselves constitute a fraction of the % of the global total water). Most, if not all the efforts of the present day "water science world" is concentrated on this fraction. Saline or brackish water may and most likely will play a significant role in the future water resource management, especially in the water scarce regions (Barker, 2003; Uche et al., 2006). Desalination technologies, may, in principle, make a revolution in water supply globally, but at present remain expensive, energy consuming and thus not competitive with conventional water supply. The costs of desalinated water provision have however dropped from \$9.0 to \$1.0 per m^3 over the last 40 years (Zhou and Tol, 2004).

Another virtually unlimited resource is solar energy. It currently constitutes only 0.03% in the global energy balance, but it has grown in the last decade from 964 MW to 30,060 MW (Brown, 2011), while the cost of installed PV systems in US has dropped from \$11.8/W in 1998 to \$8.3/W in 2007 (Wiser et al., 2009). The recent development trends in both desalination and solar power are therefore promising. The hypothesis is that in the future, as demand for freshwater increases, the cost of available water will go up. On the other hand, with the development of technology for desalinization and renewable energy, solar in particular, and government policy support, the cost of desalinated water would go down. A combination of affordable renewable energy with cheaper desalinization technology will therefore have significant impact on the future of water supply in certain regions and sectors.

The questions are i) whether desalinated water will become affordable with time due to its own technology and to clean energy development in large volumes, and if yes- how soon ii) where in the world it may become more acceptable and widely used, and iii) what implications this may have for agriculture that currently takes 80% of all current withdrawals globally (and will need to feed 9 billion people by middle of the century). These questions may be examined through formulating and simulating several scenarios, similarly to how various projections of water scarcity are constructed and scenarios of climate change are examined. This paper attempts to construct such scenarios and examine them in the context of global water-energy nexus using a global water-economic model. The focus of this study is on medium and large scale desalinization units that run with renewable energy so that they can cater to larger water demands in different economic zones and can have impact on water budget at the global level.

Water desalination and renewable energy development: recent trends

Desalination is a process that derives freshwater from sea water and brackish water. Freshwater is defined differently by multiple organizations. Water having total dissolved solids (TDS) less than 1000 mg/L is considered acceptable by World Health Organization (WHO) whereas US Environmental Protection Agency (USEPA) suggests 500 mg/L (NAS, 2008). US Geological Survey (USGS) defines fresh water having salinity less than 1,000 ppm, slightly saline water having salinity from 1,000 ppm to 3,000 ppm, moderately saline water with salinity from 3,000 ppm to 10,000 ppm, and highly saline water from 10,000 ppm to 35,000 ppm. It considers water with salinity over 35,000 ppm as seawater (website: http://ga.water.usgs.gov/edu/saline.html, last viewed: June 6th, 2011). In general, water with salinity in between fresh and sea water is considered brackish.

Desalinization technology can be broadly classified into two groups – thermal process based and electromechanical process based (Mathioulakis et al., 2007). Thermal process based technologies use distillation to separate fresh water from saline water. This involves phase change of water. Electromechanical technologies rely on semi-permeable membrane and do not involve phase change. While thermal technology is more economical to use for sea water desalinization, membrane technologies are more suitable for brackish water (Karagiannis and Soldatos, 2008). Another way to characterize desalinization is in terms of type of energy used, i.e. those that use conventional source of energy and those that use renewable energy sources (RES) (Karagiannis and Soldatos, 2008). Conventional source of energy is defined as energy derived from hydrocarbons such as coal, oil, and natural gas whereas RES is defined as energy derived from renewable sources such as water, solar, wind, geothermal etc. RES usually used for desalinization are solar, wind and geothermal energy. Although there are many technologies that exist for desalinization, three of these have become popular and will dominate in the future. These technologies are multi-stage flash (MSF) distillation, multi-effect distillation (MED), and reverse osmosis (RO) (Khawaji et al., 2008). While MSF and MED are thermal based, RO is membrane based. As of 2002, MSF and RO accounted for 36.5 and 47.2 % of total desalinization, with MSF dominating the large scale (over 5000 m^3/day) capacity and sea water desalinization (Khawaji et al., 2008).

According to the latest report by Global Water Intelligence (GWI), the current capacity of desalinization at global scale is over 44 million m^3 of water per day, most of which was developed in last two decades (Figure 3). Based on their 2006 report, the capacity of 32 million m^3 of water per day represented only 0.3 %t of total freshwater use (NAS, 2008).

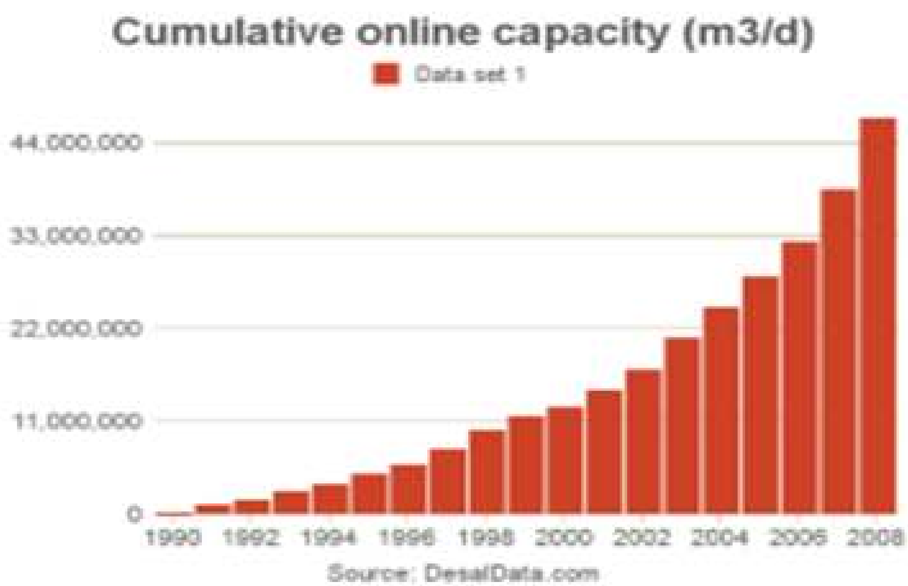

Figure 3: Cumulative global online capacity (m^3/day) of desalinization (Source: DesalData.com. Website: http://www.desaldata.com/).

The main constraining resource in the adoption of desalinization technology is the availability and cost of energy in the process. To date, it has only been used in the countries where either energy is relatively inexpensive, like in Middle East, or in affluent nations such as in US. The top three countries are Saudi Arabia, USA and United Arab Emirates (Khawaji et al., 2008). Based on the energy supply, the cost of desalinization has been cataloged by Karagiannis and Soldatos (2008) and is shown in Table 1. As can be seen from the table, the cost of water desalinization by renewable energy is still much higher than that by conventional energy. Cost also depends upon the capacity of the desalinization unit and type of desalinization technology used. While for brackish water the cost varies from 0.63 to 1.06 € for capacity less than 1000 m^3/day and 0.21 to 0.43 € for capacity between 5000 – 60000 m^3/day, for seawater, it ranges from 1.78-9.00 € for less than 1000 m^3/day, 0.56-3.15 € for 1000-5000 m^3/day, 0.35-1.3 € for 12,000-60,000 m^3/day, and 0.40-0.80 € for capacity greater than 60,000 m^3/day (Karagiannis and Soldatos, 2008).

Table 1: Cost of desalinization based on different energy sources (Reproduced from Karagiannis and Soldatos, 2008)

Type of feed water	Type of energy used	Cost (in €/ m^3)
Brakish	Conventional#	0.21-1.06
	Photovoltaic*	4.50-10.32
	Geothermal	2.00
Seawater	Conventional#	0.35 - 2.70
	Wind	1.00 - 5.00
	Photovoltaic*	3.14 - 9.00
	Solar Collectors*	3.50 - 8.00

#Conventional energy represents energy derived from hydrocarbons such as coal, oil and natural gas.
* Photovoltaic and solar collectors – both represent solar energy source. While photovoltaic produces electricity, solar collectors are used to heat water.

Energy is the main component in the cost of desalinization. It plays a bigger role in thermal based desalinization than in membrane based. The energy consumption for MSF is between 24-37 kWh_e[1]/m^3; for MED it is between 18-30 kWh_e/m^3; and for RO -less than 3.7 kWh_e/m^3 (Semiat, 2008). For MSF, the cost of energy accounts for 59% of the total cost, whereas for RO - 20% (Elhassadi, 2008). On the other hand, for renewable energy based desalination plants, energy only costs between 0 -10 % of the total cost (Al-Hallaj et al., 2006). For RO systems, the industry is reaching the upper limit of improving technology to save energy (Semiat et al., 2010), and in the best case scenario, not more that additional 15% of energy can be saved (NAS, 2008). Thus future of the cheaper desalination is linked to the development of inexpensive RES.

Now, due to much higher fossil fuel prices and due to environmental issues, conventional energy expansion is curtailed, and this trend is likely to continue due to the concerns of climate change and needs to develop RES. The data on average global growth rates in various energy sources in 2004-2009 suggest that solar power growth (based on cumulative installed capacity as a proxy) is the highest of all at 55%, followed by wind (27%) and biofuels 23% (based on volumetric production as a proxy) (Ochs, 2010). For comparison, oil, natural gas and coal energy growth rates over the same period were 0.4, 1.8 and 3.2% respectively. Figure 4 shows the dynamics of cumulative production of photovoltaic and wind power installed capacity over the last 30+ years. It is evident from the graphs that there has been exponential growth in both types of renewable energy from mid 1990s. Over the last decade the PV production increased by over 130 times whereas the wind installed capacity increased by over 90 times.

[1]"e" in kWh_e or KWe refers to electric power.

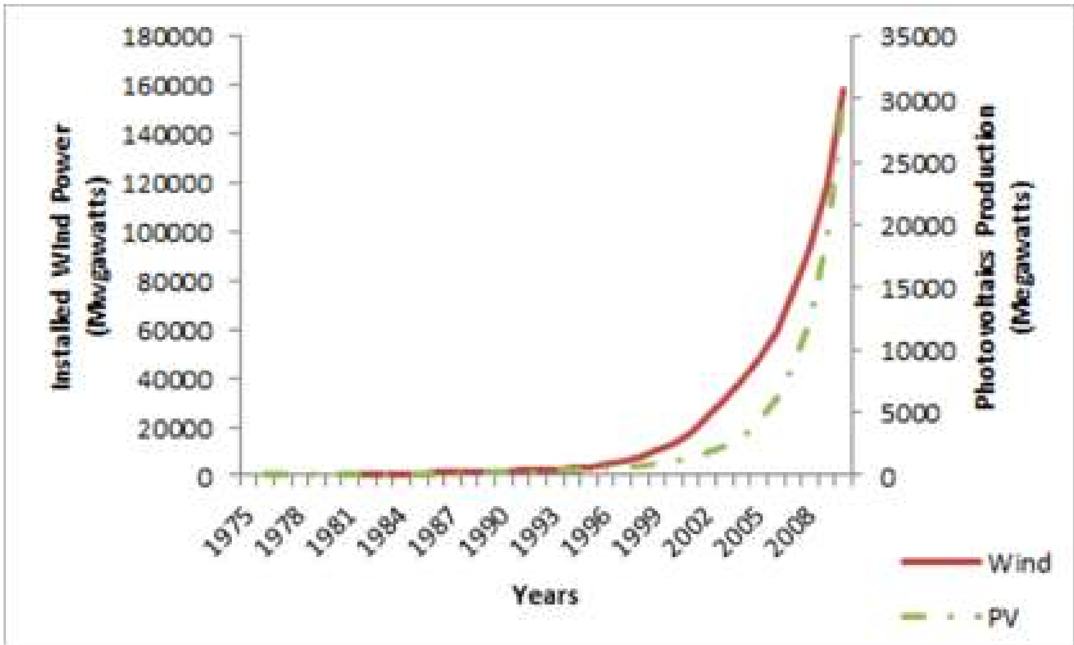

Figure 4: Time series of cumulative PV and Wind Energy production. Source: Earth Policy Institute

Most of the physically water scarce countries also fall within the Sun Belt region (Figs 1 and 2) - within 35 degree north and 35 degree south from the equator. All countries in this belt, combined, are home for 75% of the world population and 40% of global electricity demand (EPIA, 2010). The belt is characterized by intense solar radiation, and often – by high electricity prices, hence competitive potential. It is suggested that solar power (PV) can become the major source of electricity by 2030, especially if its potential in Sun Belt region is exploited (Gammal, 2010). Countries such as India, China and South Africa that fall in the Belt are also attractive investment locations for photovoltaic (PV) advancement. The countries, which are outside the Sun Belt fall within the "Westerlies" wind belt and have potential for development for wind energy. Countries such as US and most of Europe fall within this belt. Thus renewable energy, either solar or wind, if harnessed effectively may make the large scale adoption of desalinization technology feasible.

With investment in research and development and provision of subsidies, the prices of renewable energy can be brought down. In some instances, the cost of electricity generated by wind is comparable with the fossil fuel (IEA and NEA, 2010). The cost of onshore wind energy ranges from $3.7 (Switzerland) to $1.9 (France) KWe whereas the cost of coal generated electricity ranges from $4.9 (Russia) to $0.6 (China) per KWe. The off-shore wind cost ranges from $6.0 (Belgium) to $3.8 (France) per KWe. The prices of photovoltaic (PV) cells are also reducing. The cost of solar PV ranges from $7.4 (Checz Republic) to 2.9 (China) per KWe (IEA and NEA, 2010). Similarly, due to improvement of technology and higher demand, the desalinization is becoming less expensive.

The pattern of geographical feasibility of water desalination

For all practical purposes, it may be assumed that the sea water source is unlimited, but desalinated water can be made available economically within a limited coastal belt. Based on different studies, 40 to 70 percent of population lives within 70 to 100 KM strip of sea water (El-Dessouky and Ettouney, 2002; http://sedac.ciesin.columbia.edu/es/csdcoastal.html). Considering the fact that more than two third of the urban population in urban centers of more than 5 million inhabitants are partially in the 0-10 meter zone along the coast (http://sedac.ciesin.columbia.edu/gpw/docs/lecz_IIED.pdf), sea water can help meet large portion of domestic and industrial water demand along the coast. This should free up fresh water for upstream users or agriculture sector. Also inland brackish water sources may also be attractive in some cases and cannot be ignored. Some of these sources are large inland seas such as Baltic Sea, Black Sea, Caspian Sea; brackish water lakes such as Lake Charles in Louisiana; U.S., Chilka Lake in Orissa; India, Lake Issyk-Kul, Kyrgyzstan; Laguna de Oviedo in the Dominican Republic; Lake Maracaibo in Zulia State, Venezuela; Lake Monroe in Florida, U.S.etc. or coastal lagoons, marshes, and deltas such as the Burgas Lakes near the Bulgarian Black Sea Coast, the Fleet lagoon, Dorset, England, Kaliveli Lake, Tamil Nadu, India etc. The analysis of these factors combined shall lead to the outline of the regions where access to desalinated water may be possible in principle.

Technology Experience Curves

The pathway of technological development depends on multiple factors including public fund investment in the initial stages, Research and Development (R & D) investments, and demand in the market. One of the ways to look at the impact of these factors in technology (or product) development is to build experience curves (or learning curves) and extrapolate them into the future. Experience curves can be expressed in the form of mathematical equations and can be easily incorporated in a model (Argote and Epple, 1990; IEA, 2000).

An experience curve is a relationship between cumulative production of a commodity and its price in the market[2]. This is based on the premises that in a competitive market, with experience, adoption of newer technology and increased sales, the cost (and hence the prices) of commodities go down. This relationship between cumulative production and prices is a straight line on a double-logarithmic chart (Figure 5). This implies that there is a consistent reduction in any commodity price as the cumulative production of this commodity increases. Each product or technology has its own unique experience curve, which is characterized by progress ratio.

[2] In theory the relationship should be with cost. It is not easy to get the costs of commodities and studies have shown that in a stable market, the costs and prices move in parallel.

Progress ratio is defined as a change in price due to doubling of cumulative production[3]. Lower progress ratio (or higher learning rate) means that a technology or a commodity "learns" faster from the experience. Thus progress ratio is used to compare different technologies in terms of their long term cost and adoption rates. The point where experience curve meets the incumbent technology cost line is called a break-even point. The area under the experience curve and the cost curve of incumbent technology represents investment required to bring the newer technology to the break-even point. The experience curve is represented by the following equation:

$$\ln(C_t) = \ln(C_0) + \beta * \ln(n_t) \qquad (1)$$

Where C_t is expected cost at n_t cumulative production level; C_0 is known cost of product at initial phase (i.e. $n_t = 1$); and β is slope parameter obtained by regression

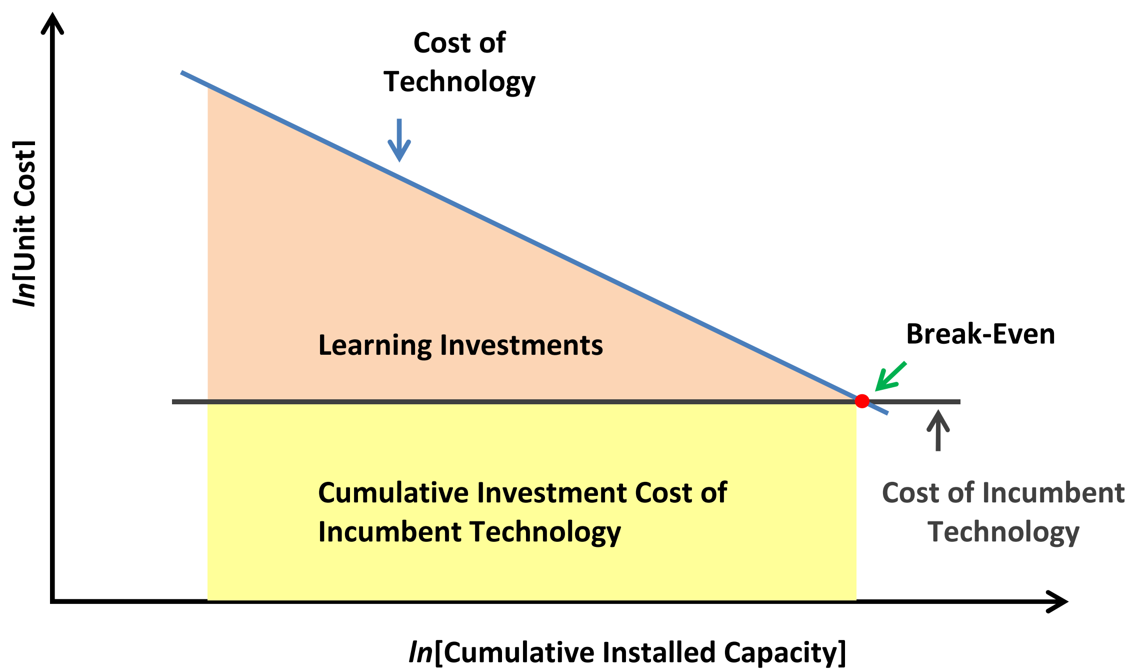

Figure 5: Representation of experience curve and investment (Adapted from IEA, 2008)

Some have modified this equation to include Research and Development (R & D) based knowledge stock as shown in equation 2 (Mikela and Schrattenholzer, 2004).

$$\ln(C_t) = \ln(C_0) + \beta * \ln(n_t) + \gamma * \ln(K_t) \qquad (2)$$

[3] Some use the term learning rate, which is (100 – Progress Ratio).

Where K_t is R&D based knowledge stock, which is made up of past R & D investment (as there is a lag time in R&D investment and its effect and the current year investment as shown in equation 3.

$$K_t = K_{t-1} * (1-\rho) + ARD_{t-I} \quad (3)$$

Where ρ is annual knowledge stock depreciation; ARD is the annual expenditure in R&D, and "i" is the lag time between expenditure and its effect. For PV technology, the typical value of ρ is 3% and "i" is 2 years (Mikela and Schrattenholzer, 2004).

Future projections of desalination at global scale need to be included in global water accounting models. It would also help answer questions such as role of investments for desalination and level of progress ratio required to counter some of the stresses in future freshwater demand. Inclusion of the future of desalination technology into global models can be achieved by representing desalination in terms of experience curves with well-defined progress ratios and the break-even points for different regions of the world.

WATERSIM model and scenario development

Water, Agriculture, Technology, Environment and Resources Simulation Model (WATERSIM) is a water balance and food trade balance model that links global hydrology (water available) to global food trade (which defines the agriculture water requirement based on food demand) (de Fraiture, 2007). The two balance models in WATERSIM run independently at different temporal and spatial scales, but are linked together through common variables such as crop harvest area and crop yield. While the water balance module runs at a river basin level, the trade balance module runs at economic region level. In the current version of WATERSIM, the globe is divided into 125 major river basins and 115 economic zones. To link the two modules, their spatial resolutions are intersected to generate 282 Food Processing Units (FPUs) – the spatial resolution of the WATERSIM model. WATERSIM can be a valuable tool to analyze the influence of water technologies (like desalinization) in the context of global economic zones, changing trends in cost of technology and competing water demands between different sectors.

The water balance module is based on water accounting framework developed by Molden (1997). It calculates water balance per basin at a monthly time step. The available resource is separated into two components: - water available in streams and aquifers, and water in the soil. The precipitation, stream flow and the groundwater recharge data is provided to the model. The demand for water is calculated as a total of agricultural, industrial, domestic and environmental flow water requirements. Domestic water demand is set to have the highest priority, and agriculture - the lowest. The available water, that can be depleted, is stored in the basin, the capacity of which is defined as "Basin Equivalent Storage" (BES). BES is a virtual storage that includes the actual storage and other sources of water that are made available for use in the basin. Water, in excess to the BES, flows to the downstream basin. If the available water falls short of demand, the water is optimized between different demands and spread over months.

In the food trade module, the demand and supply for each commodity within each region is determined based on available commodity, regional prices, supply side elasticity and demand side elasticity. Demand is made up of domestic and animal feed and is determined based on prices, income and population growth. Supply is defined as a function of harvested area and yield response function. A global equilibrium is reached by adjusting the global commodity price so as to bring the global trade in balance. This helps in determining the future commodity price. This price, along with available water from the water balance module determines the harvested area and crop yields thus linking both modules.

Agricultural water use is highly impacted by the global food demand and supply, regional policies and technological development. WATERSIM is one tool that can help quantitatively examine possible impacts of combined desalination and RES developments on future water availability in different regions, countries and river basins. It is the right tool to answer related questions in the context of virtual water trade and regional governments' investment in desalination and renewable energy technologies. To simulate the impacts of progressing technologies on water availability for agriculture the following steps will be required

- Calculate industry and municipal demands along the defined coastal zone
- Develop a database of prices and production of renewable energy and desalination projects based on the economic regions of the WATERSIM
- Define the current and future water pricing trends in industry and domestic water use
- Develop learning curves for desalination from solar energy for economic regions / FPUs
- Compare the learning curves to price trends of water for industry and urban domestic water use
- Develop a relationship between learning curve, water pricing and proportion of water from desalination that will be bought (and used) by industry and municipality.
- Include this relationship in the WATERSIM model within its water balance routine.
- Run future scenarios for different progress ratios and investments by regional governments in desalinization technology.

Conclusions

As desalination from RES cost gets closer to breakeven point, the proportion of desalinized water forming part of the water supply will increase. This increased supply may cater for industrial and municipal demands since both sectors will likely to be willing to pay the cost of freshwater. This will not only reduce competition with agricultural sector but would also provide more water to meet environmental flow requirements.

WATERSIM, a global food trade and water balance model is being used to examine trends and impact of investment in desalination and renewable energy technology to make desalination a viable force in future water scenarios.

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