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Photovoltaic powered water purification — challenges and opportunities

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Abstract

One third of the world population does not have access to clean water sources and most of these people are not connected to the electrical grid at the same time. Therefore, photovoltaic (PV) powered water purification suggests itself to be one of the solutions in areas with high sun radiation like India or the MENA (Middle East and North Africa) region. Furthermore, the environmental impact of the process can be reduced substantially as no fuel supply is required.

The paper presents a concept of combining a membrane filtration plant with PV power supply only. As PV is a fluctuating energy source and the conventional membrane process needs a constant power input to maintain pressure and flow on the membranes to guarantee their lifetime, some challenges in the system design need to be addressed. Mere coupling of off-the-shelf components does not do the job.

A full-scale system for sustainable water purification has been designed and tested in the lab and a pilot location. The results are presented in the paper.

Beyond the environmental benefits, the system also competes with standard systems on the market. Based on the experimental results, a cost model has been derived, the main cost factors for the system will be established and a design strategy for a small-scale PV powered system, able to supply a farm or village with safe potable water, is presented.

Keywords: Membrane filtration; Photovoltaic power; Decentralized water production

1. Introduction

It is undoubted that the growing water scarcity is one of the world's most severe problems. It is expected that in 2025 almost 3.5 billion people, 48% of the world's population, will have an insufficient water supply [1]. At the same time, about one third of the world's population, 2 billion people, is not connected to an electrical grid [2].

State of the art purification technologies can convert almost any water into potable water but they do require energy, mainly in the form of electricity.

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Thus, the water problem can also be seen as an energy problem since seawater, brackish water or freshwater of unknown quality are abundantly available but significant amounts of energy are required in order to make it suitable for drinking.

Photovoltaic (PV) powered water purification is an opportunity to solve this issue. It can provide potable water and on top, small independent minigrids that supply people with electricity, too.

2. Challenges

With every new technology there are some changes required on previous views and the way systems are designed. This also applies to coupling a membrane filtration system to PV power.

2.1. Design considerations

With the integration of the power production from photovoltaics, i.e., generating electricity from sunlight, into the water system a few extra thoughts need to be spent on the system design in order to address the specifics of the power source. The following only applies to full extent if the system is merely powered by photovoltaics, for "pseudo-photovoltaic" powered systems, i.e., systems where the power supply is decoupled from the power consumption via an energy storage or an additional electrical grid, some aspects can be neglected.

2.1.1. Dynamics of power supply

Since solar power is an intermittent energy source, the water purification system has to be able to cope with the variable power output in two ways: there is a daily fluctuation, because of the peak in irradiation at noon and zero irradiation at nighttime (shown on the right in Fig. 1), and a seasonal fluctuation, because winter days are shorter and have less irradiation than summer days (shown on the left in Fig. 1). The graphs are derived from a simulation for a solar generator of 1 kW peak power and are based on real irradiation data from a project in Saudi Arabia in collaboration with NASA [3].

Current filtration membranes are designed for a very narrow operating range and a permanent water input at a certain pressure. Strong variations in pressure and flow during the day are not possible with state of the art purification membranes. Fouling and scaling are consequences of disobeying the boundary conditions. After every stop of the system, an extensive

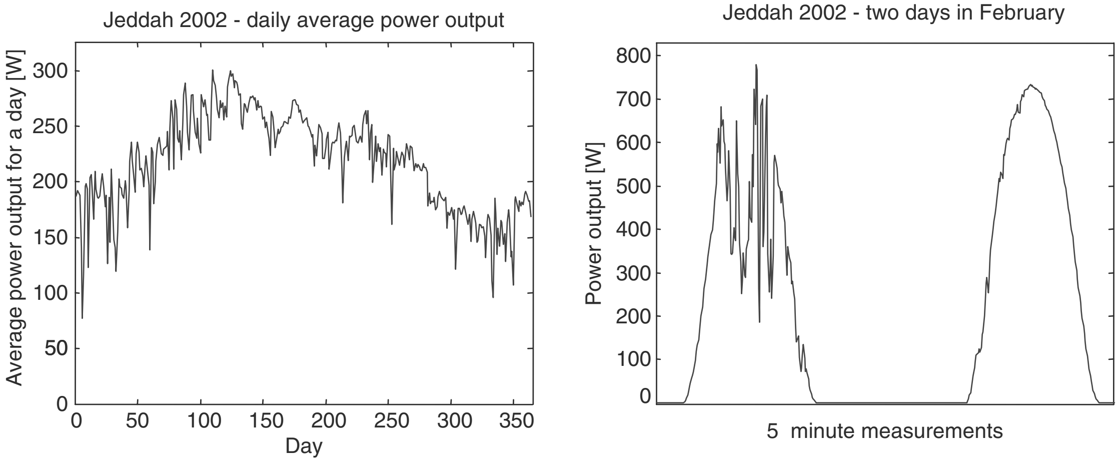

Fig. 1. Simulation of power output for 1 kWp solar cell based on statistical data for Jeddah [3].

cleaning process has to be started. This results in a constant 24/7-power input for the conventional systems.

So the first approach has been to energetically decouple the power generation and the power consumption by including an energy storage device like a battery. Sized correctly, this configuration levels out the fluctuations in solar power and allows a constant operation regime for the membrane plant. These systems have been installed in the field especially for seawater RO plants with high operating pressure it allows working with PV power. Nevertheless, the battery increases the system costs around 30–50%, requires regular maintenance and has a limited lifetime (depending on the depth of discharge).

Recent research efforts are looking for battery less configurations at least for low-pressure RO or ultrafiltration systems (cf. chapter 4). Here, the membrane system has to tolerate a certain variation in power supply without being damaged.

Dealing with the seasonal fluctuations, simulations and cost models show that it is not cost-effective to store electricity during the summer time for the winter. It is more reasonable to have a boost purification unit during summer time to utilize the additional energy produced by the PV panels. This correlates very well with the usually higher water demand in summer.

2.1.2. Reverse design approach

The dependency on the power provided by the solar array requires a different design strategy. For standard membrane plant design and the corresponding software tools, the target water production is the starting point. Based on the membrane performance data the size of the membrane area needed is determined, considering the boundary conditions of permeate flux and recovery. Thus the total flow rates are known and the pump size is selected. Energy is not a constraint, only for efficiency and economic assessments it is considered.

For PV powered off-grid systems only the power provided by the solar array is available for the filtration. Via a first guess for the specific energy consumption per cubic meter of water produced an upper limit for initial water output and plant size can be estimated. Then, in a reverse design approach, the membrane array and the pumps can be designed iteratively with the standard design tools, always crosschecking with the power requirements.

2.1.3. Site-specific sizing

Solar panels are specified according to the maximum power they can produce under optimum conditions, called peak power in Wp. This is not a good indicator for the actual power production over a day. Fig. 1 shows that the power produced by a solar PV module is fully dependant on solar irradiance and changes instantly over the day due to fixed orientation of the generator. For the given location this needs to be considered for matching the power available with the power demand (cf. chapter 2.1.2). Irradiation data is available for many locations; this needs to be fed into performance models for the PV array, also considering additional factors like day length, ambient temperature to get a realistic assessment of the energy production. Within a certain range it is then possible to predict the performance of the photovoltaic system.

2.2. Economic assessment

Due the autonomy in power supply all capital budgeting calculations need to be modified. For conventional grid-connected systems, energy costs are itemized under operation and maintenance (O&M) costs, for desalination usually around a third of O&M is energy costs.

In a solar powered water purification system, the running costs tend to be far lower because no money is spent for fuel or electricity. In times of rising energy costs like we are currently experiencing, this is an advantage for the system. On the other hand, the initial investment is higher as the photovoltaic system needs to be considered, too (about 5 €/Wp).

In a total life-cycle cost balance, solar electricity is still more costly than electricity produced from fossil fuels in large-scale power plants (which have been highly subsidized).

If no grid is available, though, the situation is different: The costs of PV have to compete with traditional decentralized power supply technologies like diesel generator sets or alternative energies like wind energy.

3. Opportunities

Especially in warm and dry regions, like in Middle Eastern North Africa (MENA), PV suggests itself to be the energy source of the future for water purification, because there is a high sun irradiation and a large water shortage. The sun radiation of 3–8 kWh per m^2 and day is a similar to the energy content of 1–2 barrels oil per year and square meter.

3.1. Environmental and social benefits

Photovoltaic electricity production has a good reputation and generally a high acceptance. It offers a small distortion of nature with no noise or exhaust gas emissions during operation. Smaller systems blend into the environment very well. For developing countries the paradigm shift to smaller decentralized systems creates new opportunities for micro financing and local entrepreneurship, thus raising the wealth in the region.

3.2. Economic benefits

The costs of the end product potable water not only have to be compared with water purified on site, but also with costs for water supplied from distant locations.

The transport distance for water will influence the availability and the price of water. For example, some Mediterranean islands are almost completely without their own water supply and rely on water imports, because of large visitor volumes [4]. They have to import energy in the form of fossil fuel or water to serve their demands. An alternative energy-based water purification system would make them independent from main land supply [5].

PV is highly reliable and is often chosen because it offers the lowest life-cycle cost, especially for applications requiring less than 10 kW, where grid electricity is not available and where internal-combustion engines are expensive to maintain [6].

It is hard to give one cost figure, as most cost factors are strongly site-dependent, not only the predominant solar irradiation, but also the labor costs. Our calculations show that on a good site with high solar irradiation, the cost of water can be as low as €1/m^3 desalinated water for seawater desalination. In the context of off-grid applications it should not be forgotten that in many places the PV and water systems are rather competing with bottled water transports at prices of up to \$500/m^3 for premium brands than with large-scale water systems due to the lack of adequate distribution systems.

Government incentives further reduce the capital costs of renewable powered systems. So overall, PV powered water filtration systems are not only attractive for people with a "green attitude" but for customers in off-grid areas who calculate sharply.

4. Pilot plants at GE Global Research Europe and first commercial systems

For a thorough understanding of the PV and water system, extensive testing is indispensable. Therefore, we enjoy having an excellent test facility at GE Global Research Europe in Munich.

Fig. 2. Photovoltaic generator (45 kW peak) on the roof of GE Global Research Europe in Munich.

The test setup in Munich is specialized on the design of the PV array sizing. With the 45 kWp PV generator on the roof of our facility as shown in Fig. 2, it is possible to connect different combinations of solar strings in series or parallel. This enables experiments over a wide range of voltages and currents.

The test RO desalination unit equipped with two 2.5 "pressure vessels" (depicted in Fig. 3 on the left) with a permeate production of around 2.5 m^3/day for seawater allows experiments with different membrane types and water salinities. In addition, tests for a dynamic water production depending on the energy availability can be performed.

As not all water purification requires reverse osmosis and GE Water has excellent ultrafiltration hollow fiber membranes in the product portfolio, there is also a pilot system with these membranes based on the Homespring providing up to 7.57 m^3 (2000 U.S. gallons) clean water per day (Fig. 3 on the right).

A pilot unit with a low-pressure RO system for the filtration of brackish water, which has been donated during the Tsunami Relief efforts in Indonesia, and demonstration units in India in cooperation with GE Water & Process Technology India are operated and monitored to get firsthand experience with systems in their designated environment.

The topic has become mature and grown beyond a research program: Just recently it has been announced that GE is supplying its ecomagination-certified 200-Watt solar modules and 5000 Homespring ultrafiltration units that are capable of providing 7.57 m^3 (2000 U.S. gallons) of water, enough water to meet the daily

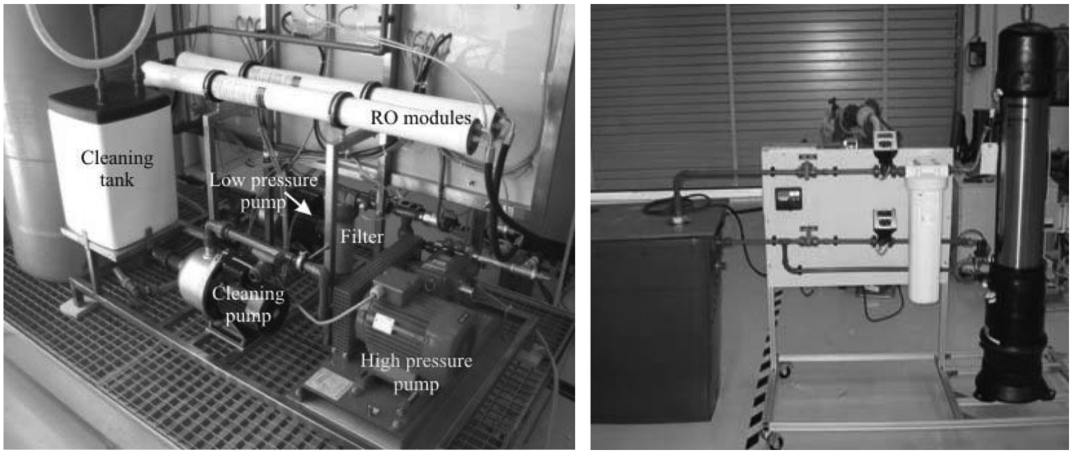

Fig. 3. Reverse osmosis (left) and ultrafiltration (right) pilot plants at GE Global Research Munich.

requirements for 500 people, to a new initiative, launched by a developer, to increase the availability of clean drinking water in rural areas of India and in other developing countries of Southeast Asia and Africa [7].

5. Conclusion

The ongoing research for PV powered water purification in Munich proves the feasibility of the concept. For a large market introduction, the costs needed to be optimized. A reliable and robust technical design is significant for the practical success of the system.

The system has to be energy efficient, since investment costs for renewable energies are still high compared to conventional grid powered applications. Therefore, membrane filtration has been chosen for the system.

For small-scale off grid applications, PV powered membrane water purification is more than an alternative to conventionally powered systems. With an optimized design it is also economically competitive.

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