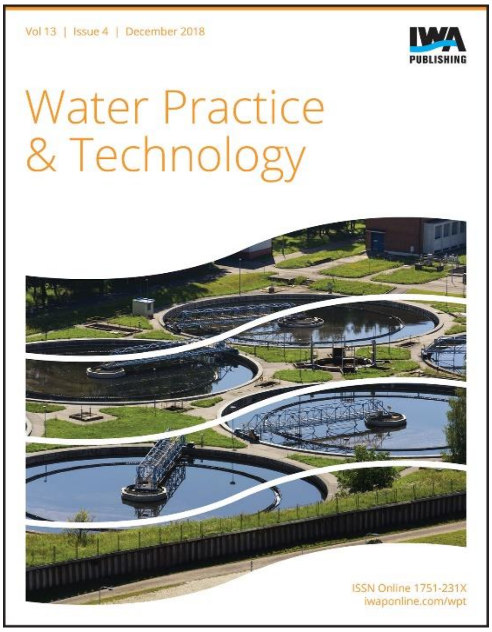
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771

Simulation of sizing of energy storage for off-grid decentralized wastewater treatment units: A case study in the Netherlands

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Abstract

Constant energy supply for decentralized wastewater treatment plants (DWWTPs) is crucial in order to ensure its functionality and prevent contamination of rivers and human illnesses due to pollution. However, power blackouts are a common problem in rural areas, which can affect the reliability of wastewater treatment plants. This paper presents a simulation study of sizing of solar photovoltaics and Sea-Salt batteries for powering a DWWTP working in 100% off-grid mode. The analysis is performed for two different DWWTPs: a prototype membrane bioreactor (MBR) and a Bever III compact wastewater aerobic system. The study is performed using the simulation package DEMKit developed at the University of Twente in the Netherlands. Results show that a solar photovoltaic system of 15 kWp coupled with a 20 kWh Sea-Salt battery may provide 100% of the electricity necessary during summer and up to 75% during winter in the Netherlands for the Bever III. In the case of the MBR, a photovoltaic system of 30 kWp in combination with a Sea-Salt battery of 50 kWh meets 100% of the electricity needs during summer and up to 65% during the winter in the Netherlands. Furthermore, in order to power the DWWTPs during the months of low sunlight, the dimensions of the solar photovoltaic system and the Sea-Salt battery needs to be increased by a factor of three.

Key words: batteries, decentralized, off-grid electricity, photovoltaics, wastewater

INTRODUCTION

Decentralized wastewater treatment plants (DWWTPs) are intended to treat wastewater before it is discharged back into natural watercourses when a centralized solution is not suitable. Rural areas are generally suitable for the installation of DWWTPs. A DWWTP is usually a recommendable alternative for sanitation in small settlements ranging from one to a hundred households. However, in rural areas electricity blackouts are more common than in cities, especially in developing countries. This situation is often due to the unreliability of the existing power grid. In literature a few cases are reported and explained in detail for countries such as India (Palit & Bandyopadhyay 2017), Zambia (Kesselring 2017), Tanzania (Burlando 2014), and Colombia (Olaya *et al.* 2016) among others. These studies all report that electricity supply is defective in rural areas and causes problems for the normal

Water Practice & Technology Vol 13 No 4
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development, implementation, and control of technologies that protect people and the environment. For instance, in the case of Colombia, the country has been increasing the sanitation coverage of wastewater treatment plants in recent years. Nevertheless, the selected solutions are mostly centralized systems for large communities. Even after the wastewater treatment systems are implemented, rapid population growth and poor planning make these technologies insufficient for treating the large flows and the organic loads that are generated in the cities. This can be observed in heavily polluted rivers near highly populated areas around cities like Bogota, Medellin, and Cali (Olivero-Verbel 2011).

To stay with the example of Colombia, rural areas here have lower sanitation coverage of wastewater treatment compared to large cities. The National Statistics Department of Colombia (DANE in Spanish) reported that only 17.3% of the rural population in 2016 has its wastewater treated before its discharge into rivers (Perfetti Del Corral 2017). From an economic and technical perspective, this is a large constraint when implementing a DWWTP. Some alternative solutions like the installation of conventional septic tanks are implemented. However, this technology may not be capable of achieving the removal of solids and organic matter required to protect the rivers and aquifers from pollution (Richards *et al.* 2017). A DWWTP with a low cost, small footprint, and which is simple to implement may be a good and possible alternative for households in rural areas with untreated or partially-treated wastewater. However, DWWTP requires electricity to power mechanical pumps, blowers, and electrical parts for its normal operation. A possible solution to achieve a constant supply of electricity for a DWWTP could come from creating a 100% off-grid solution based on renewable energies.

In literature, attempts have been reported to create off-grid, self-sufficient DWWTPs that are powered by renewable energy using technologies such as hydropower (Bousquet *et al.* 2017), wind turbines (Yang & Chen 2016), biomass (Naqvi *et al.* 2017), microbial fuel cells (Wang *et al.* 2017) and solar PV (Han *et al.* 2013). However, the implementation of these technologies as the only source of electricity for a DWWTP is still a challenge for large-scale implementation. For example, Gu *et al.* 2017 researched the feasibility of implementing self-sufficient wastewater systems, and Schäfer *et al.* 2017 investigated the available flexibility of the electricity supply of wastewater treatment plants. These studies concluded that the implementation of self-sufficient wastewater treatment systems is in principal possible, but further analysis of technologies, simulations, and methods to ensure its reliability need to be done in order to prevent environmental problems.

In this paper, we investigate if a combination of solar PV and Sea-Salt batteries is able to provide electrical power to a DWWTP for a whole year. We use a distributed energy management (DEM) methodology developed by our group in the Netherlands for smart grids (Hoogsteen *et al.* 2015; Hoogsteen 2017). For this, we analyzed the energy consumption of two innovative DWWTPs implemented in two cities in the Netherlands (a compact wastewater treatment system (commercial name Bever III) and a prototype membrane bioreactor (MBR) that can be operated at high biomass concentrations). The electricity consumption and the behavior of these systems are measured and monitored to observe their electrical behavior. Based on these results, the size of the solar PV and Sea-Salt battery needed to operate the DWWTPs in a 100% off-grid mode can be determined. The paper is organized as follows. In the next section, the background information on the two DWWTPs, the considered solar PV system, the Sea-Salt batteries and the DEMKit tool are described. In the following section, the experimental results are presented into two parts: the analysis of the solar PV and Sea-Salt batteries, followed by the dynamic sizing/characterization of the solar PV and the Sea-Salt battery powering the DWWTPs. The final section presents the conclusions.

Water Practice & Technology Vol 13 No 4
doi: 10.2166/wpt.2018.087

BACKGROUND INFORMATION

The decentralized wastewater treatment plants

The two DWWTPs being considered were tested under real conditions for the treatment of domestic wastewater. The goal is to model them in a scenario where they can operate entirely on electricity from photovoltaics and batteries. The wastewater treatment units have two main characteristics: first, a small footprint for installation, and second, a high wastewater treatment efficiency. The electricity consumption of both systems was monitored during an operating period of 30 days under real conditions to observe the energy consumption during the day and night. Then, based on the power load for 30 days, an estimate of the power consumption for a year was extrapolated. Before we come to these outcomes, the two DWWTPs are described below.

Prototype MBR

The innovative MBR system described by Barreto *et al.* 2017 is capable of increasing the treatment capacity of a conventional MBR, with high efficiencies. Figure 1(a) shows a description-setup and some pictures of the prototype MBR. The system was designed to cover the demands of 25 households. The MBR uses a supersaturated aeration system to provide oxygen at high biomass concentrations, allowing a higher treatment capacity. The system was installed in the Netherlands in the Harnaschpolder wastewater treatment plant in Delft and has been constantly researched in recent years.

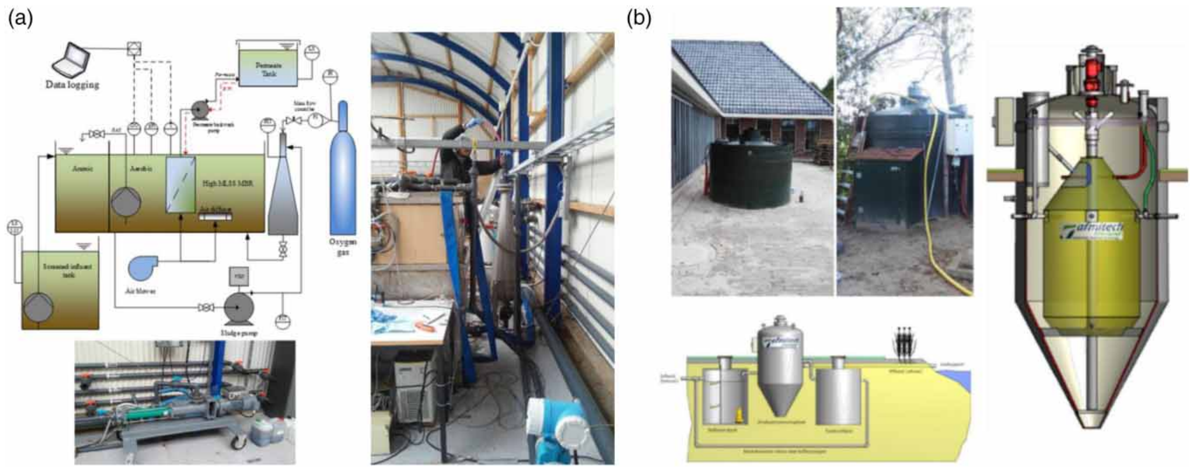

Figure 1 | (a) Schematic process flow diagram and pictures of the installed prototype MBR setup in Delft, the Netherlands; (b) decentralized wastewater treatment system Bever III from the company Afmitech in Friesland, the Netherlands.

Decentralized wastewater treatment system (Bever III)

The Bever III is a decentralized wastewater treatment system (Bever III) developed by the company Afmitech Friesland (Boule De Jong 2016). Figure 1(b) shows the setup of the DWWTP Bever III and some pictures of the installed system. The Bever III was designed for the treatment of wastewater equivalent to 10 households in the city of Joure in the Netherlands. The Bever III is a compact biological wastewater treatment unit. The system combines the aerobic treatment tank with a settler in one single unit. This system has BOD (biological oxygen demand) and COD (chemical oxygen demand) removal of up to 95%.

Water Practice & Technology Vol 13 No 4
doi: 10.2166/wpt.2018.087

Solar PV and the Sea-Salt battery

Solar PV panels of 300 W (LG Neon 2 black Cello Design) were used as a main electrical source for the design characterization. The modules have an energy efficiency of up to 18%. The used solar irradiation data was collected from a real case study in Lochem, the Netherlands during 2016 (Hoogsteen *et al.* 2015) and is given with a minute time resolution.

In order to be able to store the electricity from the solar PV, a Sea-Salt battery was used. The battery was developed by the company Dr Ten as part of the ongoing research of electrochemical storage systems (Ten Kortenaar 1999; Quintero Pulido *et al.* 2017). The battery is currently being researched at the University of Twente for use in smart grid applications (Quintero Pulido *et al.* 2018). The Sea-Salt battery is a technology based on a mixture of sea salts (mostly sodium chloride) and carbon graphite. The battery has a low cost and long cycle capacity, making it a good candidate for storage of electricity from renewable energies. One advantage of the battery is the capacity to be 100% discharged without damage. In this paper, we used the Sea-Salt battery as an ideal device that can be charged to 90% and discharge until 20% of its full capacity. During the simulation deterioration of the battery was not taken into account.

The DEMKit software

The DEMKit is a software tool developed at the University of Twente (Hoogsteen 2017). The goal of the software is to provide a simple way for simulating and executing a DEM. The tool is used in smart grid applications for controlling devices. Many DEM methodologies are often used in academia for simulations that are developed in complex software environments that require various intertwine domains in specific tools. The complexity of this system usually affects the transition from such models to a proof of concept. In contrast to this, the DEMKit is capable of simulating, co-simulating, and generating simple demonstrations. The software was developed using Python language, which allows users to use this platform with different operational systems. Furthermore, the data is stored in an InfluxDB and can be visualized in Grafana or any other graphic environment.

The system configuration in the DEMKit with the solar PV, Sea-Salt battery, and the DWWTPs is shown in Figure 2. All the components in the system provide constant feedback to validate the data and the fleet controller is connected to multiple controllers for the DWWTP with the battery and solar PV. The data to be studied gets collected in the host system and then stored in the database.

RESULTS

Design of a solar PV-battery

Table 1 shows a standard calculation for sizing a solar PV and batteries for an off-grid scenario. The calculation is performed to power a Bever III and an MBR for wastewater treatment for one year. In order to calculate the total solar PV power production in one day, an estimation of 3 h/day of sunlight was used (this value is based on the average number of sunlight hours per day in a year in the Netherlands). Based on the calculation presented in Table 1, the MBR needs a solar PV of 30.2 kWp and a Sea-Salt battery of 48 V and 4.6 kAh. On the other hand, the Bever III needs a solar PV of 14.4 kWp and a Sea-Salt battery of 48 V and 2.2 kAh. The calculation is performed only on the basis of the power that can be harvested using solar PV in a day. In this paper, we used this calculation as a base to start the simulation. The details of the test are explained in the next section.

Water Practice & Technology Vol 13 No 4
doi: 10.2166/wpt.2018.087

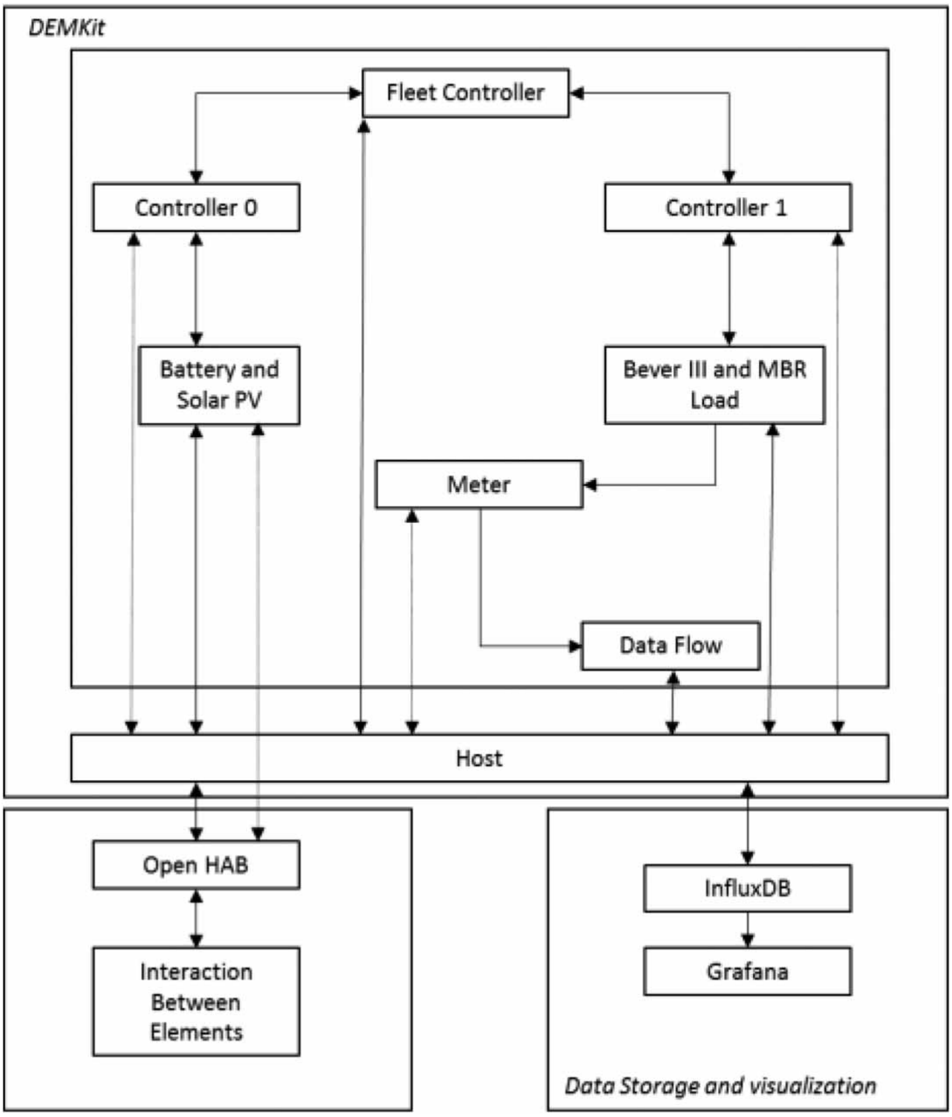

Figure 2 | Diagram of the DEMKit platform with a model and external software.

Performance simulation of solar PV and the Sea-Salt battery

For the simulation, the data collected from solar energy during 2016 is used with one-minute distribution. The MBR and the Bever III power load was measured for a period of 30 days. Then the data was extended for one year, assuming a constant electricity consumption behavior of the DWWTPs during one year.

In the DEMKit, the solar PV and the DWWTPs power load data are connected in the simulation environment in order to power the DWWTPs when electricity is available from the solar PV. The surplus of electricity from the solar PV is stored in the ideal Sea-Salt battery. The battery is charged with the solar energy and discharged during the periods where sunlight is not available or not sufficient to power the DWWTPs. Figure 3 shows the simulation results of the solar PV and the Sea-Salt battery used to power a DWWTP during the months of June 2016 and November 2016. In the case of the MBR (Figure 3(a) and 3(b)), the results of June 2016 show that the battery state of charge (SOC) is above 20 kW during the entire month and the solar PV produced a peak power of 30 kWp on the sunniest day (4th of June).

On the other hand, during November 2016 the solar PV generated a peak power of 12 kWp in the sunniest day of the month (10th of November) and the Sea-Salt battery was discharged fully during the periods of low sun irradiation. This is more noticeable in the periods between the 10th to the 20th and

Water Practice & Technology Vol 13 No 4
doi: 10.2166/wpt.2018.087

Table 1 | Solar PV and Sea-Salt battery sizing calculation based on the power consumption of MBR and Bever III

SOLAR PV CHARACTERISTICS	Bever III	MBR	Unit
DWWTP avg. energy consumption	1,080	2,300	kWh/month
AC/0.85 = DC correction factor	1,271	2,706	kWh/month
DC consumption per month	42	90	kWh/day
DC consumption per day	42,353	90,196	Wh/day
PV modules			
Power	300		Wp
Solar PV voltage	32.5		V
Solar PV current	9		A
Daily avg. solar radiation in the Netherlands	3		h/day
Total power produced daily by each PV module	900		Wh/day
Number of modules needed	48	101	
Possible system configuration			
Voltage	750	1,600	V
Current	18	18	A
Power produced/day	43,200	90,900	Wh/day
Modules in series	24	50	
Modules in parallel	2	2	
SEA-SALT BATTERY CHARACTERISTICS	**Bever III**	**MBR**	**Unit**
Capacity	2,000	2,000	Ah
Voltage battery system	48	48	V
Total daily Ah requirements	882	1,879	Ah/day
Recommended reserve time	2	2	days
Percent of usable battery capacity	0.8	0.8	%
Minimum battery capacity	2,206	4,698	Ah
Batteries in parallel	2	3	
Batteries in series	32	32	
Total number of batteries	64	96	
STANDARD BATTERY DIMENSIONS	**Bever III**	**MBR**	**Unit**
Voltage	1.5		V
Capacity	2,000		Ah
Length	51.3		cm
With	27.3		cm
High	24.2		cm
Weight	85		kg
Area needed for batteries	89,631	134,447	cm^2
	9	13	m^2
Total weight	5,440	8,160	kg
	5.44	8.16	tons

the 24th to the 30th of November. In this month, the solar PV with the Sea-Salt battery was still capable of supplying up to 65% of the demand. A similar case is observed for the Bever III (Figure 3(c) and 3(d)). During June 2016 the solar PV had a peak power of 15 kWp on the sunniest day (4th of June) and the Sea-Salt battery SOC was above 12 kW, supplying enough electricity to the Bever III during the month of June 2016. However, in November 2016 the solar PV produced a peak value of 7 kWp on the sunniest day (10th of November) and the Sea-Salt battery was capable of covering

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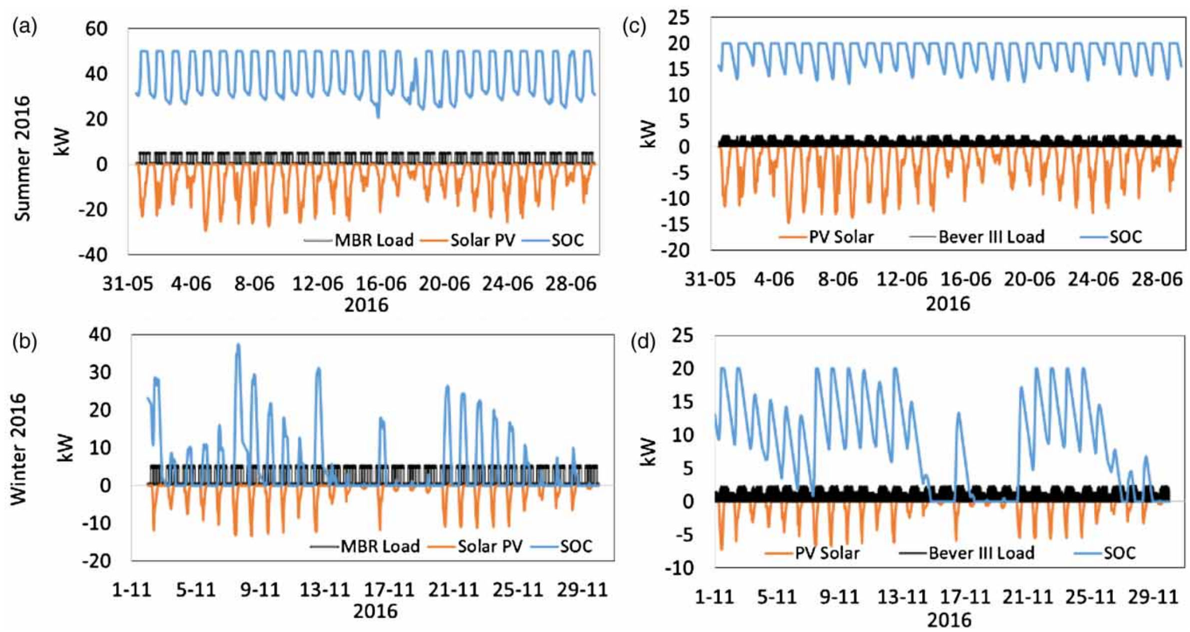

Figure 3 | Energy profiles of the DWWTP using solar PV and the Sea-Salt battery in a 100% off-grid scenario: (a) MBR during June 2016; (b) MBR during November 2016; (c) Bever III during June 2016; and (d) Bever III during November 2016.

the demand of electricity during almost 75% of the month. In both cases, the MBR and the Bever III were capable of operating 100% off-grid in the month of June. However, in the month of November, both systems could only provide around 70% of their demand.

In order to achieve a 100% off-grid scenario for the DWWTPs during the month of November, the capacities of the solar PV and Sea-Salt battery were theoretically increased to determine the size of the off-grid system needed to meet the energy requirements. Figure 4 shows the simulation results of the oversized energy profiles for the DWWTPs during the months of June and November 2016.

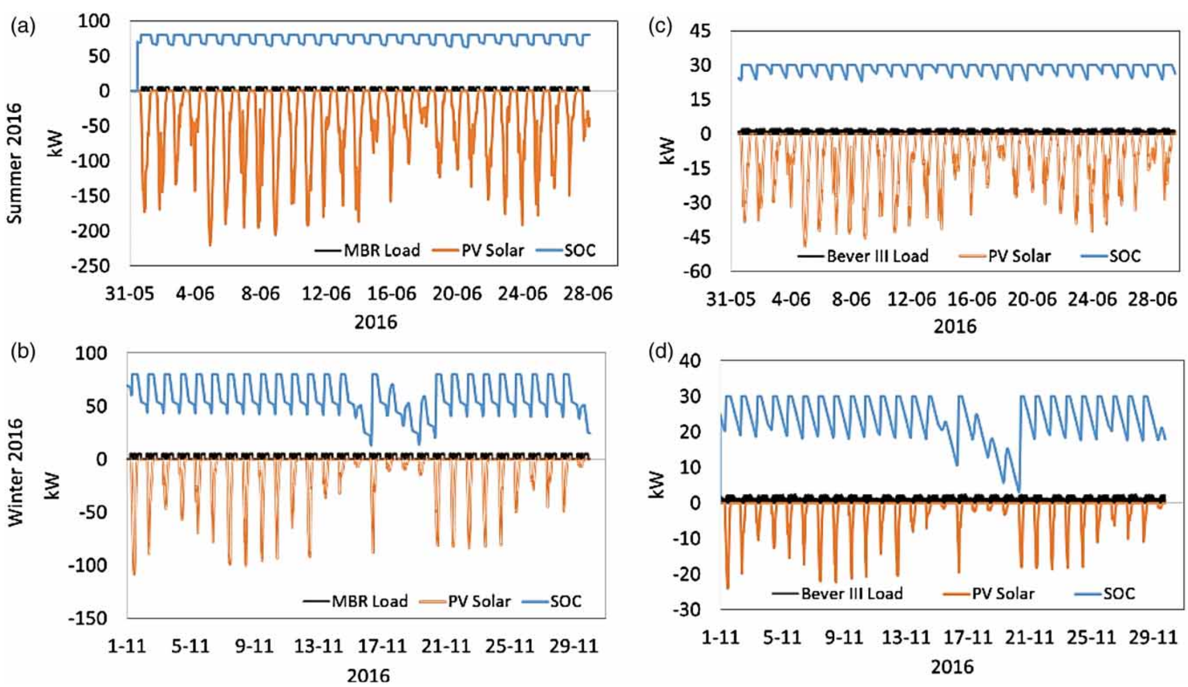

Figure 4 | Oversized energy profiles for the DWWTP using solar PV and the Sea-Salt battery in a 100% off-grid scenario: (a) MBR during June 2016; (b) MBR during November 2016; (c) Bever III during June 2016; and (d) Bever III during November 2016.

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As expected, during June 2016 the MBR and the Bever III could operate without energy shut down. In detail, in the case of the MBR (Figure 4(a)), the solar PV shows a peak power of 240 kWp on the sunniest day (4th of June) and the Sea-Salt battery had 60 kW of electricity reserve during the entire month. In the case of the Bever III, the peak power was 50 kWp on the sunniest day (4th of June), with a reserve battery SOC of 25 kW (Figure 4(c)). Further, during the month of November 2016, both DWWTPs could be powered during the month in a 100% off grid mode. In detail, the MBR (Figure 4(b)) had a solar PV peak power of 100 kWp during the sunniest day (10th of November) and a Sea-Salt battery SOC of 10 kW. On the other hand, the Bever III had a peak power of 22 kWp and a Sea-Salt battery with a minimum SOC of 5 kW during the entire month.

The cases observed in Figure 3 and 4, show that standard sizing of solar PV and batteries as shown in Table 1 may not achieve a 100% off-grid scenario for a DWWTP during certain periods of the year. Simulations and smart power steering of the DWWTP may be an option to provide a degree of flexibility to the characterization of the solar PV and battery. In addition, more research should be performed on cost analysis and alternative technologies to provide the electricity needed during low sunlight periods.

CONCLUSION

This paper shows that the proposed method can be used in a simulated environment to determine sustainable energy sizing/characterization for powering DWWTPs working in off-grid mode, even during months with low solar radiation. The results definitely indicate that solar PV and a Sea-Salt battery can provide the energy requirements of a DWWTP. However, in order to power a DWWTP during months of low sunlight, the dimensions of the solar PV and the Sea-Salt battery need to be increased by a factor of three. The simulations performed with the DEMKit tool show that a solar PV of 15 kWp and a 20 kWh Sea-Salt battery may provide 100% of the electricity necessary during the summer and up to 75% during the winter in the Netherlands for the Bever III. In the case of the MBR, it is necessary to have a PV system of 30 kWp and a Sea-Salt battery of 50 kWh to meet 100% of electricity needs during the summer and up to 65% during the winter in the Netherlands.

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