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# The off-grid PV-battery powered home revisited; the effects of high efficiency air-conditioning and load shifting

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ABSTRACT

The potential for residential households to go 'off-grid' with a photovoltaic-battery storage system in a location where a conventional connection to the electricity network is available has received recent attention. Several studies have reported that at present, in Australia the economics are not justified. These studies have used unmodified electricity consumption profiles from grid-connected households as input to their off-grid system analyses. However, households looking to go off-grid may be motivated to make basic modifications to their consumption pattern so as to minimise the size of the PV-battery system. Here the effects of (i) shifting the booster time of electric storage hot water system to coincide with peak irradiance, (ii) improving the efficiency of air-conditioning appliances, and (iii) shifting pool pump operation and improving pump efficiency are compared and assessed. The analysis uses sub-circuit measurements of electricity consumption from 28 households for up to 2 years. Results show that the hot water and air-conditioning adjustments in particular can improve the economics considerably, even accounting for the fact that the appliance efficiency improvements also lower the grid connected electricity costs. For households seeking to go off-grid, any changes to electricity load profiles that provide a more uniform match of consumption to generation in particular, improve off-grid system economics in comparison to grid electricity, since the true cost of delivering electricity from the grid at peak times is typically spread across all consumers.

## 1. Introduction

Residential buildings relying solely on solar photovoltaic panels combined with battery storage, with no connection to the conventional electricity network, are currently attracting considerable interest, both in the research and wider communities. Off-grid systems are indeed nothing new, generators have been powering off grid houses and communities since the invention of the internal combustion engine. However, key attractions of solar-battery systems are there zero emissions, silent operation and minimal maintenance.

Off grid residential power generation is often associated with hybrid systems powered by a combination of a fossil fuel and renewable energy sources (for example diesel generators combined with solar (Tutkun, 2014), gas engine and solar (Treado, 2015) or diesel and wind power (Merei et al., 2013). Internationally, most research has focused on systems aimed to deliver affordable and reliable electricity to non-electrified houses in developing countries (see for example Ghafoor and Munir, 2015; Lemaire, 2011). In developed countries with an existing, reliable electricity grid, off grid residential system design studies using a single energy source are limited, a reflection of both the intermittent nature of renewable energy and the relatively recent introduction of mass market home battery storage systems.

In Australia, the combination of the high electricity prices by world standards in absolute terms (i.e. before adjustment for wages) (Mark Intell, 2016), high solar irradiance, a high proportion of detached single story residential homes with large available roof space, falling PV (Solar Choice, n.d.), and battery prices (Brinsmead et al., 2015), and rising electricity prices (Jacobs Pty Ltd, 2016) are lending an increasing weight to the purely economic justification of off-grid residential PV-battery systems. However, there is some evidence to suggest that economics may be just one of many factors influencing consumer's decision to go 'off-grid' (Fisher et al., 2014). A desire for self-sufficiency, isolation from future electricity prices rises, availability of supply during natural disasters or outages, and simply wanting to have that latest technology are commonly cited reasons that may lead to increasing uptake in a portion of the market irrespective of pure economic viability. Mainstream grid disconnection has been identified as potentially severely disruptive to the current status quo (Green and Newman, 2017).

Choosing to disconnect from an existing grid, or to not connect a

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new household to the grid, is not without risk. Significant capital outlay is required and electricity availability is ultimately limited. Hu and Augenbroe (2012) have discussed the energy management challenges of off-grid solar houses. The viability is highly dependent on the particular combination of electricity demand profile (governed mostly by lifestyles and building and appliance stocks), climate and economic parameters. This means that findings from a study in one country are not necessarily applicable to the unique conditions in another country.

In the Australian context, several researchers have investigated in detail the economics of off-grid solar-battery systems (Liu et al., 2011; Al-Falahi et al., 2016; Khalilpour and Vassallo, 2016, 2015; Percy et al., 2016; Yap and Karri, 2015; Ren et al., 2016). Khalilpour and Vassallo (2016), used a year of measured energy consumption data for an average Sydney household to assess the economics of different combinations of battery and PV systems. They then investigated the effect of variations to electricity tariffs, prices, different typical daily consumption patterns and location, for grid connected systems. Off-grid systems were considered in a second publication (Khalilpour and Vassallo, 2015). For off-grid systems, they show that the approach to 100% grid independence is typically asymptotic. That is, an increasingly higher capacity PV and battery system is required to achieve full independence for the final few high demand/low solar operating hours in the year. Their conclusion, consistent with other studies, is that such a large system required to achieve full independence is both costly, and leads to a high proportion of the electricity generation being curtailed for much of the year (in the absence of any other use for the generated electricity). Although a number of PV-battery systems were found to have positive NPV after 10 years, none of these were capable of providing 100% grid independence.

A commonly used assumption is that the electricity consumption pattern of a household would remain the same pre and post grid disconnection. That is, that the consumption patterns of a given household with grid connected electricity would remain the same after that household elected to go 'off-grid'. A separate but related consideration is the extent to which households are willing to accept a less than complete solution, for example a solution where power demand is met 99%, or 99.5% of the time. Some evidence for consumer willingness to accept this type of arrangement can be seen from grid connected commercial customers who opt for significantly lower power bills in return for a reduction in available power during a limited number of critical 'peak' power events throughout the year (AusNet Services, n.d.).

Nevertheless, predicting consumer behaviour changes is a difficult task in general. Fortunately consumption pattern changes can also result from equipment operating pattern and technology changes. For example, using a daily consumption pattern for a household with an off-peak electric storage hot water system designed to switch on at night time when grid electricity demand is lower, makes no sense for an off-grid solar system. Simply changing the hot water system to operate during the day-time is a simple solution. A similar situation exists for other loads that are not time-critical such as pool pumps and, to a lesser extent, washing machines and dishwashers.

In the case of air-conditioning, which contributes significantly to both the total energy consumption and the peak consumption, the most efficient vapour-compression systems currently on the market (Australian Government, n.d.) are more than twice as efficient as the Australian sales weighted average efficiency of split-system air-conditioners sold 10 years ago (Energy Efficient Strategies, 2006) (noting that the average age of replaced non-ducted systems in 2014 was 10.8 years (BIS Shrapnel, 2014)). Alternative technologies such as indirect evaporative coolers with electrical efficiencies above 20 (or approximately 7 times the estimated average of existing systems) are also beginning to enter the market (Duan et al., 2012). Of course, purchasing these systems requires an initial outlay, but the average efficiency of installed systems is also increasing over time as a result of natural replacement of older units at the end of their life. This is reflected in the long term reduction in both total and per capita energy consumption (a proxy for per household consumption) (Department of Industry, Innovation and Science, 2015, 2016).

For households with a swimming pool, pool pumps consume on average 18% of the total household electricity and there are approximately 1.1 million residential pools in Australia (Department of the Environment and Energy, 2016). In the year 2014–15, 70% of pool pump sales were of relatively inefficient single speed pumps (Department of the Environment and Energy, 2016). As a result, minimum performance standards are currently being introduced. These standards should result in a natural shift towards more efficient variable speed pumps as more inefficient units reach the end of their life and are replaced with pumps potentially several times more efficient.

Improving appliance efficiency and shifting operation times are two examples of simple changes that should reduce required PV-battery system size. Thus, here the analysis of the design of off-grid PV-battery systems for residential applications is revisited with a special focus on determining the effect of making these types of changes to the prior measured 'grid-connected' electricity consumption profiles. This is made possible by the use of sub-circuit electricity metering measurements from the Residential Building Energy Efficiency (RBEE) study (Ambrose et al., 2013). This study involved sub-circuit measurements for over 200 households in Brisbane, Adelaide and Melbourne over several years. Here we analyse 28 of these households identified as having both air-conditioning and electric storage hot water systems. Seven of these households also had pool pumps. The households range from low to very high electricity consumers. The impact on system sizing and economics is assessed using current cost data.

## 2. Data analyzed

Electricity sub-circuit measurements at 30 min intervals and household and appliance information obtained in the Residential Building Energy Efficiency (Ambrose et al., 2013) study were used for this analysis. Data from 28 households with sub-metered electric storage hot water and air-conditioning circuits were considered. These included both solar boosted, heat pump and conventional electric solar hot water system types. All of the households had vapour-compression air-conditioners with the majority being reverse cycle. Seven of the households also had a sub-metered pool pump circuit.

Households were located in the greater Brisbane and Adelaide areas. These correspond to sub-tropical and temperate climates respectively. For many houses 2 years of data was used commencing June 2012, though for several only 1 year of data was available. In all cases whole years of data were used.

The electricity sub-circuit measurements were combined with hourly ambient temperature measurements from the Bureau of Meteorology (BOM) (Australian Bureau of Meterology, 2016) station nearest to each household. Ground solar radiation data at hourly resolution was obtained for the postcode location of each household from the AREMI web-service (Australian Renewable Energy Mapping Infrastructure, n.d.). This data is derived from satellite imagery processed by the BOM.

For each household, the total loads were determined by summing the energy consumed by each sub-circuit excluding any solar sub-circuit if present. Hence, the presence of existing solar PV on any of the houses did not influence the load measurements. In addition to the electricity metering data, information on the occupant demographics, selected appliances and the building were also available. A summary of selected key information for the 28 households considered is given in Table 1.

## 3. Method of analysis

The sub-circuit load, ambient temperature and irradiance data was combined with mathematical models of a crystalline silicon PV array and lithium-ion battery storage system (Goldsworthy, 2017) and simulations were run with the full 1 or 2 years of data at 30 min time-step