Renewable Energy 198 (2022) 1254–1266

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Techno-economic modelling for energy cost optimisation of households with electric vehicles and renewable sources under export limits

Yan Wu *, Syed Mahfuzul Aziz, Mohammed H. Haque

UniSA STEM, University of South Australia, Mawson Lakes, SA, 5095, Australia

ARTICLE INFO

Keywords:
Electric vehicle
Renewable energy sources
Solar photovoltaic
Battery energy storage
Energy cost optimisation
Particle swarm optimisation

ABSTRACT

With the proliferation of electric vehicles (EVs), EV charging cost will become an integral part of household energy cost. This research proposes a novel household energy cost optimisation method for grid-connected homes with EV under power export constraints. It addresses the limitations of previous studies by incorporating more realistic variable EV charging characteristics, power export limits, degradation of battery energy storage (BES) and battery salvage revenue into a comprehensive techno-economic energy system model. Cost optimisation results are presented for four system configurations using relatively new *time-of-use (ToU)* tariff and real load and photovoltaic (PV) generation data for South Australian households. Sensitivity analysis for annual energy cost (AEC) is conducted by varying daily household load demand, PV/BES capacity, power export limits and PV/BES cost. Power flow and peak demand analyses are presented to the impacts of PV, BES and EV on household demand. Results show that PV with BES and EV is the most economical configuration for individual households, where the AEC can be reduced by up to 39.6% compared to a normal household without EV, PV and BES. The BES can effectively reduce household power and energy demands during peak periods by up to 80.4% and 89.1%, respectively.

1. Introduction

Electric vehicle (EV) will become an important component of household energy consumption globally under the plans to replace cars based on internal combustion engines (ICE). Significant increases in EV sales have been observed in several countries/regions since 2018 [1]. The proportion of home charging can reach 50%–85% of the total EV charging events for some countries/regions because people are more willing to charge their EVs at home if they have private parking space [2]. Almost half of the private EV owners (45%) prefer to charge EVs using renewable energy sourced from household rooftop photovoltaic (PV) system and battery storage (31%) or from grid electricity with green energy or carbon emission offset (14%) [3]. The charging cost is one of the main concerns for EV owners (54%) [3].

The wholesale price of rooftop PV systems has reached a record low as a result of continuing decrease over the last two decades, from around $4,550/kW in 2000 to $650/kW in 2020 [4]. The price of battery energy storage (BES) has also seen a steep decline, from $1,430/kWh in 2010 to $203/kWh in 2020 [5]. However, it may not always be economical for households to install rooftop PV and BES unless their capacities are carefully chosen.

Numerous studies have been conducted on optimising the household energy cost using renewable sources. In Ref. [6], to minimize the daily household energy cost, optimal sizing of new PV and BES systems are proposed, however, only grid-to-house (G2H) mode is considered. This means excess PV-generated power cannot be exported and no export revenue was considered. Sharma et al. [7] proposed a technique to minimize the energy cost of Net Zero Energy (NZE) homes through optimal sizing of new BES and used bidirectional power flow, i.e. grid-to-house (G2H) and house-to-grid (H2G). It considered South Australian households with existing PV systems; thus PV installation cost wasn't considered. Ke et al. [8] proposed a method of BES sizing for a university campus to decrease renewable curtailment using prediction of load and PV generation, but neglected the impact of battery degradation. The study presented in Ref. [9] compared the optimal results, including annual cost of electricity and capacity of PV and BES, between individual and community customers with various consumption levels, however, EV charging demand was not considered. In Ref. [10], a cost optimisation method for flat tariff was proposed for Zero Energy Buildings (ZEB) through optimal PV and BES sizing for both residential and commercial customers, however, no export limit was considered.

* Corresponding author.
E-mail addresses: yan.wu@mymail.unisa.edu.au (Y. Wu), mahfuz.aziz@unisa.edu.au (S.M. Aziz), mohammed.haque@unisa.edu.au (M.H. Haque).

https://doi.org/10.1016/j.renene.2022.08.066
Received 15 March 2022; Received in revised form 12 August 2022; Accepted 14 August 2022
Available online 17 August 2022
0960-1481/

List of nomenclature

Abbreviations and Symbols

AC	Annual cost
BE	Battery energy capacity
CC	Capital cost
CRF	Capital recovery factor
D	Distance travelled
N	Number of modules
NPC	Net present cost
OC	Operation & Maintenance (O&M) cost
P	Power
RC	Replacement cost
SoC	State of charge
SR	Salvage revenue
e	Escalation rate
i	Interest rate
i'	Effective interest rate
m	Component lifetime
n	Project lifespan
η	Efficiency
λ	Energy price
Δt	Time interval

Superscript

B	Battery energy storage (BES)
H	Household
E	Energy
PV	Photovoltaic system
EV	Electric vehicle
S	System component
G	Grid
F	Fossil fuel

Subscript

ch/dch	Charging/discharging
inv	Inverter
chgr	Charger
max/min	Maximum/minimum value
l	Limit
pp	Per pack
dp	Dumped
pu	Per unit
ee	Energy economy
ra	Rated
ini	Initial
ug	Unit generation
imp/exp	Import/export

Another method to optimise the PV and BES size for both residential and commercial customers was proposed in Ref. [11] under different tariff structures, however, battery degradation and export power constraints were not considered. The impact of PV and BES capacity on household annual electricity cost and peak demand reduction were illustrated in Ref. [12] based on capacity optimisation without considering battery degradation. Based on lifetime cost minimization using a simplified battery degradation model [13], proposed cash flow analysis and customer guidelines for household PV-BES system under flat tariff. Aiming at minimizing the payback period and lifetime capital cost [14], introduced two factors (energy autonomy and power autonomy) to measure the independence of the designed system from the grid after the installation of PV and BES. None of the above studies considered the load demand due to household EV charging. Also, most of these studies did not consider important parameters such as house-to-grid export power limit, battery degradation and battery salvage revenue.

Although the optimal approaches to household renewable energy integration proposed in Refs. [15,16] included the EV charging demand, realistic EV charging characteristics were not considered. These two studies assumed a constant-current charging rate to represent the household EV load, however the actual EV charging involves multiple charging stages with different levels of power consumption. This means that the studies in Refs. [15,16] weren't able to use accurate overall household load profile including EV. Furthermore, the optimisation algorithm proposed in Ref. [15] determines the PV capacity first and then obtains the BES capacity, which means that the influence of BES on PV capacity is ignored. In Ref. [16], the capacity reduction of the BES with age wasn't considered. Table 1 summarises the notable features of the existing studies for optimisation of household renewables and BES. Clearly, energy cost optimisation of households involving EVs is considered in only the last three studies of Table 1. Among them, only this paper considers *household-to-grid* power export limits and variable

Table 1
Limitations of the existing studies.

Ref.	EV	Decision variables	Optimisation method/tool	Limitations			Other limitations
				Export power limits	Battery degradation	Salvage revenue	
[6]	×	PV-BES capacity	Dynamic programming algorithm	×	×	×	No replacement cost, no H2G or feed-in-tariff (*FiT*)
[7]	×	BES capacity	Minimization program in MATLAB	×	NA	NA	No PV capital cost
[8]	×	BES capacity	OpenDSS	×	×	NA	No PV capital cost
[9]	×	PV-BES capacity	Genetic algorithm (GA)	×	×	NA	–
[10]	×	PV-BES capacity	Particle swarm optimisation (PSO) algorithm	×	NA	NA	–
[11]	×	PV-BES capacity	GA	×	×	NA	–
[12]	×	PV-BES capacity	AusZEH Design Tool	×	×	×	–
[13]	×	PV-BES capacity	PSO	✓	NA	NA	–
[14]	×	PV-BES capacity	PSO	×	NA	NA	–
[15]	✓	step1: PV capacity step2: BES capacity	Self-developed, mothed not known	×	NA	NA	Fixed EV charging rate
[16]	✓	PV-Wind-BES capacity	Monte Carlo and PSO	×	×	NA	Fixed EV charging rate
This study	✓	PV-BES capacity	Monte Carlo and PSO	✓	✓	✓	Two-stage charging

battery charging rates along with battery degradation and salvage revenue. It is not possible to obtain accurate optimisation results without considering all these key parameters.

To address the above research gaps, this study proposes a novel cost optimisation method for grid-connected households with EV. The proposed optimisation model incorporates a combination of important parameters not considered simultaneously within a single model by previous approaches. These parameters include more realistic two-stage variable battery charging rates as opposed to a fixed charging rate, power export limits, battery degradation and battery salvage revenue. Due to the reasons stated above, the proposed method is expected to deliver more accurate results compared to the existing methods. Due to the increasing adoption of cost-reflective retail electricity tariffs worldwide, this study presents comprehensive cost optimisation results and critical analysis for households with EV under an existing Australian *time-of-use* (*ToU*) tariff. For simplicity, this study has used half-hourly household load and PV generation profiles, and linear battery degradation. The results can be further enhanced by using higher resolution load and PV generation profiles as well as more realistic battery degradation and charging characteristics. Nonetheless, the analysis presented in this study has revealed new findings on the influence of PV/BES cost, PV/BES capacity, daily household energy demand and power export limits on the annual energy cost (AEC) of households with and without EV. These findings will inform and greatly facilitate cost-effective integration of household EVs with optimally sized PV and BES.

The study is limited to households owning only one vehicle, either ICE or EV. In case of EV, it is assumed to be charged only at home. The households are assumed not to include natural gas as a source of energy. The gasoline and electricity prices are assumed to have the same escalation rate. The household car is assumed to travel a fixed daily average distance based on Victorian travel data. Despite these assumptions, this study will provide valid optimisation results and annual energy costs for households, and it will be possible to extend the results for the cases not covered by this study. For example, the impact of different travel distances can be easily determined by conducting a sensitivity analysis.

The paper is organized as follows: Section 2 presents the objective function of the cost-based optimisation mothed and various home energy system configurations. The overall optimisation mothed is presented in Section 3 along with the rule-based energy management strategy for each configuration. Section 4 presents the simulation model of the system components including PV, EV and home battery. The input data used in the simulation is presented in Section 5, which include economic and technical parameters, EV usage data, household load and PV generation profiles, and electricity tariff. In Section 6, the optimisation results for the different system configurations are compared, and the sensitivity analysis is presented along with power flow and peak demand analyses. Finally, Section 7 concludes the paper.

2. Problem formulation

In this section, the optimisation problem is introduced. The objective is to minimize the net present cost incurred for the household renewable system components over the lifecycle and the energy consumption over the same period. The *objective function* takes the following general form:

Objective function:

$$\textit{Min}\ (\textit{Net present cost})$$

$$\textit{subject to}\ \begin{cases} \textit{System power balance constraint} \\ \textit{Other constraints} \end{cases}$$

To arrive at the objective function, the system configurations and rule-based energy management strategies need to be identified. Also, models of the system components, such as PV, BES and EV, will need to be established. The system configurations are presented in this section, while the rule-based energy management strategies and the component models are presented in Sections 3 and 4 respectively.

Table 2
Household energy system configurations.

Configuration	Home load	ICE	EV	PV	BES
Basic	✓	✓			
1	✓	✓		✓	
2	✓	✓		✓	✓
3	✓		✓	✓	
4	✓		✓	✓	✓

2.1. Home energy system configurations

Table 2 lists the various components of five different home energy system configurations. The *basic configuration* is a standard home with an ICE car. In Table 2, *configurations 1–4* represent alternatives to the basic one stated above. *Configuration 1* is the typical one with a rooftop PV system. In c*onfiguration 2*, a BES is integrated with the PV system. *Configurations 3 and* 4 correspond to *configurations 1 and 2*, but with the ICE car replaced with an EV.

The annual household energy cost for consumption of grid electricity is:

$$AC^G = \sum_{t=1}^{N_{\Delta t}} \left[\lambda_{imp}^G(t) \times P_{imp}^G(t) \times \Delta t \right] - \sum_{t=1}^{N_{\Delta t}} \left[\lambda_{exp}^G(t) \times P_{exp}^G(t) \times \Delta t \right] \tag{1}$$

where, $\lambda_{imp}^G(t)$ and $\lambda_{exp}^G(t)$ represent the per unit imported electricity tariff and the per-unit revenue for exporting energy to the grid respectively; $P_{imp}^G(t)$ and $P_{exp}^G(t)$ represent the power imported and exported from/to the grid. If there is no PV, then $P_{exp}^G(t)$ is zero and no revenue is earned.

The annual household energy cost due to consumption of gasoline by ICE car is given by (2) [17]:

$$AC^F = \lambda^F \times D \times \eta^F \times N_{day} \tag{2}$$

where, λ^F is the gasoline price, D is the daily travel distance, η^F is the fuel efficiency of ICE car, and N_{day} is the number of days in the year.

2.2. Cost modelling

The *net present cost (NPC)* consists of NPC of system components (NPC^S) and NPC of energy consumption (NPC^E). The two decision variables are the number of PV panels (N^{PV}) and the number of BES packs (N^B). The objective function can therefore be represented by (3).

$$\begin{aligned} &Min\left\{NPC^S + NPC^E\right\} = Min\left\{NPC\left(N^{PV}, N^B\right)\right\}, \\ &\qquad \begin{cases} N^{PV} \in N+ \ and\ N^B = 0,\ for\ configurations\ 1\ and\ 3, \\ N^{PV} \in N+ \ and\ N^B \in N+,\ for\ configurations\ 2\ and\ 4, \end{cases} \end{aligned} \tag{3}$$

In any time interval, the sum of the input power, which includes the power imported from the grid (P_{imp}^G), the PV output power (P^{PV}) and the power discharged by the BES (P_{dch}^B), should be equal to the sum of the output power, which includes the home load power (P^H), the EV charging power (P_{ch}^{EV}), the power exported to the grid (P_{exp}^G), the BES charging power (P_{ch}^B) and the dumped power (P_{dp}). Accordingly, the general power balance equation of the system is given by (4). This equation can be used for all system configurations by setting the values of some terms to zero where relevant.

$$P_{imp}^G(t) + P^{PV}(t) + P_{dch}^B(t) = P^H(t) + P_{ch}^{EV}(t) + P_{exp}^G(t) + P_{ch}^B(t) + P_{dp}(t) \tag{4}$$

$$\text{where,} \begin{cases} P_{imp}^G(t) \times P_{exp}^G(t) = 0 \\ P_{ch}^B(t) \times P_{dch}^B(t) = 0 \end{cases}$$

because export and import cannot occur simultaneously, and battery charging and discharging cannot occur simultaneously.

2.2.1. Net present cost of system components (NPC^S)

The NPC^S can be calculated using (5). Here, the NPC of the component's operation and maintenance cost (OC) is calculated over a *n*-year project lifespan using an interest rate *i*. The NPC of the component's replacement cost (RC) and salvage revenue (SR) is calculated every *m*-year, where *m* is the component lifetime.

$$NPC^S = CC + OC \times [(1+i)^n - 1] / [i \times (1+i)^n] + (RC - SR) \times \sum_{k \in Z} 1/(1+i)^k, \quad Z = \{m, 2m, \ldots\} \tag{5}$$

The capital cost of the system components (CC) is calculated using (6). Here, P^{PV}_{pp} and BE^B_{pp} are the capacities of the PV and battery storage per pack, respectively.

$$CC = P^{PV}_{pp} \times N^{PV} \times CC^{PV}_{pu} + BE^B_{pp} \times N^B \times CC^B_{pu} \tag{6}$$

where, CC^B_{pu} and CC^{PV}_{pu} are the capital cost per unit of the BES and PV system respectively, where the cost of the inverter is included.

$$OC = P^{PV}_{pp} \times N^{PV} \times OC^{PV}_{pu} + BE^B_{pp} \times N^B \times OC^B_{pu} + D \times \left(OC^{ICE}_{pu} + OC^{EV}_{pu}\right) \times N_{day} \tag{7}$$

where, OC^B_{pu}, OC^{PV}_{pu}, OC^{EV}_{pu} and OC^{ICE}_{pu} are the O&M costs per unit of the individual components indicated by the respective superscripts. By setting OC^{EV}_{pu} or OC^{ICE}_{pu} to zero, this equation can be used for home configurations with either EV or ICE.

The replacement cost of the system components (RC) is calculated using (8).

$$RC = P^{PV}_{pp} \times N^{PV} \times RC^{PV}_{pu} + BE^B_{pp} \times N^B \times RC^B_{pu} + BE^{EV} \times RC^{EV}_{pu} \tag{8}$$

2.2.2. Net present cost of energy consumption (NPC^E)

The NPC^E at an escalation rate *e* above the interest rate *i* is:

$$NPC^E = \sum_{y=1}^{n} \left[\left(AC^G + AC^F\right) \times 1 / (1 + i')^y\right] \tag{9}$$

where, i' is the effective interest rate defined by $i' = (i - e)/(1 + e)$.

If the house does not use natural gas as a source of energy, the annual energy cost for consumption of grid electricity and gasoline are given by (1) and (2) respectively.

2.3. Annual energy cost (AEC)

The annual energy cost (AEC), representing the equivalent annual net present cost of energy consumption over the project lifespan, is used as a measure of cost for each of the four configurations after applying the optimisations in (3). The AEC is calculated by summing the net present cost of system components (NPC^S) and energy consumption (NPC^E) after multiplying each by the corresponding capital recovery factor (CRF) [18], as shown in (10).

$$AEC = NPC^S \times CRF^S + NPC^E \times CRF^E \tag{10}$$

where,

$$\begin{cases} CRF^S = [i \times (1+i)^n] / [(1+i)^n - 1] \\ CRF^E = [i' \times (1+i')^n] / [(1+i')^n - 1] \end{cases} (11) \tag{11}$$

3. Optimisation process

Fig. 1 shows the overall flow chart of the optimisation process to achieve minimum NPC using the objective function given in (3). Particle swarm optimisation (PSO) solver in MATLAB is used to find the optimal sizes of PV and BES, because PSO has a more straightforward syntax than GA for modelling power system flow control. In addition, PSO is more effective in memory utilisation and the optimisation solution is largely unaffected by the size and nonlinearity of the problem [19]. The optimisation flow chart of Fig. 1 incorporates rule-based energy management strategy (EMS) within the PSO loop. The rule-based EMS for each of the four home energy system configurations are described in eqn. (12)–(20) and summarised in Fig. 2. These strategies are based on the knowledge of power balance equations for household energy transactions as well as the real operational conditions and constraints of home energy system components such as PV and BES. Therefore, the inclusion of the rule-based EMS helps the PSO solver to perform optimisation by reducing the number of decision variables [20] based on real operational conditions and constraints. Existing literatures reinforce this concept and have listed multiple benefits of implementing rule-based control strategies within a conventional optimisation technique. For example, the rule-based strategies (1) lead to simpler mathematical equations and lower computational complexity, (2) are easy to understand and implement, (3) provide flexibility by allowing the rules to be updated [21]. Examination of (12)–(20) reveals that it is possible to obtain continuous feedback from system components such as PV and BES. Therefore, in addition to the benefits listed above, the rule-based strategies provide the opportunity to implement closed loop control [22]. In summary, the inclusion of the rule-based EMS in the overall PSO-based optimisation flow chart of Fig. 1 is expected to reduce the

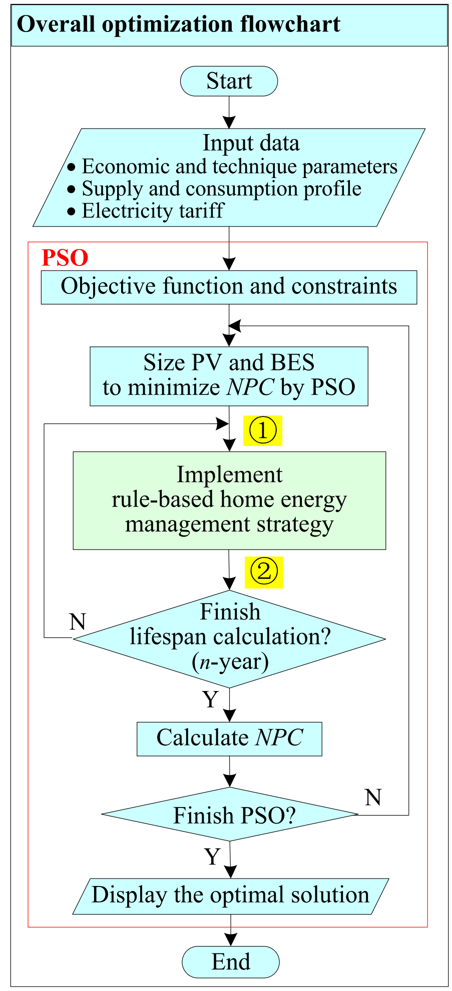


Fig. 1. Overall optimisation flow chart.

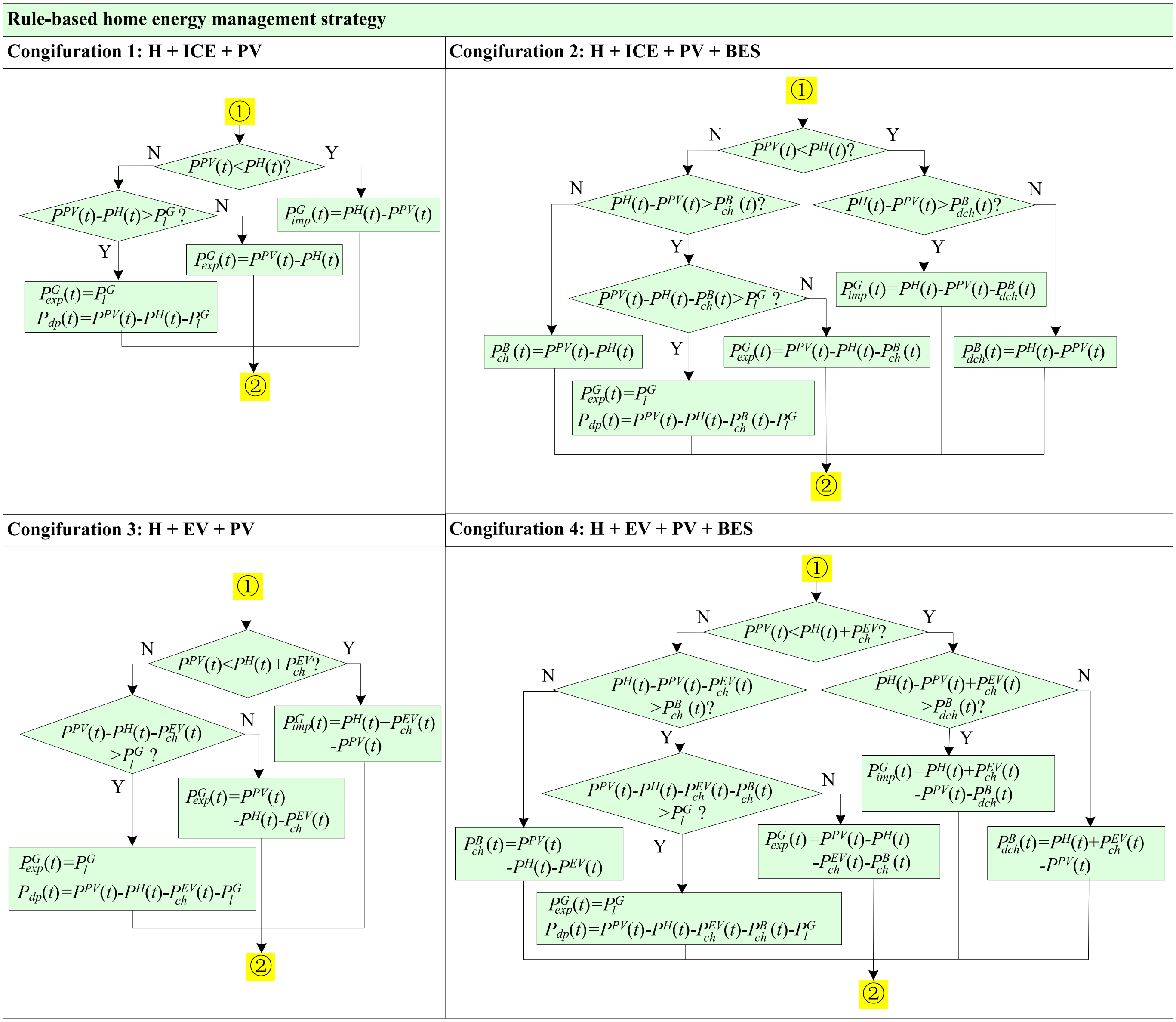


Fig. 2. Rule-based home energy management strategies.

overall computational burden, provide near optimal solution and ensure maximum utilisation of the PV generated energy to serve the household load. This will help lower household energy cost and maximise the return on investment in PV and BES.

3.1. Basic configuration: household + ICE

In the *basic configuration*, neither PV nor BES is present. Thus, the household demand will be solely met by importing power from the grid, and no energy will be exported to the grid.

$$\begin{cases} P_{imp}^G(t) = P^H(t) \\ P_{exp}^G(t) = 0 \end{cases} \tag{12}$$

3.2. Configuration 1: household + PV + ICE

In *configuration 1*, there is no energy conversion between the gasoline-based ICE car and the home energy system. When PV generation exceeds the household load demand, the excess PV-generated power is sold to the grid at the feed-in-tariff (*FiT*). The imported and exported power can be calculated using (13), and the exported power is limited by the grid export limit (P_l^G).

$$\begin{cases} P_{imp}^G(t) = P^H(t) - P^{PV}, & if\ P^{PV}(t) < P^H(t) \\ P_{exp}^G(t) = min\left[P_l^G, \left(P^{PV}(t) - P^H(t)\right)\right], & otherwise \end{cases} \tag{13}$$

The difference between the excess PV-generated power and the actual exported power is the amount of power dumped from excess PV generation (P_{dp}), as shown below:

$$P_{dp}(t) = max\left[P^{PV}(t) - P^H(t) - P_l^G, 0\right] \tag{14}$$

3.3. Configuration 2: household + PV + BES + ICE

In *configuration 2*, a BES is added. The excess power from PV generation will be first used to charge the BES; when the BES is fully charged then the excess power is exported. However, if the PV generation is less than the household demand, first the BES is discharged to supply the load before importing power from the grid. The power imported/exported from/to the grid can be calculated using (15).

$$\begin{cases} P^G_{imp}(t) = P^H(t) - P^{PV}(t) - P^B_{dch}(t), & \text{if } P^{PV}(t) + P^B_{dch}(t) < P^H(t) \\ P^G_{exp}(t) = min\left[P^G_l, \left(P^{PV}(t) - P^H(t) - P^B_{ch}(t)\right)\right], & \text{otherwise} \end{cases} \tag{15}$$

The extra PV generated power after charging the BES and exporting to the grid is the power dumped from excess PV generation (P_{dp}), as shown in (16).

$$P_{dp}(t) = max\left[P^{PV}(t) - P^H(t) - P^B_{ch}(t) - P^G_l, 0\right] \tag{16}$$

3.4. Configuration 3: household + PV + EV

In *configuration 3*, when PV generation exceeds the total household load demand and EV charging load demand, the excess PV power is exported to the grid. However, power is imported from the grid when PV generation is less than the total household demand and EV charging demand, as shown by (17).

$$\begin{cases} P^G_{imp}(t) = P^H(t) + P^{EV}_{ch}(t) - P^{PV}(t), & \text{if } P^{PV}(t) < P^H(t) + P^{EV}_{ch}(t) \\ P^G_{exp}(t) = min\left[P^G_l, \left(P^{PV}(t) - P^H(t) - P^{EV}_{ch}(t)\right)\right], & \text{otherwise} \end{cases} \tag{17}$$

The difference between the excess PV-generated power and the actual exported power is the power dumped from excess PV generation, as shown in (18).

$$P_{dp}(t) = max\left[P^{PV}(t) - P^H(t) - P^{EV}_{ch}(t) - P^G_l, 0\right] \tag{18}$$

3.5. Configuration 4: household + PV + BES + EV

In *configuration 4*, a home BES is added to *configuration 3*. When the PV generation exceeds the total household demand and EV charging demand, the excess PV-generated power is first used to charge the BES. However, when the PV generation is less than the total household demand and EV charging demand, first the BES is discharged to supply power to the home before importing from the grid. The imported and exported power can be calculated using (19).

$$\begin{cases} P^G_{imp}(t) = P^H(t) + P^{EV}_{ch}(t) - P^{PV}(t) - P^B_{dch}(t), & \text{if } P^{PV}(t) + P^B_{dch}(t) < P^H(t) + P^{EV}_{ch}(t) \\ P^G_{exp}(t) = min\left[P^G_l, \left(P^{PV}(t) - P^H(t) - P^{EV}_{ch}(t) - P^B_{ch}(t)\right)\right], & \text{otherwise} \end{cases} \tag{19}$$

The extra power after charging the BES and exporting to the grid is the power dumped from PV generation, as shown in (20).

$$P_{dp}(t) = max\left[P^{PV}(t) - P^H(t) - P^{EV}_{ch}(t) - P^B_{ch}(t) - P^G_l, 0\right] \tag{20}$$

4. Component modelling

4.1. PV simulation model

PV generation can be calculated using (21) and the output power is limited by the rated power of the PV inverter, P^{PV}_{inv}.

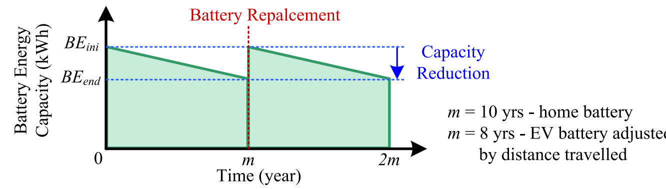


Fig. 3. Variation of battery energy capacity due to degradation and replacement.

$$P^{PV}(t) = min\left[P^{PV}_{inv}, N^{PV} \times P^{PV}_{pp}(t) \times \eta^{PV}\right] \tag{21}$$

where, $P^{PV}_{pp}(t)$ is the instantaneous power generated by a pack of PV panel and η^{PV} is the inverter efficiency. The size of the PV inverter (P^{PV}_{inv}) is η^{df} times the capacity of the PV system ($P^{PV}_{inv} = P^{PV}_{pp} \times NPV \times \eta^{df}$), where η^{df} is the derating factor of the PV panels and is assumed to be 80%.

4.2. EV and home battery simulation model

Both the home battery and the EV battery will suffer degradation over time and require replacement within the project lifespan. The variation in battery capacity within the project lifespan is shown in Fig. 3. The BES and EV are both assumed to use lithium-ion batteries and the available capacity at the end of the battery life is considered to be 70% of the initial capacity [23,24]. Li-ion home batteries from leading manufacturers are available for Australian household PV systems with a 10-year warranty with 70% energy retention for unlimited charging/discharging cycles [25]. Hence, we consider the home battery to have a lifespan of 10 years. The EV battery lifespan is sourced from Nissan Leaf 2019, which is representative of small-size EV models. This EV battery comes with a warranty of 8 years or 160,000 km, whichever occurs first [26]. Hence, we consider 8 years to be the maximum lifetime of the EV battery, which is adjusted according to the distance travelled. The battery capacity will be back to 100% after replacement at that time. Assuming that the battery capacity degrades linearly over time to a residual capacity at the end of the expected lifespan (BE_{end}), the available battery capacity in each year is given by (22).

$$BE = BE_{ini} - [BE_{ini} - BE_{end}] / m \times y \tag{22}$$

where, $0 \leq y \leq m$, and BE_{ini} represents the initial capacity of a new battery.

A battery charging model based on the two-stage charging characteristics proposed by Ref. [27] is used in this study. The charging sequence moves from a constant-current (CC) stage to a constant-voltage (CV) stage when the SoC reaches a predefined switching point value (SoC_{sw}). In the CV stage, the battery charging process is terminated when the charging power reaches a predefined termination SoC (SoC_{tm}). In this study, 80% of SoC_{max} is selected as SoC_{sw} [28–30], and SoC_{max} is selected as SoC_{tm} value. The power drawn by the battery charger at time t is calculated using (23).

$$P_{chgr}(t) = \begin{cases} P_{ra} \,/\, \eta_{ch}\,, & \text{if } SoC(t) \le SoC_{sw} \\ \{P_{ra} \times [\,SoC_{max} - SoC(\,t-1)\,] \,/\, [\,SoC_{max} - SoC_{sw}\,]\,\} \,/\, \eta_{ch}\,, & \text{if } SoC_{sw} < SoC(\,t\,) \le SoC_{tm} \\ 0\,, & \text{if } SoC(t) > SoC_{tm} \end{cases} \tag{23}$$

where, η_{ch} is the charging efficiency of the battery charger.

For the household BES, the recommended rated charging power (P_{ra}) should be equal to or less than 80% of the battery capacity [29]. Meanwhile, based on the rule-based home energy management strategy we have adopted, the BES will be charged only using renewable energy. This means that the actual charging power drawn by the BES ($P^{B}_{ch}(t)$) can at times be less than the BES charger power ($P^{B}_{chgr}t$), as shown by (24). The BES inverter comes as an integral part of the BES and the size of the BES inverter is 80% of the battery capacity. The state of charge (SoC) of the BES at time t can therefore be calculated by (25).

$$P^{B}_{ch}(t) \le P^{B}_{chgr}(t) \tag{24}$$

$$SoC^{B}(t) = SoC^{B}(t-1) + \left[\left(P^{B}_{ch}(t) \times \eta^{B}_{ch} - P^{B}_{dch}(t) \,/\, \eta^{B}_{dch}\right) \times \Delta t\right] \,/ BE^{B} \tag{25}$$

where, $SoC^{B}_{min} \le SoC^{B}(t) \le SoC^{B}_{max}$. η^{B}_{ch} and η^{B}_{dch} represent BES charging and discharging efficiencies respectively.

For EV battery, since charging is part of the household load, the charging power is equal to the calculated charger power, as shown in (26).

$$P^{EV}_{ch}(t) = P^{EV}_{chgr}(t) \tag{26}$$

The SoC during charging is calculated by (27). The SoC of the EV battery when arriving home after daily travel can be calculated by (28).

$$SoC^{EV}(t) = SoC^{EV}(t-1) + \left(P^{EV}_{ch}(t) \times \eta^{EV}_{ch} \times \Delta t\right) \,/\, BE^{EV} \tag{27}$$

$$SoC^{EV}_{ar}(t_{ar}) = SoC^{EV}_{de}(t_{de}) - \left(D \times \eta^{EV}_{ee}\right) \,/\, BE^{EV} \tag{28}$$

where, $SoC^{EV}_{min} \le SoC^{EV}(t) \le SoC^{EV}_{max}$. η^{EV}_{ee} is the EV energy economy. Each EV is charged continuously once a day at home until it is fully charged or until the departure time of the EV, whichever occurs first.

5. Input data

The household energy cost optimisation methods proposed in this paper are applicable universally irrespective of region or country. In this study, data for South Australian (SA) homes are used to validate the methods, as this state has one of the highest household PV installations in Australia, where around 39.3% of homes have rooftop solar panels [31]. Also, a battery subsidy is available through the SA Home Battery Scheme [32] to encourage the integration of household PV with BES. The remainder of this section describes the three types of data used in the simulation.

5.1. Economic and technical parameters

Table 3 lists the economic and technical parameters used. The project lifespan is set as 20 years. From July 2022, SA Power Networks (SAPN) plans to introduce a limit of 1.5 kW on the PV-generated power that can be exported to the grid by a single-phase grid-connected home [33]. This grid constraint is used in this study while optimal results for pre-July-2022 export limit of 5 kW are also included for comparison.

The EV charging rate of 3.7 kW is used, which is a typical Type 2 household charging rate based on the plug-in EV charger standard in IEC 62196 [39]. The initial battery capacity and the energy economy of EV are sourced from Nissan Leaf 2019, which is representative of small-size EV models. The parameters of the ICE car are taken from Nissan X Trail, which is a gasoline-based car with horsepower similar to that of Nissan Leaf. The fuel price (λ^{F}) is \$1.43/Litre as at 10 March 2022 and fuel efficiency (η^{F}) is 0.10 Litre/km. As shown in Table 3, the lifetime O&M costs of ICE car and EV are \$0.14/km and \$0.07/km, respectively [17].

For a PV system, the retail capital cost in Australia for 2020 is taken as \$900/kW [35] and the O&M cost is \$17/kW/year [36]. The lifespan of PV panel is 25 years, which is longer than the project lifespan, therefore PV panels will not require replacement within the project lifespan. However, the PV inverter has a 10-year lifespan and needs to be replaced within the project. Therefore, a PV system replacement cost of \$300/kW is considered to represent the replacement cost of the PV inverter only. In the Australian retail market, the most common PV panel capacity is 370 W/panel and BES capacity is 1 kWh/pack. Therefore, the optimal results for PV and BES capacities are rounded to multiple of these two sizes, however the proposed optimisation method can easily accommodate other PV/BES panel capacities.

The market price of BES system (battery plus inverter) in Australia was ~\$1000/kWh in 2020. Using the South Australian Government BES subsidy of \$300/kWh, \$700/kWh is used as the capital cost of BES system. With 10-year lifespan, the replacement cost of the BES system needs to be included. The O&M cost of the BES system is relatively low and therefore it is set to zero in this study.

5.2. EV usage, PV generation and consumption profile

The typical household energy consumption profile in South Australia (SA) is shown in Fig. 4(a). It is obtained by scaling down the 2020 half-

Table 3
Economical and technical parameters.

Home [33]	$P^{G}_{l} = 1.5$ kW			
Project	$i = 3\%$	$e = 2\%$	*Lifetime* =20-year	
EV [17,26,34]	$SoC^{EV}_{min} = 0.2$	$\eta^{ee} = 0.164$ kWh/km	$RC^{EV} = \$300$/kWh	$OC^{EV} = \$0.07$/km
	$SoC^{EV}_{max} = 0.95$	$BC = 40$ kWh	$SR^{EV} = \$80$/kWh	*Lifetime* = 8-year/160,000 km
	$\eta^{EV} = 90\%$	$P^{EV}_{chgr} = 3.7$ kW		
ICE [17]	$\lambda^{F} = \$1.43$/Litre	$\eta^{F} = 0.1$ Litre/km	$OC^{F} = \$0.14$/km	
PV [35–37]	$P^{PV}_{pp} = 370$ W/penal	$\eta^{df} = 80\%$	$RC^{PV} = \$300$/kW	*Lifetime*= 25-year
	$\eta^{PV} = 94\%$	$CC^{PV}_{pu} = \$900$/kW	$OC^{PV} = \$17$/kW/year	*Inverter lifetime*= 10-year
BES [7,32,37,38]	$BE^{B}_{pp} = 1$ kWh/pack	$\eta^{B}_{ch} = 90\%$	$RC^{B} = \$700$/kWh	$OC^{B} = \$0$/kWh/year
	$SoC^{B}_{min} = 0.1$	$\eta^{B}_{dch} = 90\%$	$SR^{B} = \$80$/kWh	*Lifetime* = 10-year
	$SoC^{B}_{max} = 0.95$	$CC^{B}_{pp} = \$700$/kWh		

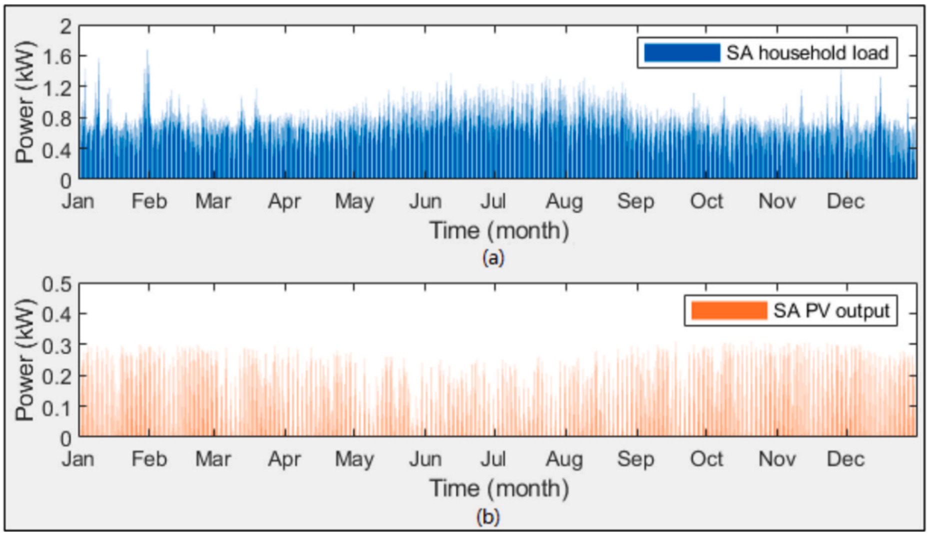


Fig. 4. (a) Household demand in SA for 2020 and (b) PV generation per penal.

hourly household consumption profile of the entire South Australian state to 17 kWh/day [40]. For PV output, the half-hourly solar generation data of a 1 kW PV system in SA is sourced from the renewable ninja website [41] and scaled down to 370 W/panel as shown in Fig. 4(b). The usage pattern of privately owned vehicles is extracted from the Victorian Integrated Survey of Travel & Activity (VISTA) 2018 [42]. According to this, the average daily travel distance of privately owned vehicles is around 36.7 km, and the departure and arrival times of the highest number of cars are 08:00 and 16:00 respectively.

5.3. Electricity tariff

In SA, the percentage of residential customers on a single rate tariff is around 80% [43]. As *time-of-use (ToU)* tariffs provide incentives to customers for reducing load demand during peak periods, the SA (South Australian) Power Networks (SAPN) intends to achieve 50% of residential customers to be on *ToU* tariffs by 2025 [43]. Thus, in this study, a *ToU* tariff called "Lightning" introduced by IO Energy is used, as shown in Fig. 5 [44]. A solar *FiT* of \$0.06/kWh is offered throughout the year under this tariff.

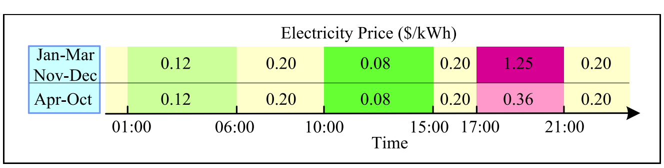


Fig. 5. Time-of-Use electricity tariff [44].

6. Optimisation results and analysis

In this section, the optimisation results are presented for all the configurations along with sensitivity analysis, power flow analysis and peak demand analysis.

6.1. Optimisation results

Table 4 shows the optimal results for PV capacity, BES capacity, NPC, AEC reduction of AEC and computation time for the four configurations along with the results for the *basic configuration*. The *basic configuration* presents the household energy cost without PV, BES and EV. Using the AEC of the *basic configuration* as a reference value, the percentage of AEC reduction is calculated for the other configurations. For clarity of understanding, results for some of the home *configurations* under various conditions are presented in separate groups, namely A, B, C and D.

For *configurations 1* and *2* (homes with ICE car), the same optimal PV size is obtained. In *configuration 1*, installing an optimally sized PV of 4.07 kW reduces the AEC by 6.71% to \$5,118.60/year. For *configuration 2*, the using optimally sized PV and BES (4.07 kW and 4 kWh) can reduce

Table 4
Optimisation results for various system configurations.

Configuration	Number of PV panels (P^{PV} in kW)	BE^B (kWh)	NPC (\$)	AEC (\$/year)	AEC Reduction (%)	Computation Time (s)
A. Gasoline-based car only						
Basic	–	–	93,313	5,486.72	–	–
1	11 (4.07)	–	85,489	5,118.60	6.71	677.90
2	11 (4.07)	4	80,852	4,917.41	10.38	875.44
B. EV only with charging occurring upon arrival at home (16:00 h)						
3	33 (12.21)	–	66,103	4,160.55	24.17	571.02
4	21 (7.77)	11	56,861	3,731.15	32.00	905.27
C. EV only with charging time delayed to early morning off-peak (~1:00 h)						
3′	11 (4.07)	–	56,769	3,515.24	35.93	661.53
4′	11 (4.07)	4	52,131	3,314.05	39.60	829.16
D. No household export limit						
4*	2703 (1000.11)	2	−351,600	−3,247.36	159.19	687.95

The last column in Table 4 lists the computation times for various configurations taken by the built-in PSO solver in MATLAB running on a Windows PC having an Intel Core i5-8500T Processor and 4 GB RAM. Using half-hourly time interval, the number of data points calculated by the algorithm for the year 2020 is (366 days × 48 half-hours/day) = 17568.

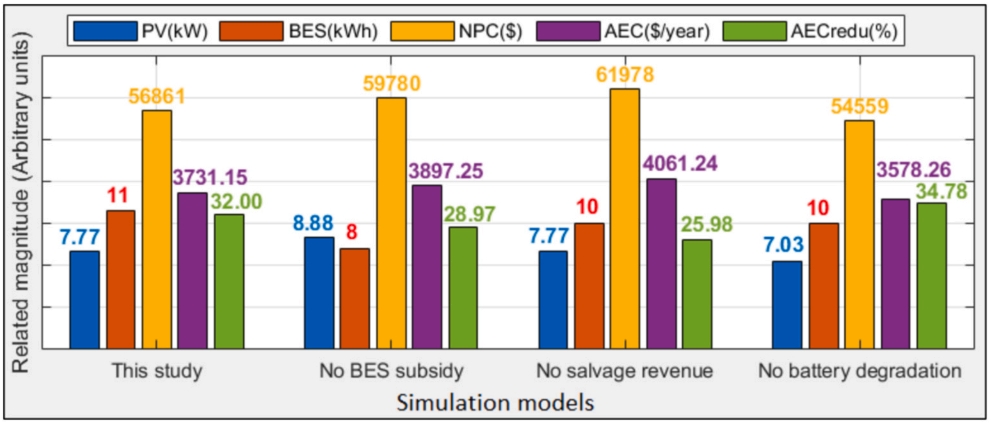


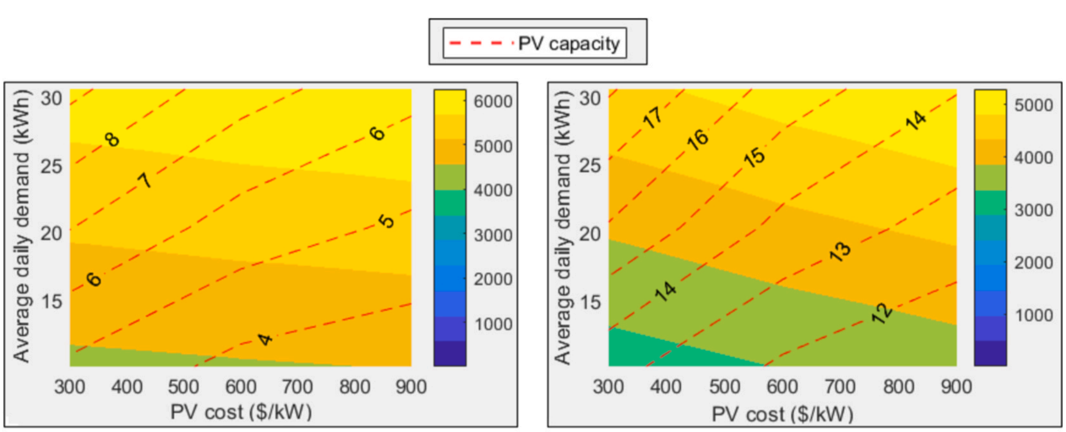
Fig. 6. Comparison of optimisation results for *configuration 4* when using the proposed model versus existing models which ignore some parameters.

AEC by 10.38% to $4,917.41/year. For *configurations 3* and *4* (ICE car replaced by EV), the optimal capacities of PV and BES are bigger. For *configuration 3*, the high per unit energy cost under *ToU* tariff during summer evenings (17:00–21:00) causes the optimal PV size to significantly increase to 12.21 kW to meet part of the peak demand, and the AEC is modestly higher than *configuration 2*. In *configuration 4*, due to installing BES, the optimal PV size is somewhat reduced compared to *configuration 3*, however the optimal BES capacity is significantly higher than *configuration 2*. Interestingly, in *configuration 4*, the introduction of EV with optimally sized PV and BES leads to the highest reduction in AEC (32.00%). The AEC can be reduced significantly below this level by shifting the EV charging start time to early morning off-peak period starting at ~01:00 when the electricity price is the second lowest under the *ToU* tariff shown in Fig. 5. These results are shown under group C in Table 4, and 35.93% and 39.60% AEC reductions are achieved for *configurations 3* and *4* respectively (shown as *configurations 3′* and *4'*). The optimal capacities of PV and BES are also reduced to the same levels as *configurations 1* and *2*. The last row of Table 4 (group D) presents the results if there is no export limit for *configuration 4* (shown as *configuration 4**). In this case, the optimized PV size soared to the upper limit (1000 kW) set for this variable in the simulation. Due to the low cost of PV systems, PV generated energy is cheaper than the *feed-in-tariff (FiT)* most household customers receive for exporting PV-energy to the grid. Hence, if there is no export limit, the cost-based optimisation minimises the household energy cost by selling as much power to the grid as possible leading to unreasonably high PV size as well as negative NPC and AEC. The above results highlight the importance of considering export limit as a key parameter in the optimisation model for household PV sizing.

To ascertain the efficacy of the proposed simulation model, analysis was conducted without the BES subsidy or battery salvage revenue or battery degradation. The effects of ignoring these parameters on the optimisation results for *configuration 4* are shown in Fig. 6. If the government subsidy for BES capital cost is ignored, then the optimal BES size is decreased due to the relatively higher BES cost leading to increases in the optimal PV size, NPC and AEC. If the salvage revenue of components is ignored, the optimal BES size is decreased with increases in NPC and AEC. If the degradation of the BES and EV battery is ignored, then ideally more energy could be stored in these batteries, resulting in lower optimal PV and BES sizes and lower energy costs. The above analysis demonstrates that when one parameter is ignored then the optimisation results deviate from those obtained using the model proposed in this paper. This shows the efficacy of the proposed energy cost optimisation model where all relevant parameters are incorporated whereas the existing models exclude some of these parameters.

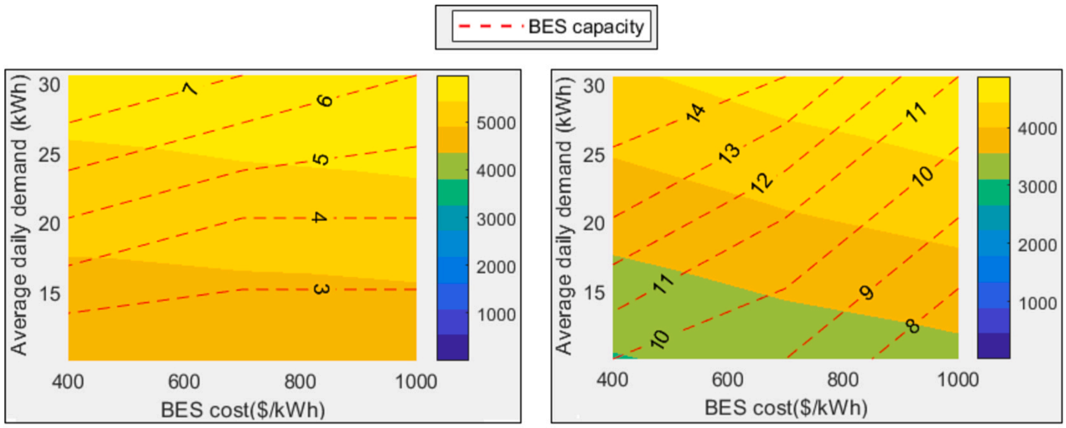
6.2. Sensitivity analysis

Fig. 7–9 illustrate the sensitivity of AEC against various factors when the charging start time is not shifted to off-peak periods. The coloured bars represent the AEC scale, the *x*-axis and *y*-axis represent two variables, and the red dashed lines (Figs. 7 and 8) represent the optimal capacity of PV or BES. For *configurations 1* and *3*, Fig. 7 shows that at a fixed PV cost the optimal PV capacity increases with higher household demand leading to increases in AEC. For a certain load demand, declining PV capital cost increases the optimal PV capacity and reduces



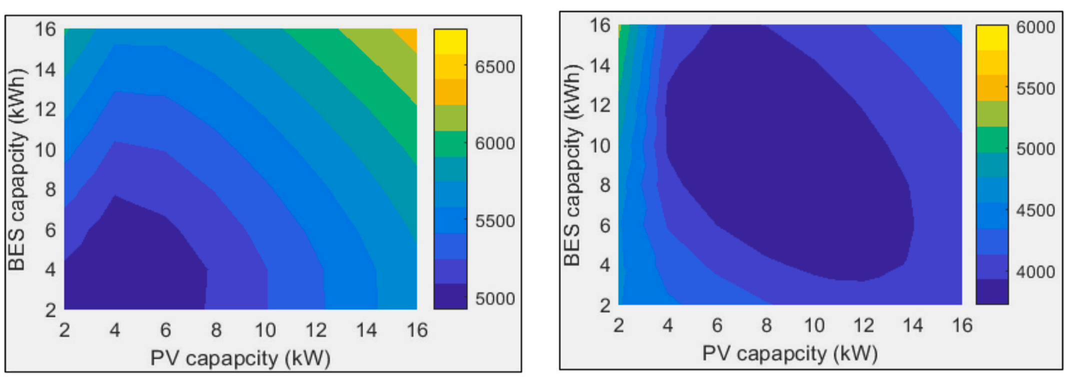
(a) (b)

Fig. 7. Variations of AEC with household demand and PV cost: (a) *configuration 1*, and (b) *configuration 3*.



(a) (b)

Fig. 8. Variations of AEC with household demand and BES cost: (a) *configuration 2*, and (b) *configuration 4*.



(a) (b)

Fig. 9. Variations of AEC with PV and BES capacities: (a) *configuration 2*, and (b) *configuration 4*.

AEC. Fig. 7(b) reveals that much higher PV capacity is warranted for households with EV.

For *configurations 2* and *4*, Fig. 8 shows that at a certain BES cost the optimal BES capacity increases with higher household demand leading to increases in AEC. For a certain load demand, declining BES capital cost increases the optimal BES capacity and reduces AEC. Fig. 8(b) reveals that much higher BES capacity is warranted for households with EV. Fig. 9 shows the effects of changing PV and BES capacities on AEC. For *configuration 2* (without EV), PV capacity of 4 kW and BES capacity of 4 kWh are optimal for the household demand used in this study. However, for *configuration 4* when EV is included, optimal PV and BES capacities increase to around 8 kW and 11 kWh, respectively.

All the results presented above are for an export limit of 1.5 kW. Fig. 10 compares the effects of the two grid export limits, i.e., 1.5 kW and 5 kW, on the optimal results for *configuration 4*. Clearly, with the higher export limit of 5 kW, the optimal PV capacity is higher, and the optimal BES capacity and the AEC are lower. These results are consistent with the 4.4 times higher exported energy for the 5 kW export limit.

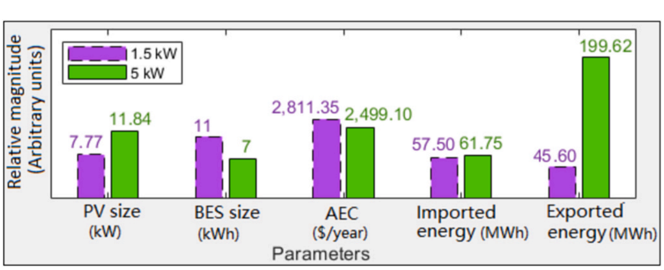
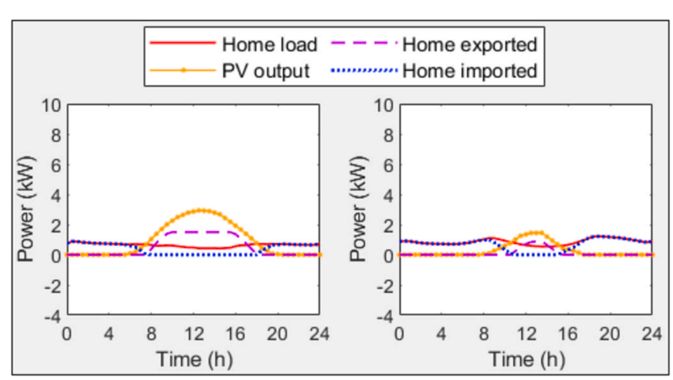


Fig. 10. Comparison of optimal results between two grid export limits for *configuration 4*.

6.3. Power flow analysis

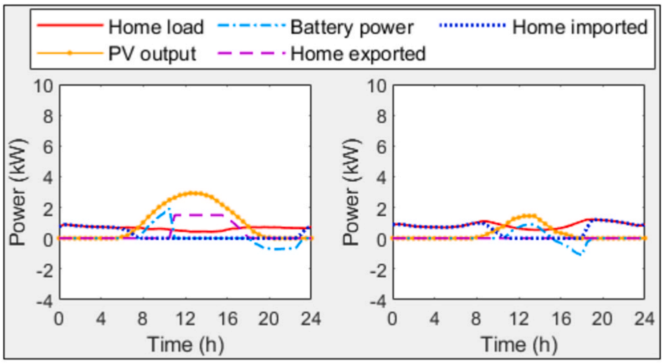
Fig. 11–14 present the power flow of the home energy system for different configurations. The energy exchange among various system components, namely, the power grid, household load, PV, BES and EV are shown for typical summer and winter days.

For *configuration 1*, as shown in Fig. 11, the PV generation can feed the household demand during the daytime and export the excess PV



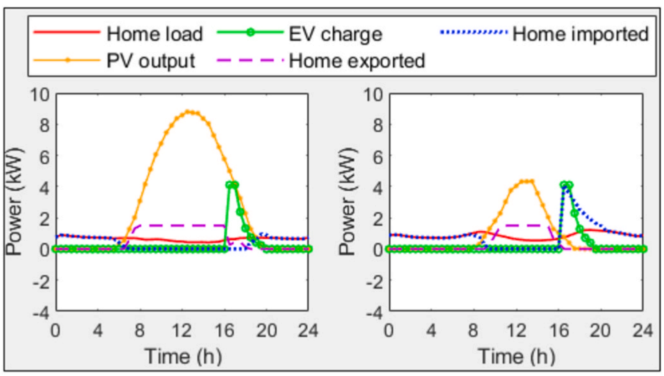
(a) (b)

Fig. 11. Daily power flow for *configuration 1* on a typical day: (a) summer, and (b) winter.



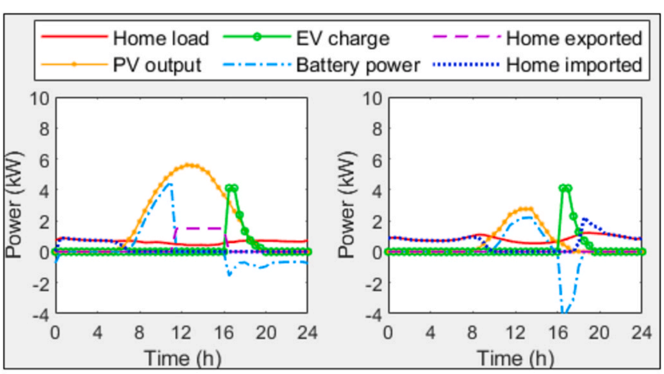
(a) (b)

Fig. 12. Daily power flow for *configuration 2* on a typical day: (a) summer, and (b) winter.



(a) (b)

Fig. 13. Daily power flow for *configuration 3* on a typical day: (a) summer, and (b) winter.



(a) (b)

Fig. 14. Daily power flow for *configuration 4* on a typical day: (a) summer, and (b) winter.

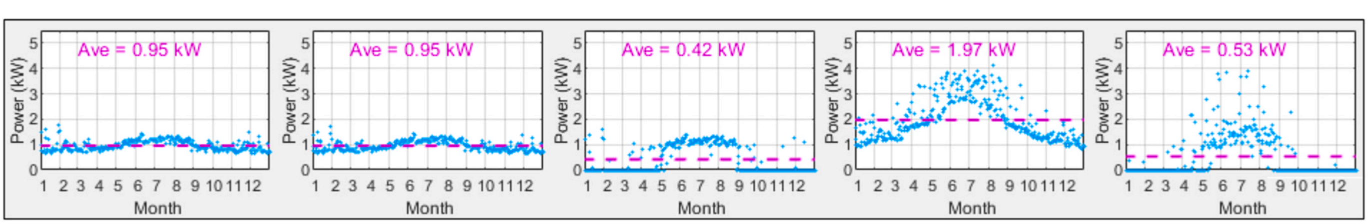
generation to the grid subject to the export limit (1.5 kW). Clearly, the PV output during summer is higher than that during winter. Fig. 12 shows the power flow for *configuration 2*, where a BES is integrated. Clearly, some of the excess PV energy is stored by charging the BES during the daytime, which enables the BES to meet some of the household demand during the evening peak.

Fig. 13 shows the power flow for *configuration 3*, where the EV charging demand is included. In summer, most of the EV charging energy is supplied by PV output. However, in winter, the EV charging energy is predominantly sourced from the power grid, thus leading to a sharp spike in imported power. This means that the evening peak demand of the power grid will increase due to unregulated EV charging, especially in winter. Compared to Fig. 13, the household BES in *configuration 4* can supply the power required for EV charging during the evening as shown in Fig. 14, consequently reducing the spike in imported power. The EV charging energy is sourced from PV and BES in summer, and mainly from the BES in winter. The power flow analysis for *configurations 2* and *4* (Figs. 12 and 14) reveal that the BES can help reduce the amount of imported energy during the evening peak by meeting the home and EV loads.

6.4. Peak demand analysis

Fig. 15 shows the distribution of daily maximum imported power and the daily average imported power during the evening peak period between 17:00 to 21:00 h, which is the period of peak electricity price under the *ToU* tariff of Fig. 5. The peak imported power shown in Fig. 15 (b) for *configuration 1*, when only PV is used, is almost the same as that shown in Fig. 15(a) for the *basic configuration* (the average peak value is 0.95 kW). However, in *configuration 2*, due to BES integration, the imported power has a significantly lower number of high peaks with an average value of only 0.42 kW as shown by Fig. 15 (c). Fig. 15(d) reveals that the EV charging demand in *configuration 3* increases the maximum imported power dramatically, and the average value (1.97 kW) is over 2 times that for *configuration 1*. For *configuration 4*, when EV is integrated with PV and BES, although there are some high peaks in the imported power, they are far less than the number of high peaks in *configuration 3*. The average peak imported power of 0.53 kW is lower than that of the *basic configuration*.

Fig. 16 compares the total consumed energy and the imported energy during the peak period (between 17:00 to 21:00) for the five configurations. In the basic case, the entire consumed energy is imported from the grid. When PV is added (*configuration 1*), 20.0% less energy is imported. With BES integration (*configuration 2*), imported energy is reduced by a huge 83.2%. In *configurations 3* and *4*, when is EV added, consumed energy rises significantly. However, imported energy is less than consumed energy by 34.7% and 89.1% respectively. This means that compared with homes with only PV (*configurations 1* and *3*), the integration of BES (*configurations 2* and *4*) can significantly reduce the power demand and energy demand during peak periods.



(a) (b) (c) (d) (e)

Fig. 15. Distribution of daily maximum imported power during evening peak in the first year of the project: (a) *basic configuration*, (b) *configuration 1*, (c) *configuration 2*, (d) *configuration 3*, and (e) *configuration 4*.

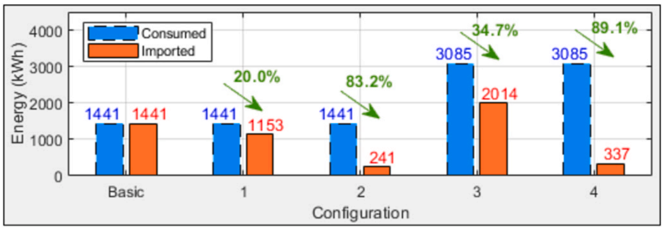


Fig. 16. Total consumed and imported energy during evening peak (17:00–21:00) in the first year of the project.

7. Conclusion

A method to optimise the annual energy cost (AEC) of households with electric vehicles (EVs) has been presented by developing a new techno-economic model.

i. The results demonstrate that households with gasoline-based cars can reduce their AECs by 6.71% and 10.38% using optimally sized PV and PV-BES systems respectively. Replacing gasoline-based car with EV can reduce AEC by 24.17% and 32.00% respectively. The most significant AEC reduction (39.60%) can be achieved under *configuration 4* with *off-peak* charging.
ii. Sensitivity analysis indicates that both higher home demand and lower capital costs of PV and BES systems can lead to higher optimal PV and BES capacities and reduce the home energy cost. For a typical household with ICE and the load profile used in this study, the optimal capacities of PV and BES are around 4 kW and 4 kWh respectively. For a household with EV, the optimal PV and BES capacities increase to around 8 kW and 11 kWh respectively.
iii. Although uncontrolled EV charging may increase the peak household energy consumption from 1441 kWh/year to 3085 kWh/year, the BES can effectively reduce the peak energy demand as well as the peak power demand on the grid. For example, in *configuration 3*, with EV and no BES, the peak household energy demand is 2014 kWh/year, and the average peak power is 1.97 kW; however, in *configuration 4*, which also has a BES, these two values are reduced to 337 kWh/year and 0.53 kW, respectively.
iv. The results obtained are expected to be more reliable than those of existing studies, which haven't considered all relevant techno-economic parameters in a comprehensive model.

CRediT authorship contribution statement

Yan Wu: Conceptualization, Methodology, Investigation, Software, Data curation, Visualization, Writing – original draft, Writing – review & editing. **Syed Mahfuzul Aziz:** Supervision, Conceptualization, Methodology, Visualization, Project administration, Writing – review & editing. **Mohammed H. Haque:** Supervision, Conceptualization, Methodology, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors acknowledge the Australian Government for the Research Training Program (RTP) scholarship awarded to the first author. The authors also acknowledge the UniSA STEM for proving her the opportunity to undertake PhD.

References

[1] International Energy Agency. Global EV Outlook 2020. [Online]. Available: https://www.iea.org/reports/global-ev-outlook-2020 (accessed 05 Jan. 21).
[2] S. Hardman, A. Jenn, G. Tal, J. Axsen, G. Beard, N. Daina, E. Figenbaum, N. Jakobsson, P. Jochem, N. Kinnear, P. Plötz, J. Pontes, N. Refa, F. Sprei, T. Turrentine, B. Witkamp, A review of consumer preferences of and interactions with electric vehicle charging infrastructure, Transport. Res. Transport Environ. 62 (July 2018) 508–523.
[3] Electric Vehicle Council, State of Electric Vehicles, 2020 [Online]. Available: https://electricvehiclecouncil.com.au/reports/state-of-electric-vehicles-2020/. (Accessed 5 March 2021).
[4] U.S. Energy Information Administration. U.S. shipments of solar photovoltaic modules increase as prices continue to fall. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=44816 (accessed 24 Feb. 21).
[5] BloombergNEF. Battery Pack Prices Cited Below $100/kWh for the First Time in 2020, While Market Average Sits at $137/kWh. [Online]. Available: https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/(accessed 24 Feb. 21).
[6] E. Bilbao, P. Barrade, I. Etxeberria-Otadui, A. Rufer, S. Luri, I. Gil, Optimal energy management strategy of an improved elevator with energy storage capacity based on dynamic programming, IEEE Trans. Ind. Appl. 50 (2) (2014) 1233–1244. Mar.
[7] V. Sharma, M.H. Haque, S.M. Aziz, Energy cost minimization for net zero energy homes through optimal sizing of battery storage system, Renew. Energy 141 (2019) 278–286, https://doi.org/10.1016/j.renene.2019.03.144.
[8] B. Ke, T. Ku, Y. Ke, C. Chuang, H. Chen, Sizing the battery energy storage system on a university campus with prediction of load and photovoltaic generation, IEEE Trans. Ind. Appl. 52 (no. 2) (2016) 1136–1147. Mar.
[9] J. Li, Optimal sizing of grid-connected photovoltaic battery systems for residential houses in Australia, Renew. Energy 136 (2019) 1245–1254, https://doi.org/10.1016/j.renene.2018.09.099.
[10] M. Mehrtash, F. Capitanescu, P.K. Heiselberg, T. Gibon, A. Bertrand, An enhanced optimal PV and battery sizing model for zero energy buildings considering environmental impacts, IEEE Trans. Ind. Appl. 56 (6) (2020) 6846–6856. Nov.
[11] O. Talent, H. Du, Optimal sizing and energy scheduling of photovoltaic-battery systems under different tariff structures, Renew. Energy 129 (2018) 513–526, https://doi.org/10.1016/j.renene.2018.06.016.
[12] Z. Ren, G. Grozev, A. Higgins, Modelling impact of PV battery systems on energy consumption and bill savings of Australian houses under alternative tariff structures, Renew. Energy 89 (2016) 317–330, https://doi.org/10.1016/j.renene.2015.12.021.
[13] R. Khezri, A. Mahmoudi, M.H. Haque, Optimal capacity of solar PV and battery storage for Australian grid-connected households, IEEE Trans. Ind. Appl. 56 (5) (2020) 5319–5329. Sept.
[14] S. Bandyopadhyay, G.R.C. Mouli, Z. Qin, L.R. Elizondo, P. Bauer, Techno-economical model based optimal sizing of PV-battery systems for microgrids, IEEE Trans. Sustain. Energy 11 (3) (July 2020) 1657–1668.
[15] G.O. Gil, J.I. Chowdhury, N. Balta-Ozkan, Y. Hu, L. Varga, P. Hart, Optimising renewable energy integration in new housing developments with low carbon technologies, Renew. Energy 169 (2021) 527–540, https://doi.org/10.1016/j.renene.2021.01.059.
[16] B. Naghibi, M.A.S. Masoum, S. Deilami, Effects of V2H integration on optimal sizing of renewable resources in smart home based on Monte Carlo simulations, IEEE Power Energy Technol. Syst. J. 5 (3) (2018) 73–84. Sept.
[17] Consumer Reports, Electric Vehicle Ownership Costs: Today's Electric Vehicles Offer Big Saving for Consumers, 2020 [Online]. Available: https://advocacy.consumerreports.org/wp-content/uploads/2020/10/EV-Ownership-Cost-Final-Report-1.pdf. Feb. 2022.
[18] F.C. Knopf, Modeling, Analysis and Optimization of Process and Energy Systems, 2011.
[19] W. Al-Saedi, S.W. Lachowicz, D. Habibi, O. Bass, Power flow control in grid-connected microgrid operation using Particle Swarm Optimization under variable load conditions, Int. J. Electr. Power Energy Syst. 49 (2013) 76–85, https://doi.org/10.1016/j.ijepes.2012.12.017.
[20] Y. Zhang, A. Lundblad, P.E. Campana, F. Benavente, J. Yan, Battery sizing and rule-based operation of grid-connected photovoltaic-battery system: a case study in Sweden, Energy Convers. Manag. 133 (2017) 249–263.
[21] R. Khezri, A. Mahmoudi, H. Aki, Multiobjective long-period optimal planning model for a grid-connected renewable-battery system, IEEE Trans. Ind. Appl. 58 (4) (July-Aug. 2022) 5055–5067, https://doi.org/10.1109/TIA.2022.3167010.
[22] S. Teleke, M.E. Baran, S. Bhattacharya, A.Q. Huang, Rule-based control of battery energy storage for dispatching intermittent renewable sources, IEEE Trans. Sustain. Energy 1 (3) (Oct. 2010) 117–124, https://doi.org/10.1109/TSTE.2010.2061880.
[23] N. Narayan, T. Papakosta, V. Vega-Garita, Z. Qin, J. Popovic-Gerber, P. Bauer, M. Zeman, Estimating battery lifetimes in Solar Home System design using a practical modelling methodology, Appl. Energy 228 (2018) 1629–1639, https://doi.org/10.1016/j.apenergy.2018.06.152.
[24] D. Wang, J. Coignard, T. Zeng, C. Zhang, S. Saxena, Quantifying electric vehicle battery degradation from driving vs. vehicle-to-grid services, J. Power Sources 332 (2016) 193–203, https://doi.org/10.1016/j.jpowsour.2016.09.116.
[25] Tesla, Tesla Powerwall Warranty (Australia and New Zealand), 2017 [Online]. [cited 2022 7 July]; Available: https://www.tesla.com/sites/default/files/pdfs/powerwall/Powerwall_2_AC_Warranty_AUS-NZ_1-0.pdf. (Accessed 7 July 2020).
[26] Electric Vehicle Database. Nissan Leaf. Available: https://ev-database.org/car/1106/Nissan-Leaf (accessed 15 Mar 2021).

[27] K. Qian, C. Zhou, M. Allan, Y. Yuan, Modeling of load demand due to EV battery charging in distribution systems, IEEE Trans. Power Syst. 26 (2) (May 2011) 802–810.
[28] T. Kang, B. Chae, Y. Suh, Control Algorithm of Bi-directional Power Flow Rapid Charging System for Electric Vehicle Using Li-Ion Polymer Battery, 2013, IEEE ECCE Asia Downunder, 2013, pp. 499–505.
[29] Battery University, Find out how to prolong battery life by using correct charge methods. [Online]. Available: https://batteryuniversity.com/learn/article/charging_lithium_ion_batteries (accessed 14 Apr 2020).
[30] H. Vu, W. Choi, A novel dual full-bridge LLC resonant converter for CC and CV charges of batteries for Electric Vehicles, IEEE Trans. Ind. Electron. 65 (3) (2018) 2212–2225. Mar.
[31] Solar Quotes. Home solar power in South Australia. [Online]. Available: https://www.solarquotes.com.au/australia/solar-power-sa/(accessed 07 Jun 2021).
[32] Government of South Australia. South Australian Home Battery Scheme. [Online]. Available: https://www.homebatteryscheme.sa.gov.au/about-the-scheme (accessed 18 Jan. 2022).
[33] Solar Quotes. Flexible solar exports to ramp up in South Australia. [Online]. Available: https://www.solarquotes.com.au/blog/sa-flexible-solar-exports-mb2141/(accessed 17 Feb. 2022).
[34] J. Sears, D. Roberts and K. Glitman, A Comparison of Electric Vehicle Level 1 and Level 2 Charging Efficiency, 2014 IEEE Conference on Technologies for Sustainability, 255-258.
[35] Solar Choice. Solar panels cost data: solar choice price index Jan 2022. [Online]. Available: https://www.solarchoice.net.au/blog/solar-power-system-prices/(accessed 18 Jan. 2022).
[36] PV Magazine. PV plants lasting longer, with lower operational cost. [Online]. Available: https://www.pv-magazine.com/2020/06/03/pv-plants-lasting-longer-with-lower-operational-costs/(accessed 26 May 2021).
[37] H. Masrur, K.V. Konneh, M. Ahmadi, K.R. Khan, M.L. Othman, T. Senjyu, Assessing the techno-economic impact of derating factors on optimally tilted grid-tied photovoltaic systems, Energies 14 (4) (2021) 1044.
[38] Solar Choice. Solar battery price index February 2021. [Online]. Available: https://www.solarchoice.net.au/blog/battery-storage-price (accessed 15 Mar. 2021).
[39] Plugs, Socket-Outlets, Vehicle Connectors and Vehicle Inlets - Conductive Charging of Electric Vehicles, Part 2: Dimensional Compatibility and Interchangeability Requirements for a.C. Pin and Contact-Tube Accessories, vol. 2, 2014. AS IEC 62196.
[40] Australian Energy Market Operator. 2019 Electricity Statement of Opportunities. [Online]. Available: https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/NEM_ESOO/2019/2019-Electricity-Statement-of-Opportunities.pdf (accessed 08 Apr. 2020) .
[41] Renewable Ninja. Solar generation profile. [Online]. Available: https://www.renewables.ninja/(accessed 13 Apr. 2020).
[42] Victoria State Government, Department of Transport. Data and publications of Victorian Integrated Survey of Travel and Activity. [Online]. Available: https://transport.vic.gov.au/about/data-and-research/vista/vista-data-and-publications (accessed 04 May 2021).
[43] S.A. Power Networks, Tariff Structure Statement Part A. [Online] Available: https://www.sapowernetworks.com.au/public/download.jsp?id=9508, 2020-25. (Accessed 19 May 2021).
[44] IO Energy, IO Energy retail price. [Online]. Available: https://www.ioenergy.com.au/?gclid=Cj0KCQjwrsGCBhD1ARIsALILBYptrd7q4w0Gg4kKc5i_D-rKSR8U-NnIs4Pzt8pYrhWO6Ik2Zr19gjQaAnLBEALw_wcB. (Accessed 17 March 2021).