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Modelling Small-Scale Stand-Alone (PV) Energy Systems with Reverse Osmosis Integration

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Abstract: Australia has a vast land mass characterised by more than 35,000km of shore-line and an abundance of renewable sources (e.g., solar and wind energy). Despite the existence of much potential to utilise sustainable pathways of power generation, there remains a general reliance on electricity generated from larger plants which are mostly grid-connected but fossil-fuel operated. In Western Australia, only a fraction of its coastal areas and inland mass is serviced by the South West Interconnected (grid) System. For the majority of its regional communities, decentralised power generation forms the prime source of power provision. This exacerbates the situation with regard to accessing electricity due to the elevated cost of obtaining fuel (for power generation) as well as reliance on smaller, less-efficient, generator sets. For many small (remote) or coastal communities' access to potable water is limited alongside good availability of renewable energies. This provides opportunity for utilising renewably powered stand-alone energy systems to help deliver the power needed to directly run utilities, operate desalination systems and reduce the associated emissions footprint.

This investigation uses modelling to analyse the performance of small-scale stand-alone (energy) systems incorporating Reverse Osmosis (RO), providing up to 15litres/day potable water. Through inclusion of physical models representing different hardware components in a Solar-Photovoltaic (PV) system, this research provides an insight into the interaction between the availability of solar energy, energy conversion into DC electric power via PV panels, power conditioning (DC to AC), battery charging/discharging and the power needed for desalination. This paper not only highlights a modelling methodology for such systems but also demonstrates how individual (system) components may be characterised and seasonal variations (of solar irradiance, localised wind speed and ambient temperature) included in the simulations. Simulations undertaken include consideration for unit quantities (solar irradiance per square metre and temporal resolution of predicted irradiance to 1hour). Such approaches provide a basis for future studies into energy system scalability, energy efficiency in small-scale (stand-alone, renewably powered) desalination systems as well as the deployment of other (non-battery) energy storage media to increase renewable energy utilisation.

Modelling yields solar irradiance predictions which are compared to measured data at locations typical of Perth, West Australia. The models also accommodate considerations for the effects of localised wind speed and ambient temperature on predicted PV panel performance. This yields more accurate conversion characteristics of PV and helps provide better resolved (dynamic) renewable energy (input) data for the simulations. Laboratory based experiments are used to verify the efficiency, water recovery ratio and power characteristics of RO as well as other energy system components. Simulations undertaken using MATLAB help analyse the energy system over a yearly period. Results allow predictions of total (renewable) energy availability, excess (renewable) energy (not captured due to battery capacity) and total potable water production (under two different amounts of daily water demand). Outcomes are discussed with regard to the benefits of incorporating more advanced predictive modelling methodologies and alternate means of (battery-free) energy storage for stand-alone PV energy systems.

Keywords: *Renewable Energy, Photovoltaic, Reverse Osmosis, Modelling, Simulation.*

1. INTRODUCTION

Continued growth in global energy demand means increased fossils fuel consumption and wider emissions. The International Energy Agency (IEA, 2010) estimates that only 0.2% of total power was generated renewably in 1973 compared to 1.1% in 2009, with a corresponding increase in power generation based on fossil-fuels from 3724Mtoe to 5170Mtoe (1Mtoe=11,630 GWh). Effects of climate change and demographics mean "the need is urgent for large-scale production of potable water from alternative water supplies for Australia's metropolitan regions, including affordable and sustainable desalination technologies" (NCED, 2011, p. 5). Access to potable water for many small (marginalised) or coastal communities is also limited alongside good availability of renewable energy sources (solar or wind). This provides an opportunity to utilise renewably powered stand-alone energy systems to power everyday utilities and operate desalination. In this regard, PV (Mahmoud, 2003; Bourouni and Chaibi, 2009; Abdallah, Abu-Hilal and Mohsen, 2005) as well as other renewable energies have been used (Bourouni, Ben M'Barek and Al Taee, 2011; Manolakos et al., 2008; Kalogirou, 2005; Kershman, Rheinlander and Gabler, 2002).

Desalination systems based on PV form the largest renewable energy conversion method in potable water production with RO being the most common pathway (Mathioulakis, Belessiotis and Delyannis, 2007). The attractiveness of solar-PV lies in its good reliability and relative ease of installation particularly for small-scale systems. This is well aligned with strategic water industry issues, namely "development of simple, low maintenance renewable energy systems that can supplement power supply for small desalination facilities" (NCED, 2011, p. X). Optimally integrating desalination into energy systems necessitates quantifying total renewable energy availability, its conversion efficiency into electrical power and subsequent utilization or storage. This can be facilitated by modelling energy system components (Deshmukh and Boehm, 2008) and desalination processes (Koroneos, Dompros and Roumbas, 2007). Although fairly complex modelling techniques have been applied (Bourouni, Ben M'Barek and Al Taee, 2011), where small, stand-alone renewable powered desalination systems are concerned there exists a need for more research into integrating battery-free energy storage (e.g., via hydrogen) and energy recovery (Mathioulakis, Belessiotis, & Delyannis, 2007). For any specific geographical location, undertaking such research first necessitates analyses into overall renewable energy availability. Studies into the effects of system design and operational parameters on water production and excess energy (not stored) are also needed. These latter issues form the focus of this paper which considers conditions typical of Perth. The research uses both modelling and experiments.

2. MODELLING - METHODOLOGY

The overall system modelled is shown in Figure 1 with simulations conducted in the MATLAB/Simulink environment. Alternative simulation software has also been used in other research into renewable energy systems and reverse osmosis (Geovanni, Orlando, Rafael, Alberto, & Sebastian, 2010). A range of laboratory based measurements were undertaken to establish relevant model parameters and (hardware specific) operational characteristics of system components. Figure 1 also depicts many of these hardware components and the experimental set-up. Simulating small-scale systems powered by PV, and incorporating RO, typically necessitates three basic energy aspects be resolved in modelling:

2.1. Renewable Energy Conversion

Photovoltaic panels convert solar irradiance (kW/m^2) into renewably generated (un-conditioned raw) DC electricity. Integrating PV power into modelling should also ideally take into account PV panel current-voltage (I_{PV}-V_{PV}) characteristics, which are hardware reliant but a factor of incident solar irradiance (I_G), and panel temperature (T_{PV}). Both I_G and T_{PV} are location dependant and dynamic (time dependant and seasonal).

- **Solar irradiance:** This data forms the basis for energy input into simulations. Although (location specific) meteorological data based on cumulative (total) daily solar irradiance is available, modelling gave (global) irradiance (I_G) resolved to 1hr. This allowed (energy system) simulations to be hourly based rather than daily, hence pseudo-dynamic. For this purpose, global irradiation models are used to predict hourly resolved I_G over 365 days. Table 1 shows parameters used in the models which are detailed elsewhere (Jamil Ahmad & Tiwari, 2011). To validate the veracity of hourly resolved I_G predictions, Figure 2 shows comparisons between total measured solar irradiance (BOM, 2011a) with 24hr (daily) predictions of I_G. Figure 3 also gives the variation of (hourly resolved) I_G at the longest and shortest (solar) days for a typical Perth location. In Figure 3, 12:00 corresponds to the sun crossing the Meridian and all solar hours plotted include standard time-zone corrections (Jamil Ahmad & Tiwari, 2011).
- **PV panels**: Table 2 gives basic hardware specifications and relevant model parameters for PV panels. The I_{PV}-V_{PV} characteristics are shown as a function of incident solar irradiance in Figures 4 and 5.

Figure 6 gives I_{PV}-V_{PV} as function of PV panel temperature (T_{PV}). In simulations, panel temperatures were derived using measured ambient temperatures (T_A) and localised wind speed (W_S). A sample of the wind data used (BOM, 2010c) is plotted in Figure 7. Considering the effects of T_{PV} and W_S on PV panels gives more accurate representations of overall power P_{PV} ($P_{PV} = I_{PV} * V_{PV}$), the effects of which are shown in Figure 8. The specific models which can be used to derive these I_{PV}-V_{PV} characteristics and predict (T_{PV}), based on W_S and T_A, are listed by Deshmukh and Boehm (2008). In the simulations, data for T_A (BOM, 2011b) was set at the peak temperature for any given day and is approximately around solar noon.

2.2. Control and Power Conversion

These are components which facilitate energy management and include, in the most basic form, inverters to convert (raw) DC power into AC power and then used to run utilities (including RO). Energy systems may also potentially include means of energy storage (commonly done with batteries) as well as power controllers to regulate the charging/discharging of energy storage media as well as the operational status of the overall system at any instant of time. It is also worth noting here that whilst many PV/RO systems include battery storage (Mahmoud, 2003) others have essentially been operated with no excess energy storage and are battery-free (Manolakos et al, 2008). Because (I_G) is highly dynamic, integrating storage media into energy systems is designed to provide supplemental power to RO over periods when incident solar radiation is insufficient to generate enough power.

- **Controller**: This can take the form of a Programmable Logic Controller (PLC) that has pre-set conditions or may feature more complicated methodologies, such as predictive techniques (Agbossou, Bilodeau, & Doumbia, 2009), to regulate the operational status of an energy system. Controllers based on basic PLC architectures, similar to the one depicted in Figure 1, may incorporate three distinct operational modes. Mode-I involves PV power used to only run utilities which may run on DC or AC power and is likely if available solar energy is relatively low. Mode-II involves PV power being used to charge energy storage media only (e.g., batteries) and typically applies if utilities are not operating. Mode-III extends to PV power supplying both utilities (DC or AC) and charging energy storage media. Whilst power controllers may fluctuate between these operational modes through the day, the likelihood of running systems in Mode-III operation increases during summer when good solar irradiance exists. In the simulations undertaken, the system is assumed to operate in either Mode-I or Mode-III based on the availability of solar energy. When RO is not operational, simulations only assume Mode II.
- **Energy storage**: Based on the availability of hourly renewable energy and the respective load (demand), there may be an excess of renewable energy. Energy storage is commonly achieved using batteries, although other forms of energy storage also exist like capacitors or even hydrogen. The simulations have used battery storage with a peak (charge) capacity of 55Ah at 12.5V discharge potential (around 687Whr). In the simulations undertaken, the rate of battery charging was not considered. Instead, the charging model used is based on energy availability. For RO to operate at its rated DC power (P_{RO}=50W), device specifications require (battery) potential at 11.0-12.5V. Based on this, system modelling assumes the battery is fully-charged at 12.5V (100%) and fully depleted beyond “practical” use at 11V (0%). When the battery is at full capacity, its State of Charge (SOC_{BAT}) is said to be at 100%.
- **Inverter**: The inverter is responsible for converting DC power which is delivered from PV panels or discharged from batteries into AC power to run utilities. Although the experiments and simulations undertaken are based on an RO unit operating only with DC power, the efficiency of the inverter was also assessed as part of the experiments undertaken. Figure 9 shows the effects of supporting an external load of 50W (commensurate with the rating of the RO unit) through either discharging DC power from a battery (does not pass through the inverter) compared with supporting a similar AC load (discharged battery power passes through the inverter). The data shows the conversion of DC power to AC is approximately 98% efficient (e.g., for a fully charged battery the energy system delivers around 12.4V in AC compared to around 12.7V in DC).

2.3. Potable Water Production

Small-scale RO units typically include pre-filters (particulate removal), a pump to yield needed osmotic membrane pressures and energy recovery to reduce specific energy consumption when making a unit amount of water. These units also have a recovery ratio for the volume of (potable) water made per unit volume of feedwater. Tests ascertained specific energy consumption at $E_{RO,SC}$=9.6kW-hr/m^3 and recovery ratio at 10%. Both device specific parameters are incorporated into models and distilled water was used as feedwater for simplicity throughout experiments.

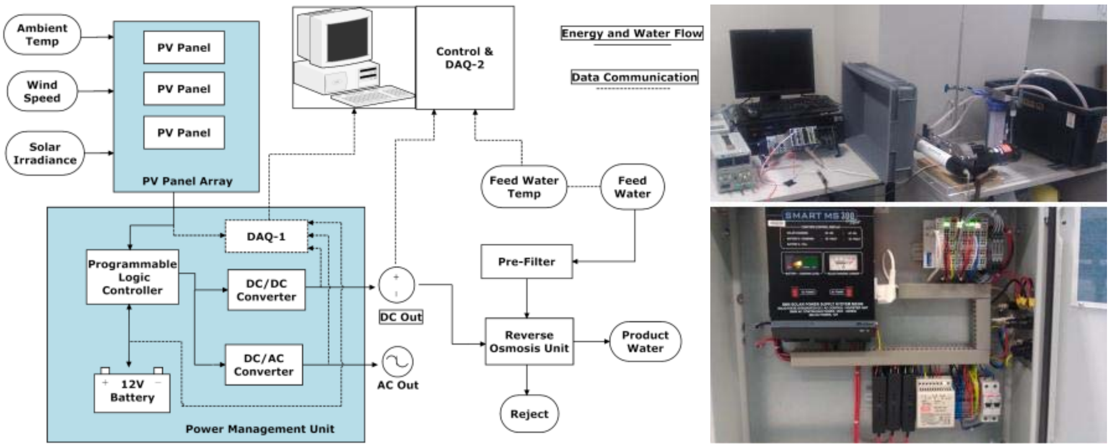


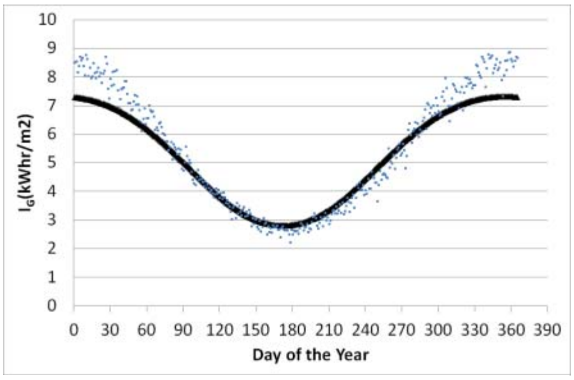
Figure 1 - Left: Overall layout of system showing components modelled and data acquisition. Right: Experimental setup with RO and Power Management Unit.

Table 1. Solar irradiance modelling parameters.

Parameter	Value	Parameter	Value
I_{SC} (irradiance constant)	1367 W/m^2	Longitude (location)	115.8°
I_D (diffuse radiation)	$0.25I_B$ (beam radiation)	Latitude (location)	-31.75°
A (model constant)	1000	B (model constant)	0.18

Table 2. Solar-PV panel specifications (each) and relevant modelling parameters (Heckert Solar, 2009)

Parameter	Value	Parameter	Value
P_{MAX}	$130W_P$	Efficiency	13.61%
T_{REF} (reference temperature)	25°C	U_{OC} (voltage max load)	17.2V



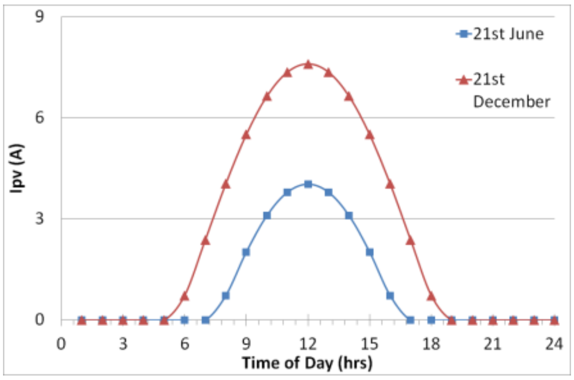
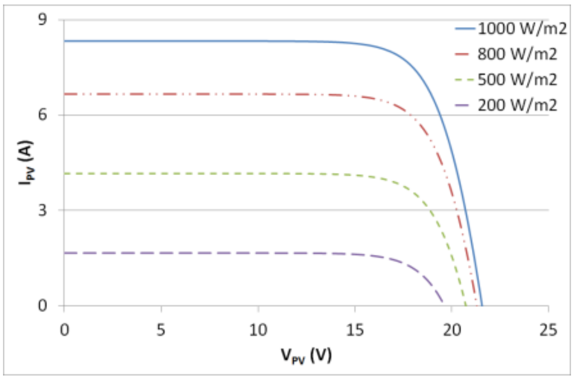


Figure 2- Validation of irradiance. Dots: measured daily I_G (data: BOM, 2011a); line: modelling.

Figure 3- Modelled daily variation of PV current for a short and long (solar) day.



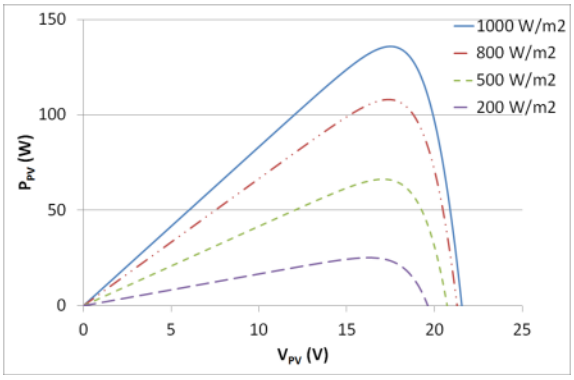


Figure 4- Modelled PV characteristics: current versus voltage at varying I_G (T_A=25°C ,W_S=0m/s).

Figure 5- Modelled PV characteristics: power versus voltage at varying I_G (T_A=25°C, W_S=0m/s).

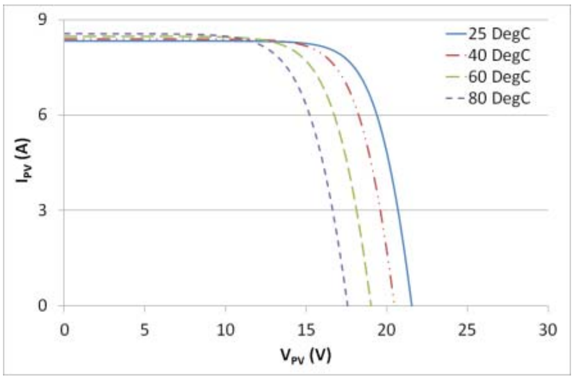


Figure 6- Modelled PV characteristics: current versus voltage at varying T_{PV} (W_S=0m/s).

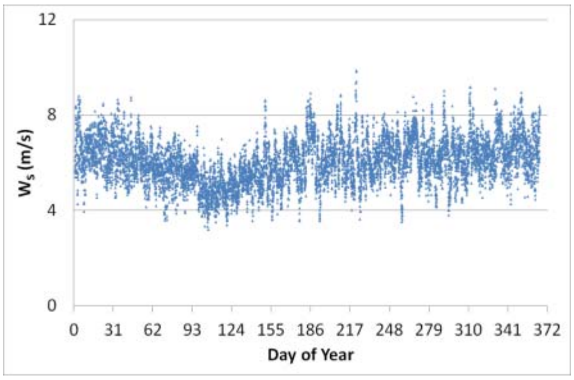


Figure 7- Annual variation of wind speed for a Perth based location (data: BOM, 2011c).

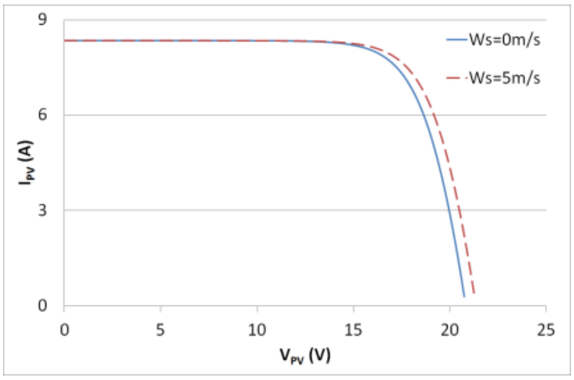


Figure 8- Modelled PV characteristics: current and voltage at varying W_S (I_G=1000W/m^2, T_A=25°C)

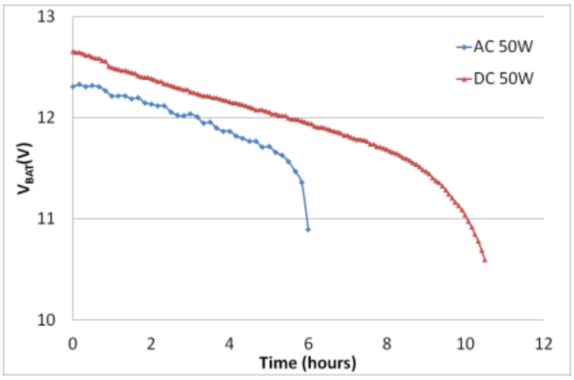
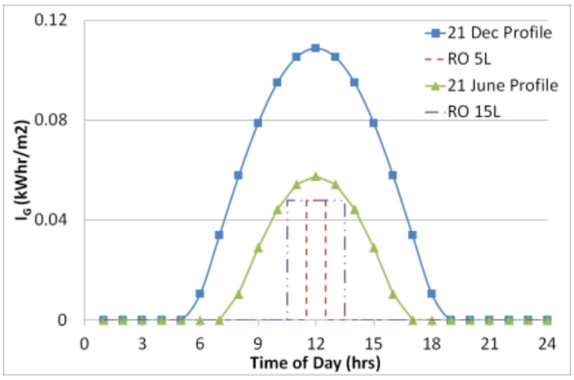


Figure 9- Measured battery discharge (55Ah, T_A=25°C) over time at 50W (DC, AC).

3. SIMULATION - RESULTS AND DISCUSSION

Using predictions of hourly resolved energy from solar-PV, simulations yield analyses for the state of battery charge/discharge and the effects of desalinated water volume on the operational status of the energy system shown in Figure 1. The operational status can be defined as the system's ability to support utilities (such as RO), maintain energy storage (SOC_{BAT}) at 100% for as long as possible and (potentially) yield excess (renewable) energy for seasonal storage. Quantifying the amount of energy storage is needed in order to meet demand but overcome seasonal fluctuations of solar irradiance. In the results presented, two different volumes of desalinated water via RO are shown (5L/day and 15L/day). This simulates varying load from utilities on the energy system. Additionally, different numbers of PV panels are also simulated to represent changing renewable energy availability. Such demand/supply analyses also provide information on the effects of system scalability on operational status. Since each PV panel has an effective area of about 0.87m^2, simulations are undertaken for panel areas of A_{PV}= 0.87m^2 (1 panel), 1.75m^2 (2 panels) and 2.6m^2 (3 panels) in addition to A_{PV}=1m^2 (unit area of PV panel).

Results presented in Figure 10 give the amount of solar irradiance available (per unit area) and the equivalent energy needed (kWhr) to run RO over short and long solar days. These results indicate energy demand (from RO) should be satisfied even with A_{PV}=1m^2. It is also worth noting that no battery charging is being simulated in this figure which essentially models an energy system with a PLC running in Mode-I. Figure 11 visualises the seasonal effect of renewable energy availability for different numbers of PV panels (again under Mode-I as there is no storage). The effect running in Mode-I and Mode-III on the potential to realise excess energy is also shown in Figure 12. As expected, these results indicate that when both RO and battery charging are underway, the amount of excess energy available for storage is reduced. Excess energy available for storage is shown in Figure 13 and this appears to peak when solar irradiation is also at maximum (Figure 2). Seasonal storage of energy is thus more likely during these periods of high I_G. However, Figure 13 also shows that in some periods of the year there is a general lack of excess energy for storage. The shortage of excess energy combined with lower energy availability (Figure 2) means SOC_{BAT} is quickly depleted as shown in Figures 14 and 15. These simulations do not however consider specific (physical) models for the battery and its SOC_{BAT} which is possible in renewably powered energy systems (Nafeh, 2011).



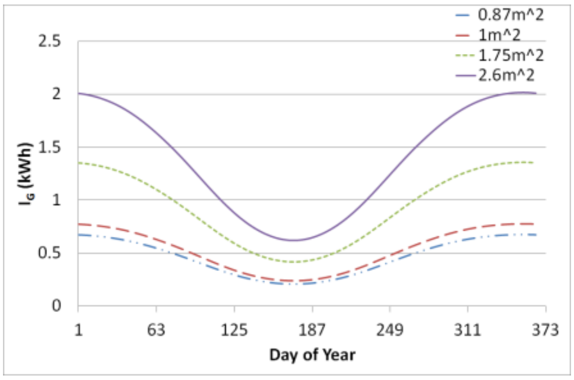
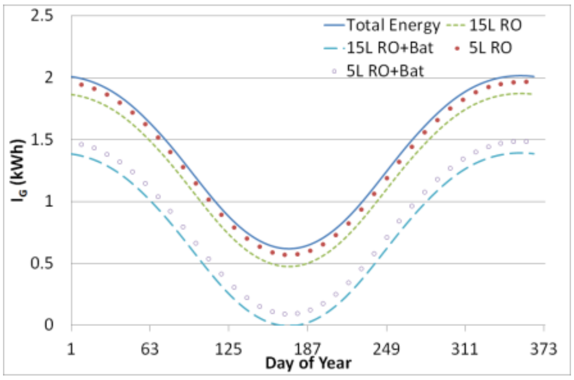


Figure 10- Solar irradiance for the shortest and longest day with energy requirements (kWhr) for desalination of 5L and 15 litres per day.

Figure 11- Solar energy available at varying PV panel area (1 panel area A_{PV}=0.87m^2, 2 panels A_{PV}=1.75 and 3 panels A_{PV}=2.6m^2).



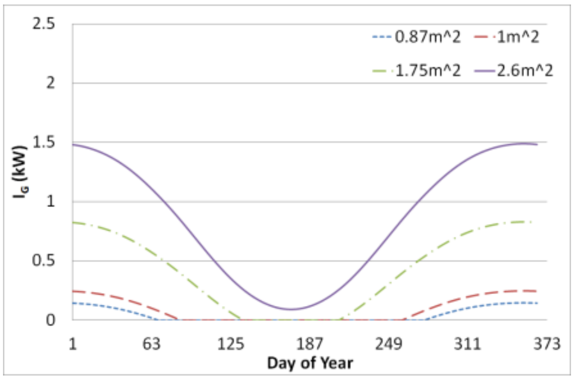
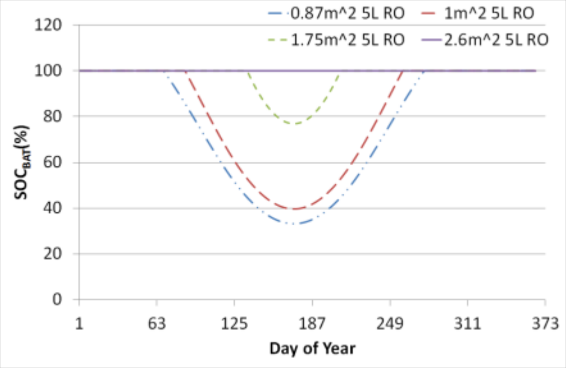


Figure 12- Excess energy available after RO and battery charging for A_{PV}=2.6m^2 (circles: 5L/day RO; dashed lines for 15L/day RO)

Figure 13- Excess energy available at varying A_{PV} (5L/day RO and battery charge to SOC_{BAT}=100%).



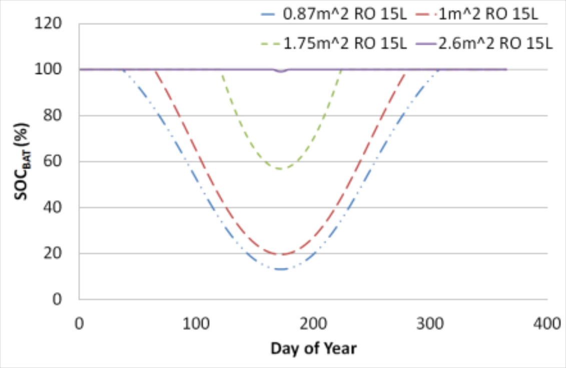


Figure 14- SOC_{BAT} at varying A_{PV} for a water production at 5L/day.

Figure 15- SOC_{BAT} at varying A_{PV} for a water production at 15L/day.

4. SUMMARY AND FUTURE WORK

A modelling methodology is given for small-scale solar-PV systems. Based on limited data, models appear able to give fairly good predictions of renewable energy availability. Both ambient temperature and localised wind speed should be considered if more accurate predictions of solar-PV are sought. Seasonal variation of renewable energy highlights the need to use energy storage to operate utilities (such as RO) during periods of low solar irradiance. The need for excess energy storage is exacerbated as the power needed to run utilities increases (more water or less efficient RO) and renewable energy availability falls. Energy storage media other than batteries should be considered particularly for protracted periods (Bielmann, Vogt, Zimmermann, & Zuttel, 2011), techniques capable of optimising systems used (Agbossou, Bilodeau, & Doumbia, 2009) and energy recovery integrated into RO (Mohamed, Papadakis, Mathioulakis, & Belessiotis, 2005).

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