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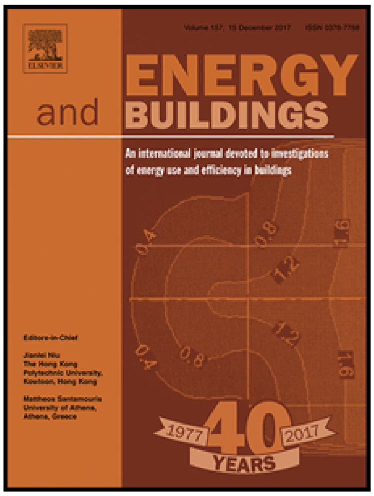

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Informed Decision Making of Battery Storage for Solar-PV Homes Using Smart Meter Data

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Abstract: As the cost of solar photovoltaic (PV) systems decreases and incentives such as feed-in tariffs (FiTs) are offered, solar-PV homes are becoming popular. Furthermore, solar-PV homes integrated with hybrid or electric vehicles (EVs) are emerging as a paradigm for future homes. Given the fact that there exists a considerable price difference between grid electricity supply and FiTs, decision making of energy storage using batteries becomes an imperative topic. This research proposes an innovative and generic framework for the decision making of energy storage using batteries based on Smart Meter data, which incorporates the actual energy generation and consumption patterns of solar-PV homes. The proposed energy storage decision is based on a developed economic model, with the consideration of the electricity price from the grid, the FiTs, and the storage cost using batteries (i.e. the average price per kWh of battery capital cost and maintenance cost). Moreover, an intelligent algorithm is developed to calculate the electricity quantities, i.e. electricity supplied from the grid, fed into the grid and stored in a battery of a given capacity, based on the monitored data obtained from a Smart Meter over a year. The results reveal that at the present utility prices of \$0.3/kWh and a feed-in-tariff of \$0.10/kWh in the studied region, energy storage with a battery cost of \$0.2 /kWh or more is excessive and not economically feasible. However, with the increasing cost of electricity in recent years and constant changes in battery price, the outcomes could quickly reverse. This research contributes an innovative framework for battery storage decision-making of solar-PV homes, based on economic analysis and Smart Meter data.

Keywords: Solar-PV homes; Smart meter; Home battery; Solar photovoltaic (PV); Electric vehicle (EV).

Nomenclature

Solar PV: Solar photovoltaic
EV: Electric vehicle
FiTs: Feed-in tariffs
PEV: plug-in electric vehicles
V2G: vehicle-to-grid
V2H: vehicle-to-home

1. Introduction

Solar-PV homes are receiving increasing attention worldwide as a means of using renewable energy to reduce fossil fuel consumption and the environmental burden of residential buildings (Baulch et al., 2018; Halder, P.K. 2016). Chapman et al. (2016) reviewed the residential solar PV policy between 2001 and 2012 in Australia, and identified that more than 2,300 MWp of residential PV was installed during that period as one of the results of policy incentives. FiTs and significant rebate incentives have been the primary driving forces for the growth of solar PV homes in the last decade; however, FiTs continue to change over time and from state to state in Australia, ranging between \$0.66/kWh to \$0.05/kWh. Nicholls et al. (2015) conducted comprehensive lifecycle economic and environmental analysis for rooftop PVs in Australia and found that the cost payback period ranges from 11 to more than 25 years in Australia. With the fall in the capital cost of PV systems (IREA 2018) and the increase in electrical cost (almost doubling in 10 years) (AEMC, 2018), the payback period of solar PV systems is expected to decrease further.

Because of the growth in popularity of solar-PV homes, a concern is the impact of solar-PV homes on the electricity grid. Agnew and Dargusch (2015) explored the disruption of the electrical distribution network by residential solar and storage. When considering the application of batteries in households, the relations between the two parties, the consumer and the distribution network operator (DNO), needs to be considered. There are advantages for the distributor when the electrical FiTs are time-of-day regulated in order to smooth the output gains to the network. As demand on the low voltage (LV) network changes due to changes in consumer behaviour, the distribution network operator will be forced to change how it operates and reinforce the network (Rowe, et al., 2014).

Both parties can prosper when battery storage contributes to this balance. As reported by Tant et al. (2013), a FiT scheme that favours the installation of battery storage, to curtail injected power and maximize self-consumption is already in place in Germany. Methods for energy storage in residential buildings include onsite battery storage and through an electric vehicle (EV). Ren et al. (2016) have analysed the impacts of integrated PV battery systems, including net present value (NPV) and peak demand for various tariff scenarios in several Australian cities for the studied cases. Horan and Luther (2016) monitored and analysed the energy performance of a solar-PV home and EV, and compared the actual energy performance of the home between before and after the PV system and EV were installed. In that study, the data includes half-hour readings from a Smart Meter installed by the electricity provider, recording the quantity of electricity drawn from and fed into the grid. Forrest et al. (2016) compared the impacts of immediate charging, smart charging, and vehicle-to-grid (V2G) charging on the scale of infrastructure required to meet renewable utilization targets, and highlighted the importance of intelligent plug-in electric vehicle charging (PEV). Sarabi et al. (2016) explored the potential of PEV for V2G charging, based on statistical data; this research provides a full picture for the utilisation of EV.

Research has been conducted to determine battery size with the consideration of operation management, continued supply and reliability, and economic objectives (Xiao et al., 2015; Wang et al., 2012), among which Xiao et al. (2015) introduced an optimal model for battery sizing of the energy storage system in micro-grid, based on cost-benefit analysis. The method of simulation is employed to demonstrate the proposed framework. Wang et al. (2012) studied the battery storage capacity for wind farms, with the consideration of continued and reliable supply and economic benefit. The study conducted by Wang et al. (2012) sizes the battery capacity to smooth wind-power variations by using spectral analysis. Both of the studies mentioned above are based on simulation and theoretical analysis. Studies on the battery sizing of grid-connected residential solar-PV homes are also identified, where it can be more attractive to consume harvested energy on-site than to export it because there is a considerable difference between the tariffs to supply electricity from the grid and to feed electricity into the grid. Weniger et al. (2014) and Hassan et al. (2017) developed simulation models based on meteorological and load demand data sets. Hassan comments that "simulation models with irradiance data can be optimistic and therefore the use of real PV data is recommended". Hoppmann et al. (2014) explored the economic viability of battery storage for residential PV in Germany under several different electricity price scenarios, using the approach of simulation. Aichhorn et al. (2012) developed a battery lifetime model, using PV generation and load power to estimate battery size and maximise profit; the approach of simulation is applied to verify the proposed framework. Muenzel et al. (2015A), studied battery lifetime prediction to optimise battery management. Muenzel et al. (2015B) have developed algorithms for determining optimal battery sizing, for a particular PV array and based upon time-of-use; the dynamic use of collected energy and periods of mismatch and missed opportunities for storage were also considered in this study. *All these prior models were primarily developed based on theoretical analysis or simulation*. In addition, some online tools have been developed to calculate battery size, energy cost, or other financial performance. For example, Solar Calculator (2017) considers household details, solar system details, battery storage options, property details, and finance options to calculate such financial performance as annual savings and solar system cost. Wholesale Solar (2019) also developed a tool to estimate battery size based on average monthly energy consumption and solar power. *These online tools were either developed based on estimation or rough monthly energy usage, while energy storage using batteries is a dynamic process and highly related* *to the actual energy profile of solar-PV homes, which requires more sophisticated analysis.*

Based on the literature review, it has been identified that theoretical analysis, simulation, or rough estimation have been conducted for battery sizing of solar PV homes in the literature. However, the actual energy profile of solar PV homes varies from one household to another, and may be different from the theoretical analysis and simulation. Moreover, energy storage using batteries is a dynamic process, which requires more sophisticated analysis. Therefore, battery storage decision using detailed monitored data, which incorporates the energy generation and consumption patterns of solar-PV homes, has been identified as the research gap.

This paper explores the use of Smart Meter data to determine what happens when batteries are introduced. Smart Meter data provides valuable information for planning energy storage, given that energy storage is directly related to the imported and exported energy, which is recorded in Smart Meters. The intermittent nature of solar PV output and the irregularity of customer-sited energy use means that savings can be achieved by using battery storage to buffer energy flows as previously discussed. Figure 1 is an example of such a period from the house being investigated when battery storage would buffer energy to the consumer's benefit. Through battery storage systems the variable output of PV to the grid can be minimised by means of better control.

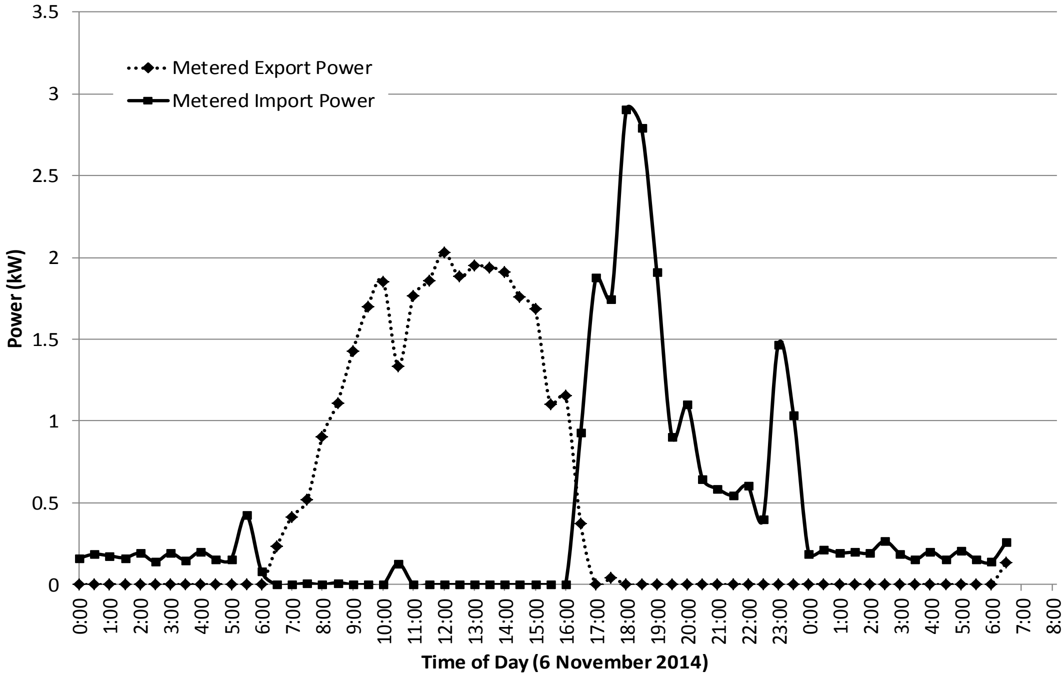

Figure 1. The mismatch of exported vs. imported energy

The use of Smart Meter is the norm for the majority of the households with grid-connected PV systems in Victoria, Australia. As Smart Meter data can be downloaded from the network supplier since two years ago, the proposed framework in this paper can be applied to any those households considering adding battery storage. Therefore, this research is generic for battery storage decision-making using Smart Meter data. Furthermore, the data with a 30-minute interval is used directly in this research, rather than using an average to characterise solar harvest and house load. As the data is real-time measured rather than averages or model predictions, the research results are more reliable and incorporate the actual energy profile of households.

This paper structure is organised as follows: section 2 presents the research objectives and the methods applied; section 3 introduces a case study to demonstrate the proposed research framework, with comprehensive analysis; and section 4 summarises this study and the future work.

2. Research Objectives and Methodology

This project considers several relevant conditions for existing solar houses that are connected to Smart Meters typical in Australia. The analysis is not speculative and is based upon measured data with the intention of devising a process to which a decision for a battery size can be made. The developed program for battery sizing accounts for the following attributes:

- Actual data allowing for occupants' behaviour;
- Analysed energy flow for energy storage using batteries for solar-PV homes;
- Calculated electricity quantities, including electricity supplied from the grid, fed into the grid and stored in a battery for a given capacity, in the absence of batteries.

With the aim of analysing energy storage for solar-PV homes, the detailed research objectives include:

(1) Investigating the energy flow of solar PV homes with onsite energy storage;

(2) Developing an algorithm to calculate the quantities of electricity supplied from the grid, fed into the grid, and stored in a battery for various given battery sizes based on data from a Smart Meter; and

(3) Analysing total electricity price for electricity storage decision making, with various electricity supply prices, feed-in prices, and storage prices considered, where a storage price is an average price per kWh of battery capital cost and maintenance cost.

Using the collected data-set from the Smart Meter, the proposed algorithm is designed to calculate the quantities of electricity supplied from the grid, fed back to it, and stored in a battery for various given battery sizes. Furthermore, considering the electricity price from the grid, the FiTs, and the storage cost using batteries, a decision framework of energy storage is proposed for solar-PV homes with smart meters. The EV-integrated solar-PV home of one of the authors is used as a case study to demonstrate the proposed framework. The analytical framework is generic and applicable to other solar-PV homes with Smart Meter data. This research contributes to onsite energy storage decision making based on metering data from smart meters.

2.1 Integrated Solar-PV Homes without Battery

There are several energy design schemes for EV-integrated solar-PV homes, determined by:

(1) The type of EV. There are two types of EVs, including battery electric EV (BEV) and hybrid EV (HEV). A BEV uses a battery that must be recharged from an external electrical power source. BEVs have been proven environmental-friendly, but require substantial electricity charging infrastructure. An HEV has more than one available power source with higher operation efficiently, but resulting in more environmental impacts compared with BEV (Erjavec, 2013; Herrmann and Rothfuss, 2015).

(2) The interaction of EVs with solar-PV homes. There are two scenarios regarding the interaction of EVs with solar-PV homes, i.e., an EV battery can only be charged from the home (charging-only), or an EV battery can also be discharged to the home (vehicle-to-home (V2H)).

(3) The charging source of EV battery. There are also two scenarios regarding this, i.e., an EV battery only be charged from the PV system, or it can also be charged from the grid.

In this research, a charging-only HEV is studied, and charging the EV battery from the grid is not considered, given that the aim is to use solar energy rather than grid energy. Thus, the EV battery is charged only from excess solar energy, with petrol as the backup energy source.

In most solar-PV homes, grid-connected solar PV systems provide electricity for the home in conjunction with electricity from the grid. When a solar PV system generates more energy than needed, the excess is exported to the grid. For the EV-integrated solar-PV home, the solar PV system and electricity grid also supply energy to the EV by charging it when necessary. If the integrated vehicle is an HEV, petrol is also used as another energy source. In some cases, solar-PV homes also use natural gas as one of the energy sources for such usages as space heating and hot water heating. Figure 2 illustrates the components and energy flows of integrated solar-PV homes without energy storage. Electricity grid and solar PV systems supply energy to solar-PV homes together, and the excess electricity generated from solar PV systems is input into the grid. Natural gas is used as a complementary energy source of solar-PV homes, and petrol is also used for hybrid EVs.

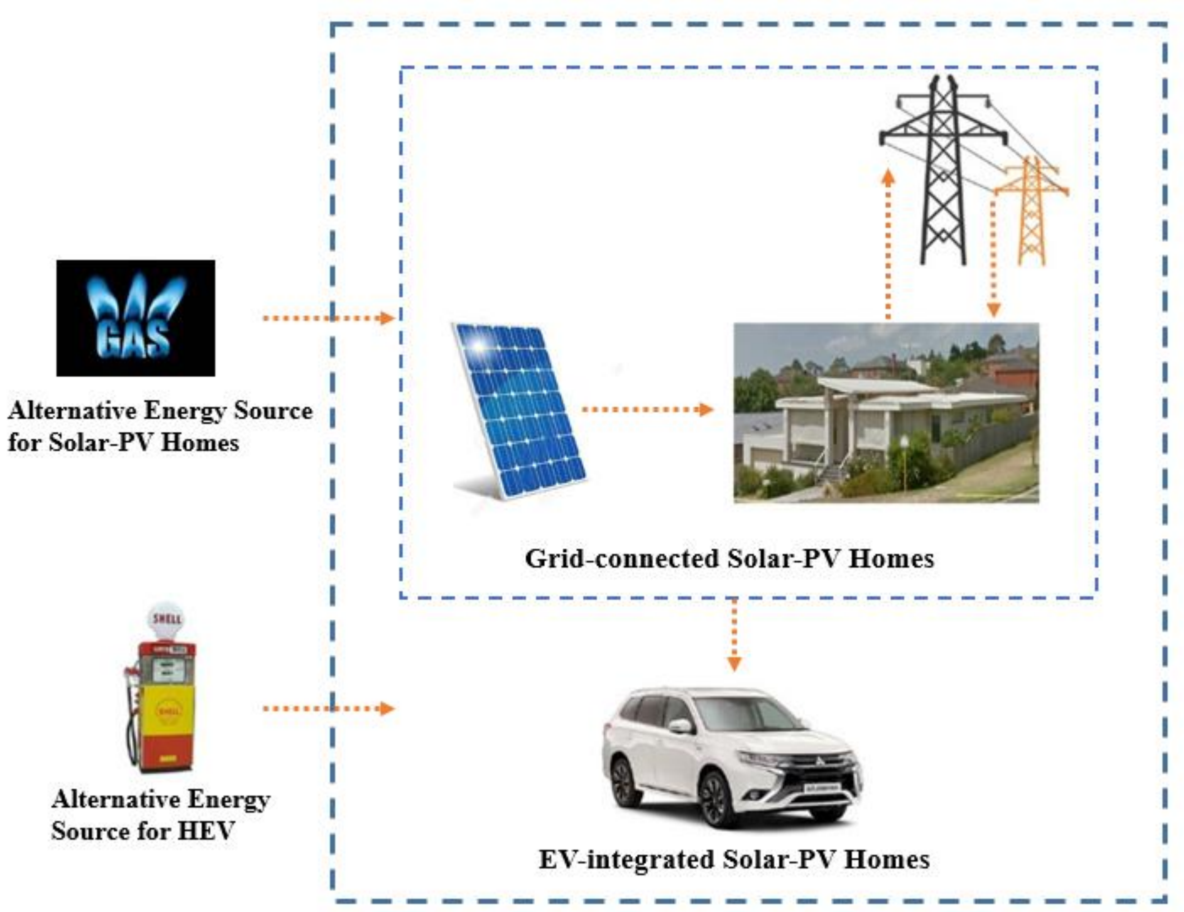

Figure 2. Energy flow of EV-integrated solar-PV homes

2.2 Energy Flows of Integrated Solar-PV Homes with Battery

Given that the cost of electricity imported from the grid is higher than that of exported ($0.3/kWh vs $0.10/kWh), onsite energy storage may benefit EV-integrated solar-PV homes. After batteries are introduced to solar-PV homes for onsite energy storage, the flow of energy becomes complex. There are various types of energy flows, including energy flows from grid to household, from solar PV system to household, from solar PV system to grid, from solar

PV system to battery, and from battery to household. In this study, the energy flow between grid and battery is not considered, with the aim of storing solar energy on-site only and the given price difference mentioned above.

The flowchart of a grid-connected solar-PV home with a battery is illustrated in Figure 3, with the solid lines demonstrating the logic of energy flow and dash lines displaying the metering systems. This flowchart considers:

(1) When the solar PV system generates more electricity than the household load including the EV, the extra electricity is stored in the battery;

(2) When the battery becomes fully charged, the excess energy is exported to the electricity grid;

(3) If the PV system generates less energy than needed by the home and EV, the required electricity is drawn from the battery;

(4) If the battery is fully discharged, the required energy from the household is supplied from the electricity grid.

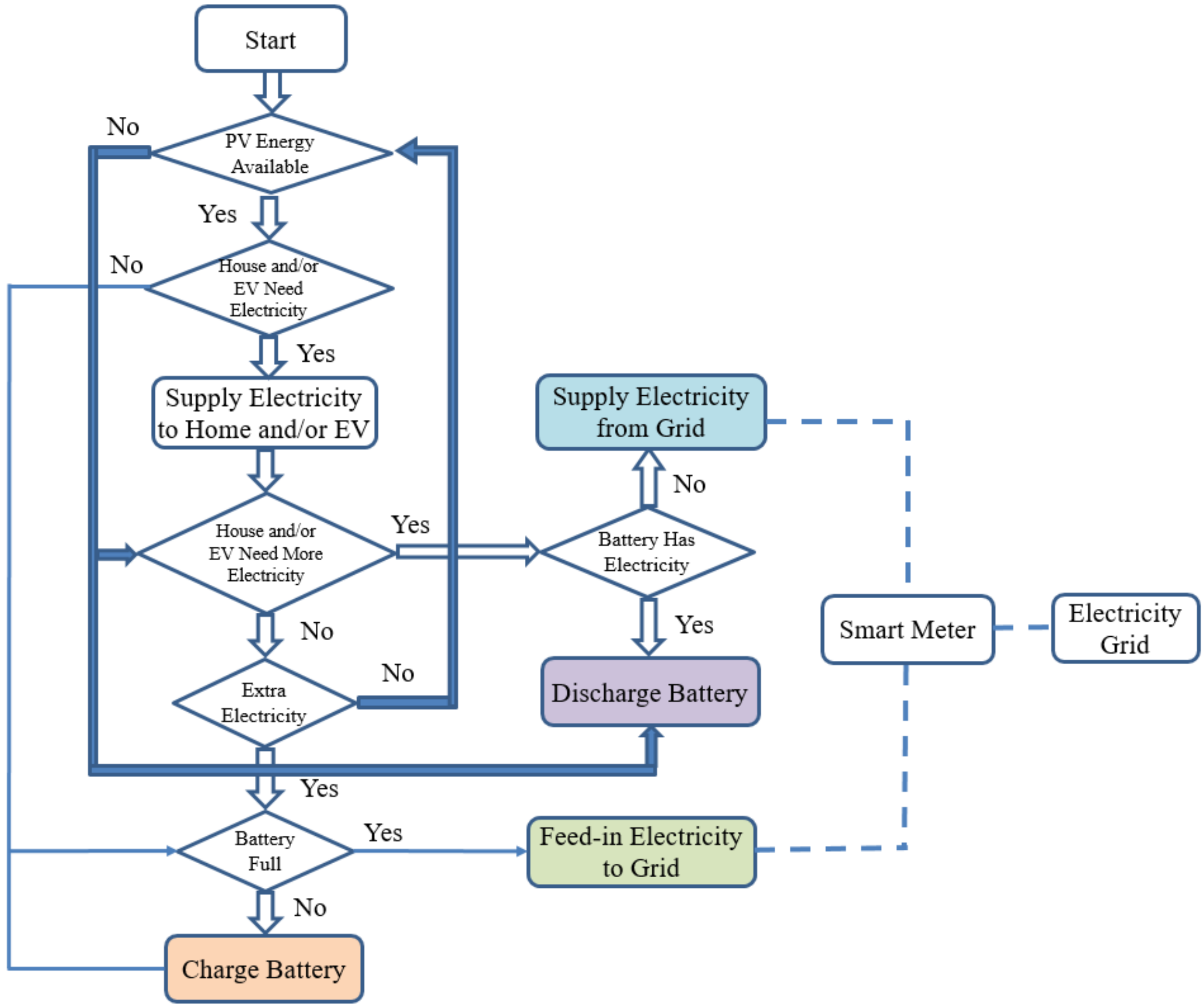

Figure 3. Energy flows and controls of solar-PV homes with batteries

2.3 Energy Storage Decision Framework Based on Smart Meter Data

2.3.1 Electricity Quantity Calculations

Based on the electricity metering data collected in the absence of energy storage, the energy imported from the grid, exported to the grid, and stored in a battery can be calculated using an algorithm proposed below.

The energy equilibrium of a solar-PV home, before introducing a home battery, can be expressed using the solar energy from the solar PV system, the imported energy from the grid, the household energy load, and the exported energy into the grid, satisfying Equation (1):

$$E_S + E_I = E_L + E_E \tag{1}$$

where: E_S represents the solar energy; E_I represents the imported energy; E_L represents the household energy load, including EV; and E_E represents the exported energy.

Equation (1) can also be expressed as:

$$E_S - E_L = E_E - E_I \quad (2)$$

Equation (2) means that the energy excess or deficit between the solar energy and the household load equals the difference of exported and imported energy. Thus the Smart Meter data, with the records of imported and exported energy, can be used to calculate electricity quantities, including electricity supplied from the grid, fed into the grid, and stored onsite, for the energy storage decision.

Given the fact that a Smart Meter provides imported and exported data with a certain time interval, e.g.30-min, the energy interaction within the time interval of a Smart Meter is not able to be considered. Therefore, the energy interaction is summarised to the time interval level based on the imported and exported data provided by Smart Meters, which constitutes an assumption of this research.

Based on the calculation rationale discussed above, the decision tree associated with the calculation equations is illustrated in Figure 4, and the detailed equations are presented as Equation 3-12.

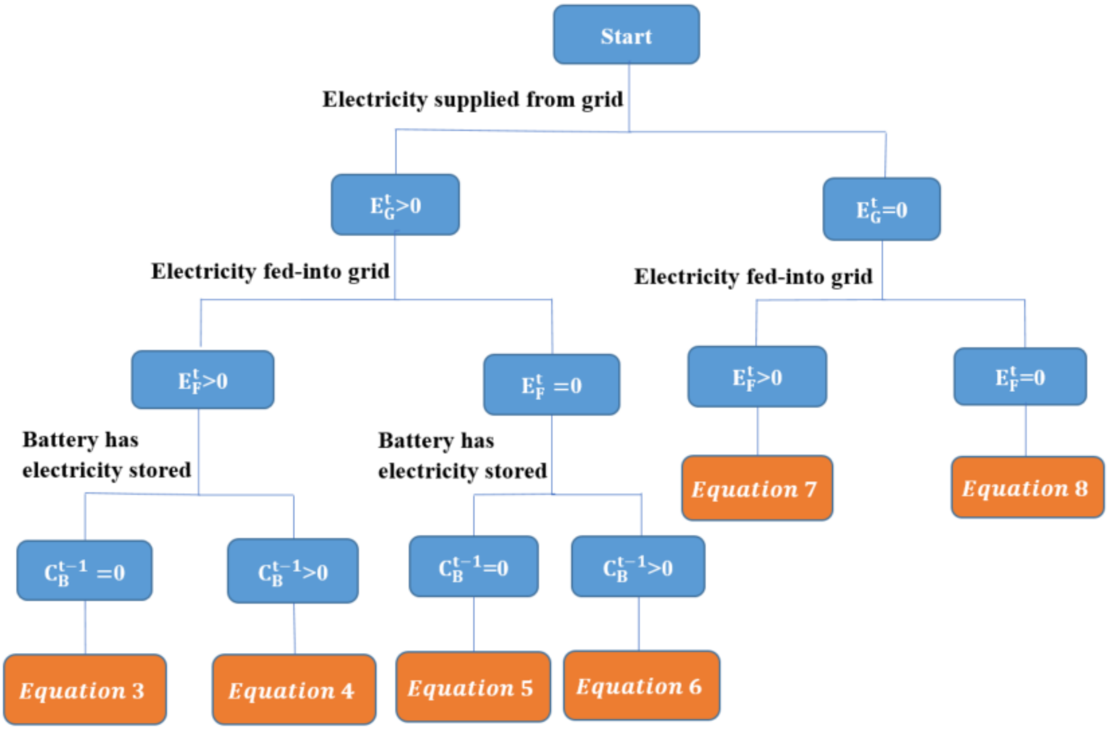

Figure 4. Decision tree associated with calculation equations

1) If $E_G^t > 0$, $E_F^t > 0$, and $C_B^{t-1} = 0$ ***(Charging only)*** (3)

$Q_G^t = E_G^t$

If $E_F^t > B$ (Fully charge)

$C_B^t = B$

$S_B^t = B$

$Q_F^t = E_F^t - B$

Else if $E_F^t \leq B$ (Partially charge)

$S_B^t = E_F^t$

$C_B^t = E_F^t$

$Q_F^t = 0$

2) If $E_G^t > 0$, $E_F^t > 0$**,** and $C_B^{t-1} > 0$ (***Discharging then charging***) (4)

If $C_B^{t-1} \geq E_G^t$ (Partially discharge)

$C_B^t = C_B^{t-1} - E_G^t$

$Q_G^t = 0$

Else if $C_B^{t-1} < E_G^t$ (Fully discharge)

C_B^t =0

$Q_G^t = E_G^t - C_B^{t-1}$

If E_F^t < B - C_B^t (Partially charge)

$Q_F^t = 0$

$S_B^t = E_F^t$

$C_B^t = C_B^t + E_F^t$

Else if $E_F^t \geq$ B - C_B^t (Fully charge)

$Q_F^t = E_F^t -$ (B - C_B^t)

$S_B^t =$ B $- C_B^t$

$C_B^t = B$

3) If $E_G^t > 0$, $E_F^t = 0$, and $C_B^{t-1} = 0$ ***(Neither Discharging nor charging)*** (5)

$S_B^t = 0$

$Q_F^t = 0$

$Q_G^t = E_G^t$

$C_B^t = 0$

4) If $E_G^t > 0$, $E_F^t = 0$, and $C_B^{t-1} > 0$ ***(Discharging only)*** (6)

$S_B^t = 0$

$Q_F^t = 0$

If $C_B^{t-1} >= E_G^t$ (Partially discharge)

$C_B^t = C_B^{t-1} - E_G^t$

$Q_G^t = 0$

Else if $C_B^{t-1} < E_G^t$ (Fully discharge)

$C_B^t = 0$

$Q_G^t = E_G^t - C_B^{t-1}$

5) If $E_G^t = 0$ and $E_F^t > 0$ (***Charging only***) (7)

$Q_G^t = 0$

If $E_F^t <$ B - C_B^{t-1} (Partially charge)

$Q_F^t = 0$

$S_B^t = E_F^t$

$C_B^t = C_B^{t-1} + E_F^t$

Else if $E_F^t >=$ B - C_B^{t-1} (Fully charge)

$Q_F^t = E_F^t -$ (B - C_B^{t-1})

$S_B^t =$ B $- C_B^{t-1}$

$C_B^t = B$

6) If $E_G^t = 0$ and $E_F^t = 0$ ***(Neither Discharging nor charging)*** (8)

$Q_G^t = 0$

$C_B^t = C_B^{t-1}$

$S_B^t = 0$

$Q_F^t = 0$

$$Q_G = \sum_{t=1}^{365\times24\times2} Q_G^t \quad (9)$$

$$Q_F = \sum_{t=1}^{365\times24\times2} Q_F^t \quad (10)$$

$$Q_S = \sum_{t=1}^{365\times24\times2} S_B^t \quad (11)$$

$$Q_G^1 = 0, Q_F^1 = 0, S_B^1 = 0, and\ C_S^0 = 0 \quad (12)$$

Symbol	Notation
B	Battery size (kWh)
E_F^t	Feed-in electricity to grid at time t (kWh), reported by smart meter before using battery
E_G^t	Supplied electricity from grid at time t (kWh), reported by smart meter before

	using battery
S_B^t	Added electricity to battery at time t (kWh)
C_B^t	Total electricity stored in battery at time t (kWh)
Q_G^t	Supplied electricity from grid at time t (kWh), after using battery
Q_F^t	Feed-in electricity to grid at time t (kWh), after using battery
Q_G	Total supplied electricity from grid for the studied year (kWh)
Q_F	Total feed-in electricity to grid for the studied year (kWh)
Q_S	Total storied electricity in battery for the studied year (kWh)

2.3.2 Energy Storage Decision

The decision on energy storage, i.e. whether storage is considered or not, and battery size, is also dependent upon:

(1) The price of electricity supplied from the grid;

(2) The price of electricity fed into the grid; and

(3) The price of electricity storage using a battery.

The installation fees of the existing solar PV system is treated as a sunk cost, thus it is excluded from the energy storage decision in this research. Based on the above prerequisites, the total electricity price and the electricity quantities, including electricity supplied from the grid, fed into the grid, and stored onsite, are calculated for the energy storage decision using the smart meter data as follows.

$$\text{TP} = (Q_G P_G - Q_F P_F) + Q_S P_S \tag{13}$$

where: TP represents total electricity price; P_G represents electricity price supplied from grid ($/kWh); P_F represents electricity price based on FiT ($/kWh); and P_S represents on-site storage price using battery ($/kWh).

Based on the calculation of total electricity price, the battery storage decision can be made for a solar-PV home regarding whether a battery should be considered and the appropriate battery size if battery storage is applicable.

3. Case Study

3.1 An EV-Integrated Solar-PV home

One of the authors of this paper has extensively collected data on their own house, and this has been studied and applied in this paper. The house is located in the southern hemisphere at a latitude of 38°, and was built approximately ten years ago. It is well insulated and double-glazed with eaves controlling sunlight. This house is heated by a gas ducted system in winter, and is cooled through natural ventilation in summer. A gas-boosted solar hot water service storage is also used in this solar PV home.

In 2013, a smart meter was installed at this house, and the records of the electricity imported from and exported to the grid have been obtained from the provider, with the time interval of 30 minutes. In 2014, a 3 kW solar PV system was installed, based on the recommendation of the solar PV system provider. The solar PV system is installed on a north-facing roof with 5° pitch. This system comprises twelve solar PV panels with a total area of 20 m^2, and each solar panel is rated at 250 W. A micro-inverter in each panel converts the output to 240 V AC; thus the panels operate independently, and a panel failure will not cause the system failure. Furthermore, more panels can be added independently, if it is necessary. However, micro-inverters also entail some disadvantages, including: (1) the micro-inverter system is more complex than an overall inverter; and (2) identifying panel failure requires individual attention, as the fault of a failure panel is masked by other working panels. Also in 2014, a plug-in hybrid vehicle was purchased. The hybrid car operates with three modes: (1) battery only; (2) series mode, where the petrol engine charges the battery which drives the car; and (3) parallel mode, where the petrol motor and the batteries drive the car together. Switching between modes is seamless, and the driver can choose to charge the battery or "save" the battery while driving.

3.2 Monitoring Instruments and Data Collection

As illustrated in Figure 5, various monitoring instruments are utilised to monitor the actual performance of the EV-integrated solar-PV home:

1) A smart meter is used to monitor the electricity imported from the grid and the

electricity exported into the grid, which provides downloadable data with a 30-min interval. Monthly summaries can also be obtained from invoices in kWh and dollars provided by the electricity supplier.

2) A solar PV monitor provided by the manufacturer is used to monitor the actual energy generation of the solar PV system. The data reported for each panel includes date and time, life-time energy harvested, power, voltage, current, grid frequency, and inverter temperature. The data can only be stored up to 30 days in the solar monitoring system, and the annual data is collected manually and sporadically for this research.
3) An EV monitor is used to collect part of the vehicle data, and other data is collected manually. The following data is collected for the EV, including:
    a) the energy of the most recent charge;
    b) the odometer reading;
    c) the battery range, before and after charging;
    d) the total range including battery and petrol, before and after charging;
    e) the seven-day average petrol price at the time of charging;
    f) petrol purchases and the price are also recorded manually.

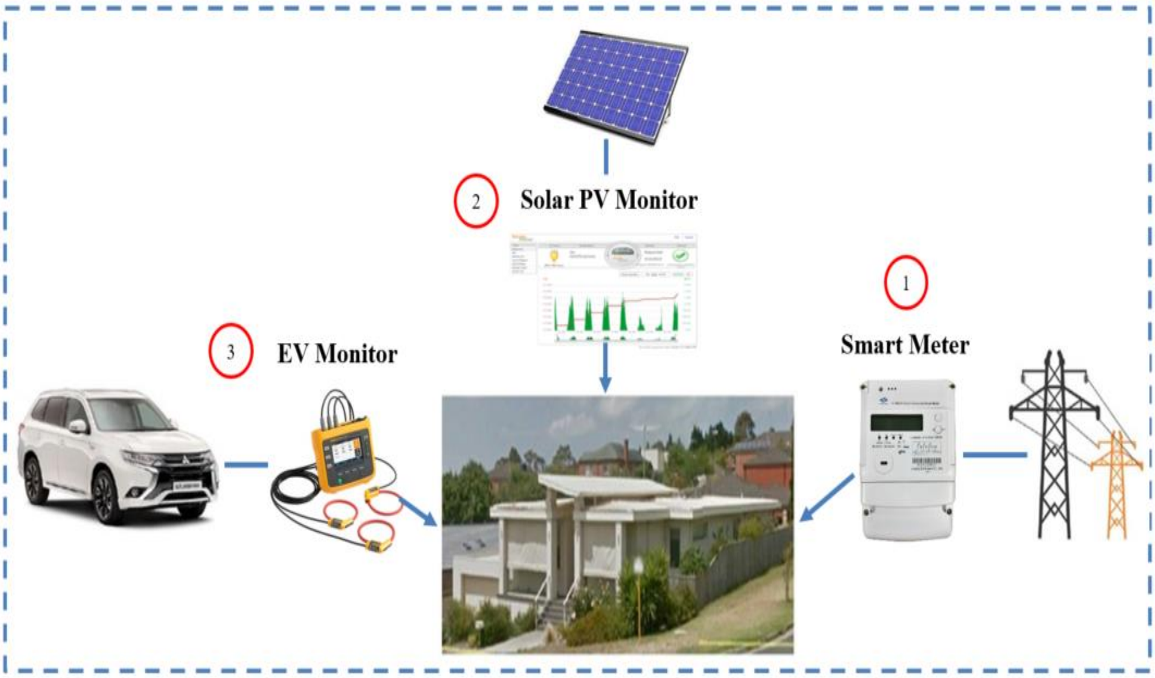

Figure 5. Monitoring Instruments

3.3 Actual Energy Performance

The annual energy performance between 1 July 2014 and 30 June 2015 is summarised for the monitored solar-PV home, as displayed in Table 1 (Horan and Luther 2016):

- This solar-PV home was supplied 4,017 kWh electricity from the grid, with the electricity bill of $1,641.98.
- The solar PV system generated 3,941 kWh of electricity.
- The house used 4,019 kWh of electrical energy.
- The car used 191 L petrol (1,833 kWh) and 1,892 kWh of electrical energy for the distance of 10,519 km.
- The solar PV system contributed 2,047 kWh of electricity to the grid, with an income of $145.20 based on the FiT.
- The solar hot water system harvested 1,694 kWh of solar energy.
- Heating and hot-water boosting used 3,573 kWh of natural gas.

The total annual energy cost of the solar-PV home is $2,292.24; compared with the energy cost before the solar system installation, which is $3,682.87, the energy cost has been reduced by 38% for this solar-PV home.

Table 1. Energy use after installing solar panels (1 July 2014 – 30 June 2015)

		Energy in (kWh)	Payments	Energy out (kWh)	Receipts
House	Electricity Grid	4,017	$1,641.98	2,047	$145.20
	Solar Panels	3,941			
	Gas	3,573	$544.56	3,573	
	Solar HWS (available energy)	1,694		1,694	
	Electricity use			4,019	
Car	Petrol (191 L)	1,833	$250.90	1,833	
	Electricity			1,892	
Total Energy (kWh)		15,058		15,058	
Total Cost			$2,437.44		$145.20
Net Running Cost			$2,292.24		

From Table 1, it can be observed that significant electrical energy flows in and out of the solar-PV home throughout the year. Although the EV was charged, 51% of the harvested energy was exported to the grid. Another interesting finding is that by charging the hybrid EV battery, the annual purchased petrol was reduced by 82.8% (from 1,113 L to 191 L, a value of $1,390), at a low opportunity cost, since the solar energy used to charge the EV would have been exported to the grid at $0.05/kWh in its absence. Alternatively, if the car were petrol only, in order to rebate $1,350 with 1,892 kWh electricity used by the car from the supplier, the FiT would need to be $0.31/kWh. In order to further reduce the electricity consumption of the solar-PV home, all the used incandescent lamps and compact fluorescent lamps were replaced with LED lamps between July 2014 and November 2014. The energy savings from lightbulb change was estimated to be approximately 15 kWh/month or $60 annually (Horan and Luther, 2016).

Considering the large export of energy from the solar-PV home to the grid and the price difference between importing and exporting energy, the present research investigates the financial benefits of a battery.

3.4 Energy Storage Based on Smart Meter Data

The collected annual data from the smart meter between 1 July, 2014 and 30 June, 2015 is used to analyse the energy storage for the solar-PV home. The annual data is averaged for each time interval, as presented in Figure 6. It can be observed that on average electricity is exported from the solar PV system to the grid between 6:00 a.m. and 7:00 p.m., and reaches its peak at the noon time.

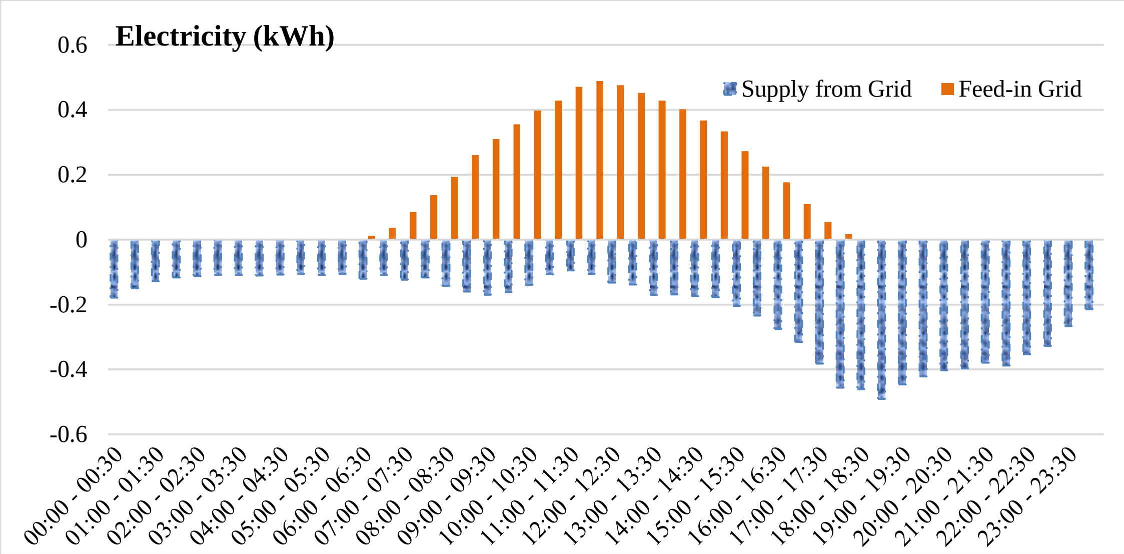

Figure 6. Average imported and exported electricity profile

The energy storage decision, to apply storage or not and the battery size, is also dependent upon the electricity supply price, the feed-in price, and the battery storage price. Furthermore, this study also considers the price variance based on the market prices, as listed in Table 2: (1) the electricity supply price ranges from \$0.20/kWh to \$0.40/kWh; (2) the electricity feed-in price ranges from \$0.10/kWh to \$0.50/kWh; (3) home battery size is assumed to be between 0 and 15 kWh (Buchholz and Brandenburg, 2018); and (4) the onsite storage price using batteries is estimated from several sources, ranging from \$0.10/kWh to \$0.40/kWh with the allowance of capital cost variation and associated maintenance cost, including:

- Research by the National Renewable Energy Laboratory (NREL) (Givler and Lilienthal, 2005) reports a battery capital cost of US\$75 with an 845-kWh lifetime per battery (equivalent to AU \$0.12/kWh). A maintenance cost of \$2.00/year is also reported in this research.
- The recent market price of batteries with parameters as reported by Solaray (2018), based on which the storage price can be calculated as follows. As the charge cycle is assured by warrantee, therefore no additional maintenance cost is considered in this case.

$$P_S = \frac{P_B}{B \times N_C} \tag{12}$$

$$= \frac{\$2650}{1.2\text{kWh} \times 7{,}300}$$

$$= \$0.30/\text{kWh}$$

where: P_S is the storage price, P_B is the battery price, B is the battery size, and N_C is the warranted number of charge cycles.

Table 2: Value Range of Parameters

Parameter (kWh)	Value Range			Iteration Number
	Minimum	**Step**	**Maximum**	
Grid Electricity Price ($/kWh)	0.20	0.10	0.40	3
Feed-in Price ($/kWh)	0.10	0.10	0.50	5
Electricity Storage Price ($/kWh)	0.10	0.10	0.40	4
Battery Size (kWh)	0	1	15	16
Total Iterations				**960**

3.5 Results and Discussion

The combination of different electricity supply price, feed-in price, battery storage price, and battery size results in 960 iterations in total. With the proposed energy storage decision framework applied to each combination of the three prices mentioned above, a minimum total energy price is calculated, based on which the corresponding energy storage decision can be achieved. A program is developed to automatically calculate these 960 iterations in this paper. Taking the price combination of $0.30/kWh grid electricity, $0.10/kWh feed-in electricity, and $0.10/kWh electricity storage as an example, the calculation results and decision-support information are listed in Table 3, from which it can be observed that: (1) The electricity quantities supplied from grid, fed into the grid, and stored onsite vary with the battery size, and (2) Onsite energy storage results in benefits for this price combination, and the larger the battery size is, the more the total energy price declines. However, for other price combinations such as: $0.30/kWh grid electricity, $0.10/kWh feed-in electricity, and $0.20/kWh electricity storage, as demonstrated in Table 4, the total electricity price remains unchanged regardless of battery size, which implies that the price combination reaches a break-even point, and no energy storage (no capital cost at all) results in a better outcome than does any battery size.

In order to obtain a full picture, the total electricity cost with battery size is plotted for the four electricity storage price options, based on the price combinations of \$0.30/kWh grid electricity and \$0.10/kWh feed-in electricity (see Figure 7). It can be observed that: (1) when the storage price is \$0.20/kWh, the price combination reaches a break-even point, and no energy storage (no capital cost at all) is the optimal solution; (2) when the storage price is above \$0.20/kWh, onsite energy storage within the given storage prices will not result in any benefits for the price combination of \$0.30/kWh grid electricity and \$0.10/kWh feed-in electricity; and (3) when the storage price is below \$0.20/kWh, onsite energy storage results in benefit gains, and the larger the battery size is, the less the total energy price. Similarly, the total electricity price is plotted for the price combination of \$0.40/kWh grid electricity and \$0.30/kWh feed-in electricity in Figure 8, from which it can be observed that: (1) onsite energy storage within the given storage prices will not reduce the total electricity price; (2) when the storage price is \$0.10/kWh, the price combination reaches a break-even point, and no energy storage (no capital cost at all) is the optimal solution; and (3) for the given storage prices other than \$0.10/kWh, onsite energy storage results in increases of the total electricity price, and the larger the battery size is, the more total energy price increases.

Table 3. Energy Storage Results 1

(Grid Electricity Price: \$0.30/kWh, Feed-in Price: \$0.10/kWh, Electricity Storage Price: \$0.10/kWh)

Battery Size (kWh)	Total Electricity Price (\$)	Electricity from Grid (kWh)	Electricity to Grid (kWh)	Electricity Stored (kWh)
0	1,038.70	4,138.60	2,028.90	0
1	984.75	3,599.30	1,489.70	539.28
2	955.71	3,309.00	1,199.30	829.60

3	932.22	3,074.10	964.44	1,064.50
4	912.62	2,878.00	768.41	1,260.50
5	897.31	2,724.90	615.28	1,413.70
6	886.44	2,616.20	506.60	1,522.30
7	878.23	2,534.20	424.55	1,604.40
8	872.04	2,472.20	362.57	1,666.40
9	867.25	2,424.30	314.68	1,714.30
10	863.46	2,386.40	276.78	1,752.20
11	860.36	2355.4	245.78	1,783.20
12	858.01	2331.9	222.33	1,806.60
13	856.43	2316.1	206.46	1,822.50
14	855.20	2303.8	194.16	1,834.80
15	854.16	2293.4	183.81	1,845.10

Table 4. Energy Storage Results 2

(Grid Electricity Price: $0.30/kWh, Feed-in Price: $0.10/kWh, Electricity Storage Price: $0.20/kWh)

Battery Size (kWh)	**Total Electricity Price ($)**	**Electricity from Grid (kWh)**	**Electricity to Grid (kWh)**	**Electricity Stored (kWh)**
0	1,038.70	4,138.60	2,028.90	0
1	1,038.70	3,599.30	1,489.70	539.28
2	1,038.70	3,309.00	1,199.30	829.60
3	1,038.70	3,074.10	964.44	1,064.50
4	1,038.70	2,878.00	768.41	1,260.50
5	1,038.70	2,724.90	615.28	1,413.70
6	1,038.70	2,616.20	506.60	1,522.30
7	1,038.70	2,534.20	424.55	1,604.40
8	1,038.70	2,472.20	362.57	1,666.40
9	1,038.70	2,424.30	314.68	1,714.30
10	1,038.70	2,386.40	276.78	1,752.20
11	1,038.70	2,355.40	245.78	1,783.20
12	1,038.70	2,331.90	222.33	1,806.60
13	1,038.70	2,316.10	206.46	1,822.50
14	1,038.70	2,303.80	194.16	1,834.80
15	1,038.70	2,293.40	183.81	1,845.10

The above results reveal that energy storage decisions depend on the combinations of electricity prices:

(1) For some price combinations (e.g., $0.30/kWh grid electricity, $0.10/kWh feed-in electricity, and $0.10/kWh electricity storage), onsite energy storage proves to be beneficial,

and the larger the battery size is, the more the total energy price decline.

(2) For a present and realistic price combination of \$0.30/kWh grid electricity, \$0.10/kWh feed-in electricity, and \$0.20/kWh for electricity storage, there is no cost benefit.

(3) If, however, the cost of grid-provided electricity increased while the battery cost per kWh decrease, the incentive for battery storage becomes attractive. As electricity cost has doubled in Australia over the last 10 years and is again on the rise, this could provide a promising outcome for battery storage.

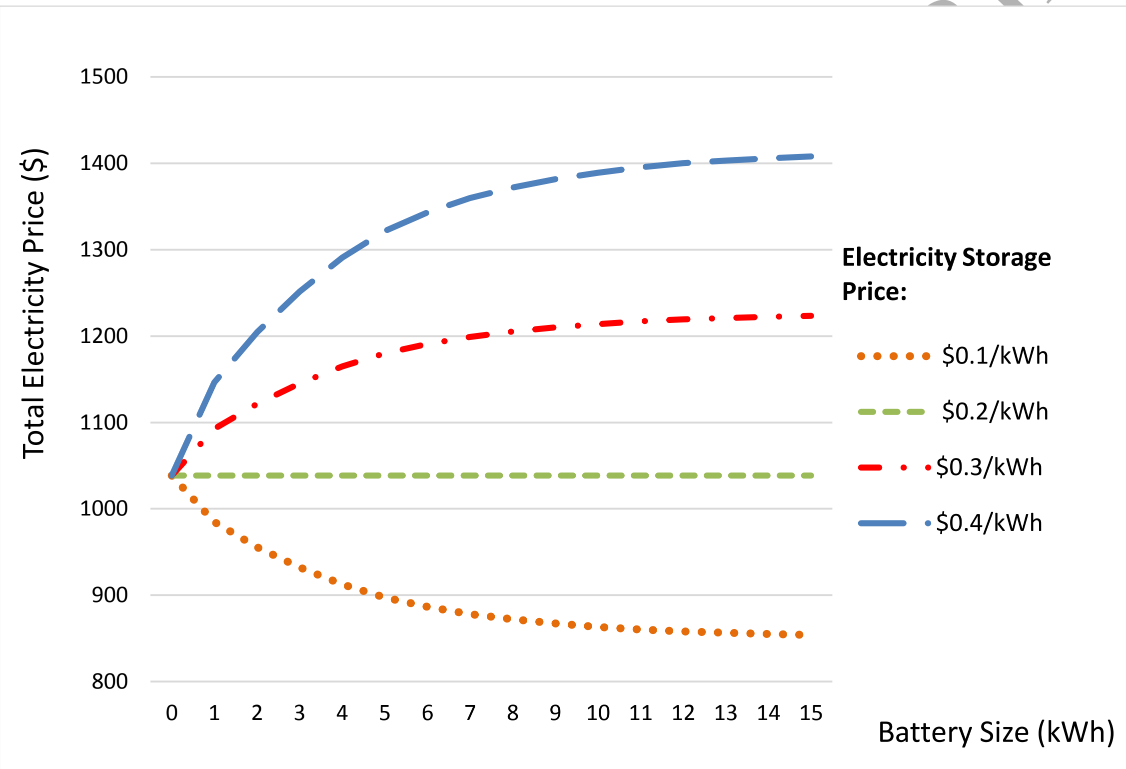

Figure 7: Total Electricity Price vs. Battery Size
(Grid Electricity Price: \$0.30/kWh, Feed-in Price: \$0.10/kWh)

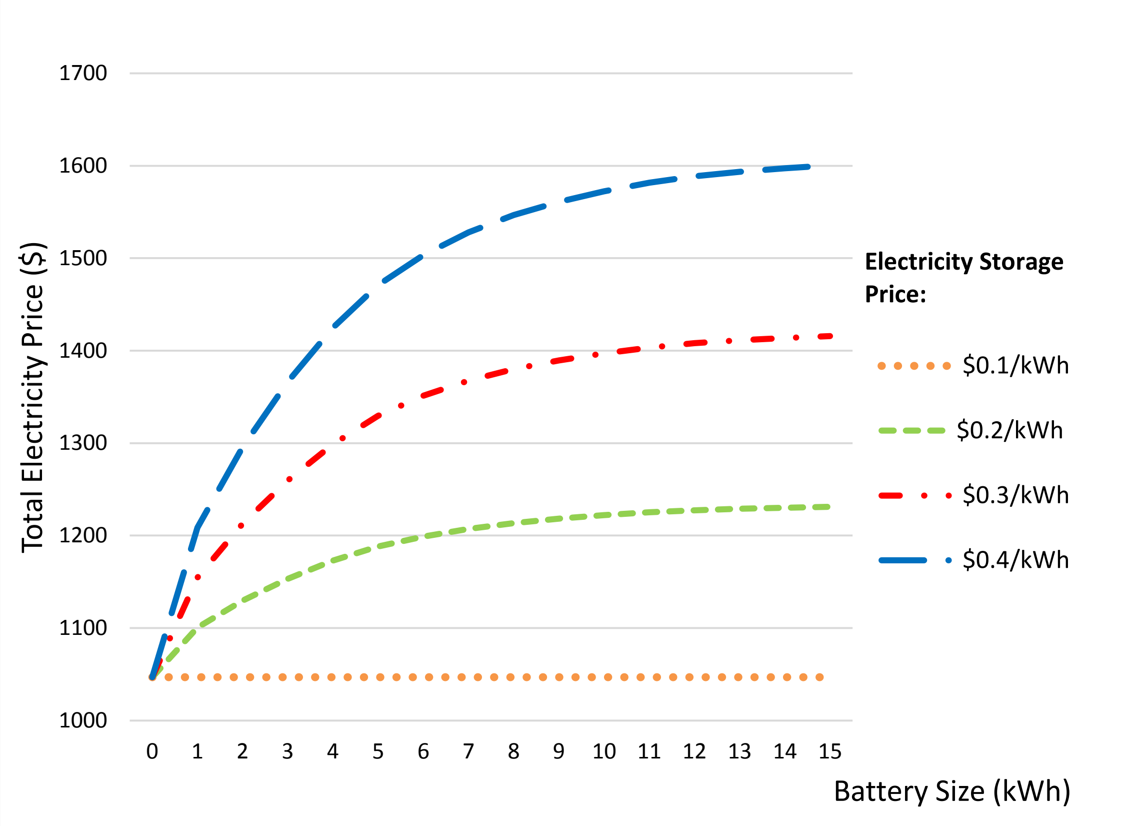

Figure 8: Total Electricity Price vs. Battery Size
(Grid Electricity Price: $0.4/kWh, Feed-in Price: $0.3/kWh)

4. **Conclusions**

As the installation cost of PV systems decreases and incentives such as FiTs are offered, solar-PV homes are becoming popular. Given the fact that there exist considerable price differences between grid electricity supply and FiTs, decision making of energy storage using batteries becomes an imperative topic. This paper studied the battery storage decision using Smart Meter data, which incorporates the actual energy generation and consumption patterns of solar-PV homes. A Smart Meter records the electricity exported from the grid and the electricity imported to the grid at a given time interval, which is related to the actual energy demands and supply of a solar-PV home, thus the smart meter provides reliable sources for the energy storage decision of a solar-PV home.

This research first analysed the electrical energy flows of an integrated solar-PV home as a case study. The analysis of the actual performance revealed that 51% of the harvested energy of the solar-PV home, which was 3,941 kWh in total, was exported to the grid while the EV was charged acting as a battery. The analysis also indicated that the EV yielded financial benefits for the household by significantly reducing petrol purchases. Given the price differences between imported and exported electricity, this research then studied the decision making of battery storage and sizing for solar-PV homes utilising smart meter data. This research proposed an intelligent algorithm to calculate the quantities of electricity supplied from the grid, fed into the grid, and stored in a battery for various given battery sizes, based on the smart meter data. Furthermore, this study analysed the total electricity price for energy storage decision, with ranges of electricity supply prices, feed-in prices, and storage prices considered. The proposed energy storage decision framework was applied to 960 combinations of electricity prices and commonly used battery sizes. The results revealed that at the present utility prices of \$0.3/kWh and a feed-in-tariff of \$0.10/kWh in the studied region, energy storage with a battery cost of \$0.2 /kWh or more was excessive and not economically feasible. However, with the increasing cost of electricity and constant changes in battery price, the outcomes could quickly reverse.

Energy storage using batteries is a dynamic process and highly related to the actual energy profile of solar-PV homes, which requires more sophisticated analysis. This research proposed an innovative decision-making framework for the energy storage of solar PV homes using Smart Meters, with the consideration of the electricity price from the grid, the FiTs, and the storage cost using batteries. As the data is real-time monitored rather than averages or model predictions, the research results are more reliable and incorporate the actual energy profile of households. The proposed framework in this paper is intelligent and generic, which can be applied for the battery storage decision of those households with grid-connected PV systems and Smart Meter data. Considering that a current Smart Meter provides imported and exported data with a time interval of 30-min, more detailed analysis will be conducted in future research when a smaller time interval is available for a smart meter. Moreover, the consideration of the power limit and efficiency of a home battery is also recommended for future research for more detailed analysis. The modelling verification will also be conducted in future when a battery is installed in this solar-PV home.

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