Decentralized Co-generation of Fresh Water and Electricity at Point of Consumption

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Most of us believe that additional anthropogenic CO_2 to the atmosphere will push the Earth into a vicious cycle and down a path of no return. Consequently, solar energy must sit at the center of the water-energy-climate nexus as the world is shifting into a decarbonized and circular economy. Simultaneous production of electricity and fresh water by photovoltaic-membrane distillation (PV-MD), a newly developed technology, turns waste heat from solar PV panels into a power source to drive efficient water distillation process. It produces fresh and clean potable-quality water on-site from various water sources with impaired quality, such as seawater, contaminated rivers, lakes, groundwater, and industrial wastewater. Due to the low barrier of entry, it is well suited to providing both electricity and fresh water in decentralized manner for point-of-consumption locations, especially off-grid communities and communities with small- to medium-sized populations even with challenging economic conditions. The adoption of PV-MD would reduce the overall cost of otherwise long-distance electricity transmission and transportation of water by conventional means and thus it is a cost-effective shortcut to achieving sustainable development goals (SDGs) stipulated by the United Nations. This essay highlights the potential of PV-MD to supply decentralized water and electricity for regions suffering from both economic and physical water scarcity as well as its promise to contribute to agriculture in (semi)arid regions.

1. Introduction

According to Chinese mythology, long ago there were 10 fury suns in the sky. The crops planted by farmers were scorched and all the rivers dried up, making Earth uninhabitable by human beings. A godly archer, named Hou Yi, had to be sent from heaven to shoot down nine suns. The remaining sun is the one we see shining today. This legend is, more or less, aligned with current thinking that the sun is to blame for ongoing water scarcity in the terrestrial world.

Today, scarcity of fresh water is among the top challenges the world faces. Previously unfathomable water crises and subsequent rationing in the last few years in large cities, such as

Cape Town, South Africa[1], Sydney, Australia[2], and Chennai, India[3], exemplify how easily human society can be pushed into a primitive living state when the water supply is not secure. There are two major types of water scarcity: physical water scarcity and economic water scarcity. Physical water scarcity is caused by inadequate water resources to meet local demands by humans and ecosystems, whereas economic water scarcity is a consequence of a lack of investment in water infrastructures that properly process water even if ample water resources are available. Physical water scarcity typically occurs in arid and semi-arid regions. In regions with access to seawater and with developed economies, seawater desalination becomes an obvious but luxurious choice to provide potable water. Due to their high water production rates and capacities, traditional seawater desalination technologies, including seawater reverse osmosis (SWRO), multi-effect distillation (MED) and multi-stage flash (MSF), have contributed to sustaining human societies challenged by severe physical water scarcity, especially in the Middle East, which accounts for 45% of the global seawater desalination capacity[4]. However, these technologies have extremely high up-front capital costs and require intensive energy consumption during operations. Water, energy and the climate are consequently closely intertwined in the Middle East and beyond. In Saudi Arabia, around 15% of produced electricity is used for seawater desalination[5]. In Abu Dhabi, the desalination sector accounts for more than 22% of the Emirate's total CO_2 emissions[6].

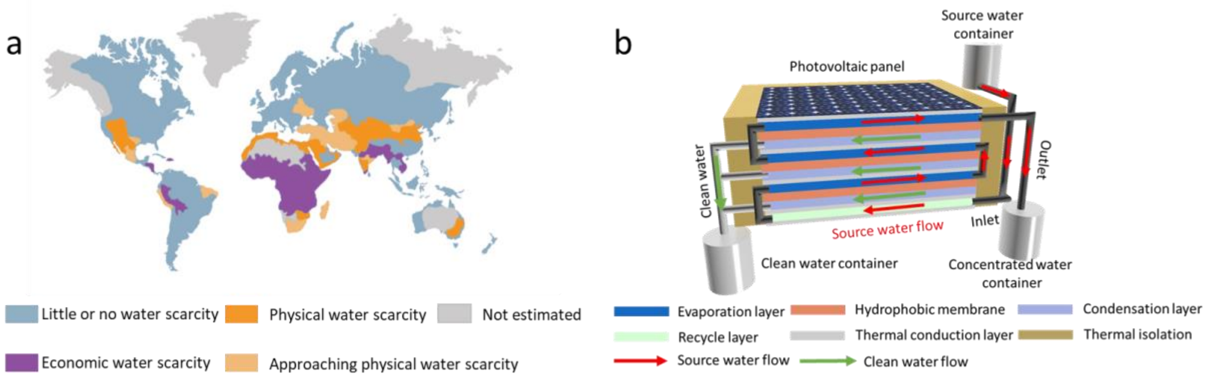

Figure 1. (a) Global map of water scarcity by 2025[7] and (b) the schematic illustration of the PV-MD device[5].

On the other hand, the economic water scarcity is found more often to be the cause of countries or regions experiencing water scarcity. About 844 million people still lack daily access to safe drinking water, resulting in more than 200 million human hours spent every day mostly by women and girls to fetch drinking water for their families[8]. The World Health Organization (WHO) [9] reported in 2017 that, due to unsafe drinking water and inadequate sanitation and hygiene, over 1.7 billion children suffer from diarrhea, which leads to more than 500,000 deaths among children younger than five years old each year. These grim facts stand in sharp contrast to the trends toward Internet-of-Things and artificial intelligence across the advanced economies. Figure 1a presents a global map of predicted water scarcity in 2025[7] when almost half of the world's population will face severe water scarcity with economic water scarcity the dominant type. Undeniably, achieving "universal and equitable access to safe and affordable drinking water for all" by 2030 as stipulated in the UN's sustainable development goals (SDGs) is a daunting task[10].

2. The global electricity demand will double by 2050, but where will the additional electricity be from?

Population growth, steadily improving living standards, and industrialization of developing nations will double global electricity demands by the middle of this century. Still, 82% of the current global energy mix is fossil fuels[11], the burning of which results in massive emissions of CO_2, the most notorious greenhouse gas. Increasing air temperatures increase the frequency and intensity of extreme droughts, which lead to increased dependence on watering systems for crop irrigation and livestock and the occurrence of destructive and frequent wild fires. Environmental changes in our seas and oceans in response to climate change will likely alter phytoplankton productivity, which in turn will increase energy inputs into seawater desalination processes. Scientists, environmentalists and policy makers in most nations agree that adding more CO_2 to the atmosphere will push the Earth into a vicious water-energy-climate cycle and down a path of no return.

We believe that solar energy must sit at the center of the water-energy-climate nexus. Studies have projected that life-cycle greenhouse gas emissions from solar power will be 3.5–12 gCO_2eq/kWh compared with 80–110 and 400–1000 gCO_2eq/kWh from fossil fuel burning plants with and without carbon capture and sequestration, respectively[12]. Moreover, the unmatched potential of vastly abundant solar energy to quench the global energy thirst is undeniable. Energy Information Administration (EIA) predicts that renewables will account for almost 49% of the global electricity generation by 2050 with solar power generation representing the most growth[13].

Converting solar energy to electricity by photovoltaics (PV) is the most popular way to produce solar power owing to its low barrier of entry and thus low and flexible capital investment, making it suitable at any scale. Equally important is PV’s minimal water consumption during operation. To generate 1 MWh of electricity, PV consumes only 2 gallons of water, whereas thermal power plants using coal and nuclear fuel as energy sources consume 692 and 572 gallons of water, respectively[5].

However, the efficiency of single-junction solar cell-based PV panels is limited to 33.7 % in theory; in practice, commercial PV panels convert no more than 25% of the adsorbed solar energy to electricity. The remaining 75% the solar energy that the PV panels painstakingly adsorb is converted into heat and unproductively dumped as waste by the panels into the ambient air.

Moreover, a common complaint against solar power is the low areal power intensity of incoming solar light, which makes any sort of solar energy project require large land areas. From a land occupation point of view, PV panels with high solar absorption should not be discouraged, but rather incentivized and value-added applications of the co-generated heat need to be invented.

3. Simultaneous generation of electricity and fresh water by photovoltaic-membrane distillation (PV-MD)

Recently, a strategy to simultaneously produce electricity and clean water from the same PV panels was proposed[5]. The strategy, called photovoltaic-membrane distillation (PV-MD), turns the waste heat from PV panels into a power source to drive a multistage MD process. The MD component is attached directly onto the backside of commercial PV panels to produce fresh and clean potable-quality water from various water sources with impaired quality, such as seawater, contaminated rivers, lakes, groundwater, and industrial wastewater.

In the PV-MD system, the heat produced by the PV panels flows into the MD component naturally. While the heat flows through the multistage MD, the latent heat from vapor condensation is collected and reused to drive multiple cycles of water evaporation (Figure 1b), leading to a record-breaking fresh water production rate. To avoid the crystallization of the salt in the device, the PV-MD system works in a cross-flow mode in which the source water flows into the device driven by gravity or mechanical pump and flows out before reaching saturation. According to calculations[5], at the same time as electricity is regularly generated at expected rates, the PV-MD also produces clean water at a rate as high as 3.5 kg/m^2/h when seawater is used as the source water. At this performance rate, on a typical summer day, more than 18 liters of fresh water will be produced by one 1 m^2 PV panel, which is enough water for six adults.

Other advantages of the PV-MD include the low barrier of entry, suitable at any scale – PV-MD can be set up as a single unit for a household or as a large, industrial PV-MD farm; and the production of fresh water in low salinity – the fresh water produced by PV-MD has less than 20 parts per million (ppm), which has a broad application such as irrigation, drinking and some other industrial application.

We believe that the PV-MD technology, once scaled up, is well suited to providing both electricity and fresh water in decentralized point-of-consumption locations. PV-MD is a cost-effective method to supply electricity and fresh water especially to off-grid communities and communities with small- to medium-sized populations because it would reduce the overall cost of long-distance electricity transmission and transportation of water by conventional means. The large-scale adoption of PV-MD would relieve a lot of pressure on currently strained electricity and water production facilities and in doing so there is no additional land area required beyond what is needed to produce solar electricity by regular PV.

The global PV installation capacity will increase to 877 gigawatts (GW) by 2024[14] and co-generated waste heat will amount to 4385 GW by then, assuming the average 20% energy efficiency of PV. This gigantic amount of co-produced heat will be an important energy source on the global scale. If all PV panels were retrofitted to be PV-MD by then, there would be 10% more drinking water for the entire world (based on consumption in 2017) produced by these PV-MD panels, along with the solar-generated electricity.

In the following, we highlight some potential PV-MD application scenarios.

3.1 Decentralized water and electricity supply for regions with economic water scarcity

PV-MD offers an immediate solution to provide much-needed drinking water from various water sources, for example, seawater, surface water, and groundwater, along with electricity in the regions with severe economic water scarcity.

First, severe electricity shortages are generally considered the cause of economic water scarcity because proper water treatment processes consume electricity. While the annual electricity consumption of the most developed countries is generally higher than 10,000 kWh per capita, it is below 200 kWh in 36 countries[15]. Most of the 884 million people who live without daily access to safe drinking water are from these electricity-scarce countries and 79% of them live in rural areas.

Clearly, centralized generation of both electricity and drinking water with the attendant long-distance transmission in these regions is neither possible nor an effective solution due to the lack of financial resources and also to low population density. For example, the cost of electricity transmission in rural electrification at a distance of 28.3 km is estimated to be $627 per person and this value increases sharply as the transmission distance increases[16]. The cost of piping water to rural regions is estimated to be around $218 per person[17].

Furthermore, the quality of water produced by PV-MD is generally better than that of conventional drinking water treatment processes. This produced water can be directly used for drinking and cooking purposes, two essential human activities. While electricity storage entails batteries or some other storage technology, fresh water, once produced, can be stored conveniently. Thus, the intermittency of solar radiation affects water production less than it affects electricity generation. The low barrier of entry of PV-MD makes it an immediate solution to provide both electricity and water to rural and isolated populations.

Figure 2. Off-grid water and electricity supply in rural region

3.2 Decentralized electricity and water production by seawater desalination in regions with physical water scarcity

There are multiple benefits from using PV-MD in regions with physical water scarcity with access to seawater.

First, most regions with physical water scarcity, particularly the Middle East, are blessed with high-quality solar energy. However, solar energy has been considerably underutilized in the Middle East. Currently, solar electricity in Saudi Arabia and the United Arab Emirates respectively accounts for less than 0.1% and 1% of total domestic electricity generation. Fortunately, these regions have demonstrated their ambitions to lead the world in solar power generation with giant solar PV projects in the making, which suggests that PV-MD will be an attractive and timely choice to co-generate electricity and fresh water.

Second, PV-MD cost-effectively supports rural and off-grid communities and promote decentralized living styles as it can readily and inexpensively supply both off-grid water and electricity at any suitable scale. While not meant to compete against conventional desalination plants, the PV-MD setup reduces the overall societal cost to hook such communities into centralized water and electricity networks. As a matter of fact, we believe that PV-MD can competitively produce and deliver drinking water to small- to medium-sized populations (e.g., fewer than 10,000 people). This is the population scale at which conventional desalination technologies are prohibitively expensive. In this sense, PV-MD is complementary to the conventional technologies and is very suitable for providing drinking water to these communities.

Figure 3. PV-MD-agriculture farm.

3.3 Water co-generation in desert PV farms to promote agriculture in arid and semi-arid regions

Recently, PV panels installed on fertile agricultural land has aroused concerns about their impact on land use. For example, the US state of Washington has imposed restrictions on large-scale solar projects citing concerns about the loss of farmland[18]. In this context, barren land in arid and semi-arid areas, especially deserts, is a logical choice for setting up PV farms. Due to lack of vegetation, these regions attract high global irradiance, which can increase the power output of PV panels.

The shade under PV panels has been found to reduce surface water evaporation rates while the PV panels also decrease wind speeds. As a matter of fact, flourishing grass is a common sight under PV panels in desert areas due to the small amount of fresh water produced by dust removal processes on regular PV panels.

We believe that establishing PV-MD along coastal deserts, in deserts with brackish or even hypersaline subsurface groundwater (e.g., the Judea Desert in Egypt), and in deserts by saltwater lakes would make growing plants in PV-MD farms possible, thanks to the significant amount of fresh water produced. Additionally, the plants under PV-MD panels can be used for grazing of herds of sheep or other livestock (Figure 3). Thus, setting up PV-MD farms in deserts would bring agriculture to arid and semi-arid regions and will green barren lands.

To end

As the world shifts into a decarbonized and circular economy by necessity, solar energy will assume a central role in the water-energy-climate nexus. Decentralized water and electricity production for point of consumption is a new paradigm, but it is a cost-effective shortcut to achieving sustainable development. PV-MD offers a solar-energy efficient electricity and fresh water co-generation approach for decentralized areas with a minimal carbon footprint. As the global PV installation capacity is rising, PV-MD provides a promising solution to addressing the water-energy-climate nexus and providing a potential force towards sustainability.

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Competing Interests

The authors declare no conflict of interest.

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