Highlights

Counteracting the duck curve: Prosumage with time-varying import and export electricity tariffs

Lisa Restel,Kelvin Say

- MILP modelling of Time-of-Use (ToU) and -Export (ToE) tariffs on PV-BESS households.
- ToU are less effective than ToE tariffs and may be regressive for low-income groups.
- ToE tariffs reduce midday feed-in and lower system peak demand via BESS discharge.
- ToE tariffs counteract the duck curve (flatten ramp rates, reduce peak system demand).

Counteracting the duck curve: Prosumage with time-varying import and export electricity tariffs

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ABSTRACT

Australia is a frontrunner in household solar photovoltaic (PV) adoption, which has helped to accelerate the energy transition but has changed demand such that the power system faces operational challenges, known as the solar 'duck curve'. The growing adoption of household batteries will change demand once again and policymakers have the means to reshape this demand through time-varying tariffs. This study evaluates the impact of time-varying import and export tariffs on household load profiles using data from 400 Melbourne households, each equipped with a 9 kW_P PV and 12 kWh battery, and a dispatch optimisation model.

Our findings indicate that time-varying export tariffs have significantly more influence on residual load profiles compared to time-varying import tariffs. With time-varying import tariffs only, households still maintain grid feed-in during the day and rely on self-consumption in the evening, exacerbating midday feed-in but preventing peak demand growth. We find that time-varying export tariffs alone reduce midday feed-in by 55.6% and extend exports past sunset. This actively counteracts the 'duck curve' by reducing midday feed-in, reducing ramp rates, and decreasing peak evening operational demand. This suggests that time-varying export tariffs may be a useful policy lever to enhance grid stability and renewable energy integration.

1. Introduction

Making the most of renewable energy generation in the electricity system is essential to decarbonise the broader energy system. In Australia, 3.7 million or approximately one in three residential dwellings have installed a rooftop solar photovoltaic (PV) system (Egan and Koschier, 2022; APVI, 2023). The rising level of rooftop PV penetration from the residential sector has increased daytime grid feed-in to the level that the utility-scale power system is experiencing its own solar 'duck curve'[1] (AEMO, 2018, 2019; Wilkinson et al., 2021). New records for minimum operational demand[2], now occurring during midday, are being established each year (AEMO, 2023). As peak operational demand continues to remain high during the evenings, this trend is leading to increasing concerns over system security. Given limited control over operational demand, the growth of residential PV presents new challenges for power system operators and planners. Policymakers are therefore developing new levers to moderate the interaction of consumer-scale distributed energy resources with the wider electricity system using *technical* methods, such as dynamically controlling grid feed-in levels per household (DEIP, 2022), and *economic* incentives, such as introducing time-varying tariff structures that incorporate midday off-peak consumption pricing (SA Power Networks, 2020) and time-of-export tariffs that disincentivise midday grid feed-in (ESC, 2023a,b; SA Power Networks, 2020; State Government of Western Australia, 2020, 2024) [3]. For these *economic* incentives to be effective, electricity customers need to respond by changing their

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[1] As characterised by falling operational demand and wholesale prices around midday, and high operational demand and wholesale prices in the evening (Denholm et al., 2015).

[2] Operational demand is defined as the electricity system demand that utility-scale generators have to match and where customer grid exports are considered as negative demand.

[3] These are time-varying volumetric tariffs, and demand charges are not widely adopted for residential consumers.

consumption patterns. Given that rooftop PV systems are increasingly expected to be complemented with battery energy storage systems (BESS) (AEMO, 2024; Neetzow et al., 2018) , these PV-BESS households (as opposed to PV-only households) can use their batteries to modify grid consumption patterns without requiring changes to occupant behaviour, which makes PV-BESS households more likely to respond to *economic* incentives for the following reasons:

First, rooftop PV-only households can only *pro*-duce and *con*-sume electricity (i.e. *prosumers*). Given that these PV-only households cannot store their PV self-generation, any excess electricity (beyond underlying consumption) is exported to the grid during the day. Once PV self-generation falls below underlying consumption, these households import the remaining electricity from the grid. As a consequence, *prosumers* that face time-varying import (ESC, 2023a) and export tariffs (ESC, 2023b) without making behavioural changes to their consumption patterns (Burns and Mountain, 2021) are likely to receive less revenue from daytime grid exports while simultaneously being exposed to higher electricity costs in the evening.

Second, households that have installed a PV and BESS are capable of *prosumage* (Schill et al., 2017; Green and Staffell, 2017; Say and John, 2021; Günther et al., 2021; Klein et al., 2019) by being able to *pro*-duce, con-*sume*, and utilise their own energy stor-*age*. This allows PV-BESS households to use their BESS to change when they import and export electricity without relying on behaviour changes. This enables *prosumage* customers facing time-varying import and export tariffs to use their BESS to more readily minimise their exposure to high import tariffs and shift grid exports to times of higher financial return.

Given the challenges of operating a power system under an increasing solar 'duck curve', policymakers are presented with an opportunity to design and introduce time-varying tariffs that financially encourage *prosumage* customers (i.e. those with a PV-BESS installed) to counteract its negative impacts. To assess the effectiveness, a detailed assessment is needed of how time-varying tariffs may induce changes in the way *prosumage* households interact with the grid.

This research evaluates the effectiveness of time-varying import and export tariffs to *economically* incentivise PV-BESS households to: (i) reduce their level of grid feed-in across midday; and (ii) encourage grid feed-in during the evening. We use 400 real household load profiles from Melbourne, Australia, and assume that each household has a $9\,\mathrm{kW_P}$ PV system and a $12\,\mathrm{kWh}\,/\,5\,\mathrm{kW}$ BESS installed. We also develop an open-source PV-BESS dispatch optimisation model, called *Electroscape*, to determine the financially optimal residual load profile for each household. By evaluating this load profile across every household and under different tariff scenarios, we use a counterfactual analysis to establish the effect of time-varying tariff structures and prices on (i) and (ii). We find that time-varying **export** tariffs are much more effective than time-varying import tariffs to counteract the problems associated with the solar 'duck curve'. This has implications for PV-BESS households, system and market operators, and decision and policy makers within electricity systems facing high and growing solar PV penetration.

The paper is structured as follows: Section 2 provides an overview of the current literature. In Section 3, we describe the methodology, the optimization model *Electroscape*, and the data used in our analysis. Section 4 presents the results of our optimization and evaluates the effectiveness of time-varying tariffs. In Section 5, we discuss the implications of different tariff structures on the solar 'duck curve' for PV-BESS households and both grid and system operators, perform a sensitivity analysis, and offer suggestions for future research. Finally, Section 6 concludes with policy implications and discusses the limitations and caveats of our study.

2. Literature review

There is a wide and growing literature evaluating the influence of consumer-scale distributed energy resources on power system operation and planning. Young et al. (2019) analyse the impact of various PV and/or BESS adoption scenarios facing flat, time-of-use (i.e. time-varying), or demand charge tariffs on electricity networks. They utilise a heuristic BESS logic model across 2,000 household profiles to establish the overall residual load profile. They find that flat tariffs generally deliver a smoother overall profile while time-of-use and demand tariffs may cause sudden fluctuations in grid demand at the start and end of peak price periods. However, they find that these time-varying import tariffs may also reduce peak evening demand. Shaw-Williams et al. (2018) assess the overall profitability of residential PV-only or PV-BESS systems for households and the network operator. By simulating 700 households subject to time-of-use tariffs in Australia, their research finds that PV-only systems (at the time of analysis) are the most profitable choice for households. However, after accounting for savings arising from deferred network augmentation, PV-BESS systems emerge as the more advantageous option. A study by Say et al. (2020) evaluates the impact of a growing PV-BESS household sector and its changes to operational demand on the least-cost utility generation and storage technology mix in West Australia's South-West Interconnected System. They find that rooftop PV largely displaces utility PV capacity, while wind power is much less affected. Furthermore, residential BESS under flat tariffs do not substitute installed utility BESS capacity, suggesting a lack of incentive to operate in a more system-friendly manner. Burns and Mountain (2021) analyse almost 7,000 electricity bills from PV-only and non-PV households across Victoria, Australia to determine if time-of-use tariffs influence consumption patterns. They find that the variation in prices between peak and off-peak periods has minimal impact, which aligns with the broader literature (e.g., Western Power Distribution and Regen SW, 2017; Green Alliance, 2017; Lanot and Vesterberg, 2021; Csereklyei, 2020) that shows electricity demand (in the short-run) is generally inelastic to electricity prices. In addition to operational or behavioural implications, concerns about fairness and social equity in electricity pricing and access are becoming increasingly prominent. The literature highlights that different tariff structures, such as time-of-use and demand charges, can disproportionately affect low-income households with limited flexibility in their consumption patterns. This growing body of literature underscores the need for equitable tariff designs and policies that consider socio-economic disparities (e.g., Han et al., 2024; Calver and Simcock, 2021; Covington et al., 2024; Muttaqee et al., 2024).

Studies on PV-BESS households predominantly utilise different import pricing structures (i.e. flat, time-of-use, and demand charges) while export (i.e feed-in tariff) prices remain flat. Time-varying export tariffs are a recent development and, to the best of the authors' knowledge, have received much less attention in the literature. However, notable examples include Pimm et al. (2018) that optimise household cost savings under time-varying import and export tariffs in the UK. They synthesise 100 demand profiles and optimise system operation in the presence of a 3 kW_P PV and 3 kWh BESS, or only a 3 kWh BESS. The study examines the effects of a three-tier import and a two-tier export tariff, which lowers the value of electricity exports between 10 am and 4 pm, while prohibiting BESS grid discharging. They find that their time-varying tariffs have little impact on reducing import and export peaks, while potentially causing a new overnight import peak from synchronised BESS grid charging at the start of the off-peak import price period. Xincheng Pan (2022) investigate the effects of time-varying and flat import and export tariffs in South Australia on the optimal PV and BESS size for a single household. They utilise a heuristic BESS logic model (without grid charging/discharging) and three-tier time-varying tariffs with their lowest prices during the night and highest prices during the evening. They determine that the optimal system size was a 10 kW_P PV and 6 kWh BESS under a time-varying import and flat export tariff. The least profitable tariff configuration for the household was the flat import and time-varying export tariff.

Despite individual attention given to time-varying import and export tariffs in the existing literature, few studies have comprehensively examined both aspects, along with their operational and policy implications. This study contributes to the literature by examining the selective effect of time-varying import and export tariffs on household PV-BESS operation (and allowing BESS grid charging and discharging). Furthermore, we use time-varying tariffs that incorporate 'solar sponge' pricing (SA Power Networks, 2020) with midday off-peak prices for both import and export tariffs. Using 400 real household consumption load profiles and assigning a 9 kW_P PV and 12 kWh / 5 kW BESS, we seek to provide insight into how time-varying tariff structures influence the way that PV-BESS households (in aggregate) interact with the grid, their effectiveness to counteract the 'solar duck curve', and the policy implications for retail tariff reform.

3. Methodology and data

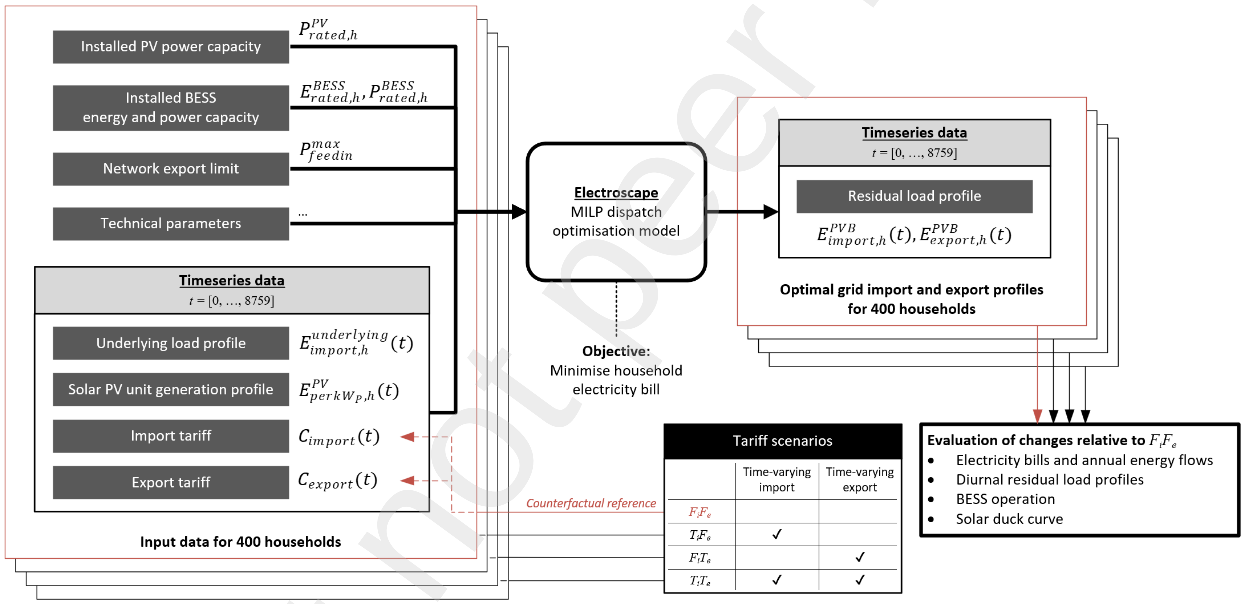

Figure 1: Research setup and overview with *Electroscape* and four retail tariff scenarios.

This research (Fig. 1) develops a mixed-integer linear programming (MILP) dispatch optimisation model, called *Electroscape*, to establish the effectiveness of time-varying import and export tariffs on a PV-BESS household to: (i) reduce the level of grid feed-in across midday; and (ii) encourage grid feed-in during the evening. The dispatch optimisation model assumes perfect foresight and is used to determine the techno-economic optimal charging and discharging behaviour of the PV-BESS (i.e. residual load profile) with an objective to minimise the household's electricity bill. The optimal dispatch is the time-series solution to a MILP problem that is constrained by the technical limitations of the PV-BESS (e.g. calendric aging, cyclic aging, inverter losses), network export limit, and conservation of energy. Real underlying load profiles for 400 households in Melbourne, Australia, are used in the analysis to represent the electricity consumption of the household sector. Reflecting current Australian installation capacities, we assign each household with a 9 kW_P rooftop PV and 12 kWh / 5 kW BESS. We evaluate four tariff scenarios representing

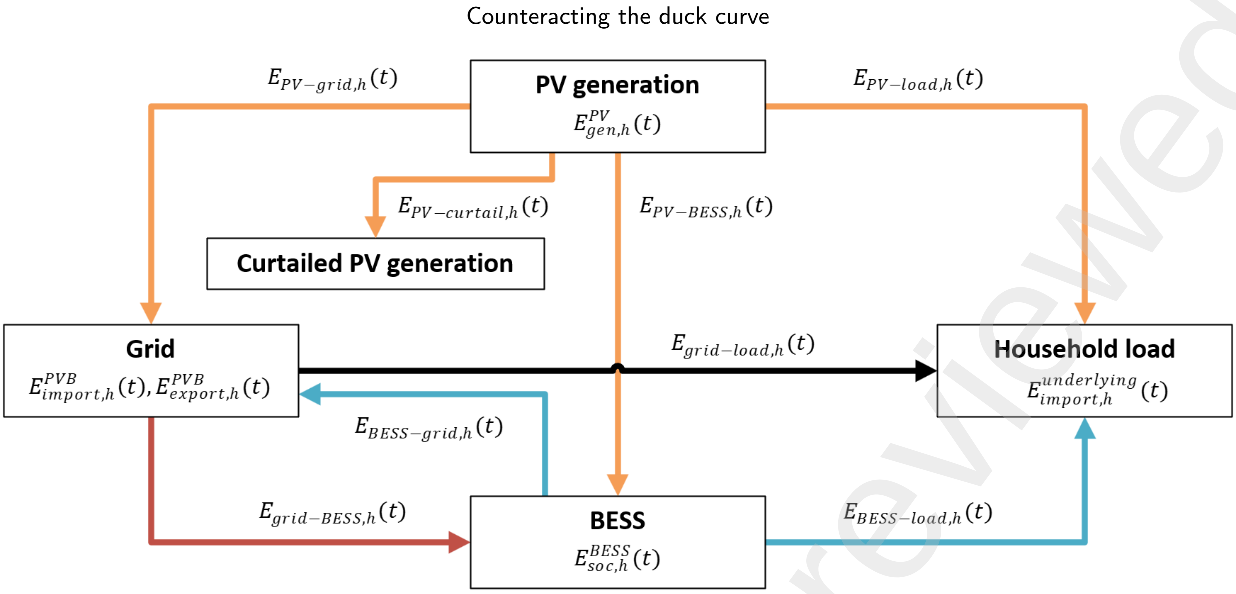

Figure 2: Flow of energy between the underlying household load, PV-BESS, and grid for household h.

each time-varying and flat tariff combination, namely flat import and flat export (F_iF_e), time-varying import and flat export (T_iF_e), flat import and time-varying export (F_iT_e), and time-varying import and time-varying export (T_iT_e). By comparing how optimal residual load profiles change in response to the tariff scenario, relative to the counterfactual time-invariant reference scenario (F_iF_e), we establish the extent to which time-varying import and/or export tariffs may reduce the level of grid feed-in across midday, encourage grid feed-in during the evening, and the overall implications of using time-varying import and export tariffs for system operation and policymakers.

3.1. Household-scale PV-BESS dispatch optimisation (Electroscape)

A mixed-integer linear programming (MILP) model is used to solve the techno-economic dispatch optimisation problem for a single household h and is adapted from Sani Hassan et al. (2017) and Hesse et al. (2017). This MILP model is written in Python and called *Electroscape*. The code is provided open source in the Supplementary Data under a permissive MIT License. Gurobi[4] is used as the optimisation solver. The MILP formulation (Fig. 2) is bound by the energy generated from the PV system $E^{PV}_{gen,h}(t)$, underlying household load $E^{underlying}_{import,h}(t)$, energy storage available in the BESS $E^{BESS}_{soc,h}(t)$, energy imported from the grid $E^{PVB}_{import,h}(t)$, and energy exported to the grid $E^{underlying}_{export,h}(t)$. In addition, it assumes direct current power-flow and an ideal electrical network.

3.1.1. Objective function

Electroscape determines the optimal flow of energy and battery operation across all time-steps t by minimising the electricity bill of the household $C_{bill,h}$:

$$\min(C_{bill,h}) \tag{1}$$

where,

$$C_{bill,h} = \sum_{t} [C_{import}(t) \cdot E^{PVB}_{import,h}(t) - C_{export}(t) \cdot E^{PVB}_{export,h}(t)] \tag{2}$$

[4]https://www.gurobi.com/

which applies the appropriate import tariff $C_{import}(t)$ and export tariff $C_{export}(t)$ in the tariff scenario to the respective grid energy flow.

3.1.2. Constraints

The following constraints define the PV-BESS operation for each household h and apply across all time-steps t. The amount of energy generated by the PV system $E^{PV}_{gen,h}(t)$ is derived from the output per $\mathrm{kW_P}$ of the household's solar resource $E^{PV}_{perkW_P,h}(t)$ scaled by its rated capacity $P^{PV}_{rated,h}$ while incorporating a linear reduction in output (i.e. state-of-health) based on its expected end-of-life capacity $SOH^{PV}_{cal}(t)$.

$$E^{PV}_{gen,h}(t) = E^{PV}_{perkW_P,h}(t) \cdot P^{PV}_{rated,h} \cdot SOH^{PV}_{cal}(t) \tag{3}$$

All PV generation $E^{PV}_{gen,h}(t)$ has to balance with its potential loads, namely, PV self-consumption $E_{PV-load,h}(t)$, BESS charging $E_{PV-BESS,h}(t)$, grid exports $E_{PV-grid,h}(t)$, and grid curtailment $E_{PV-curtail,h}(t)$.

$$E^{PV}_{gen,h}(t) = E_{PV-load,h}(t) + E_{PV-BESS,h}(t) + E_{PV-grid,h}(t) + E_{PV-curtail,h}(t) \tag{4}$$

with a further constraint to ensure that PV generation must first be consumed by the household load.

$$E_{PV-load,h}(t) = \min(E^{PV}_{gen,h}(t),\ E^{underlying}_{import,h}(t)) \tag{5}$$

The household load $E^{underlying}_{import,h}(t)$ has to balance with its potential sources of electricity, namely, PV self-consumption $E_{PV-load,h}(t)$, BESS discharge $E_{BESS-load,h}(t)$, and the grid $E_{Grid-load,h}(t)$.

$$E^{underlying}_{import,h}(t) = E_{PV-load,h}(t) + E_{BESS-load,h}(t) + E_{grid-load,h}(t) \tag{6}$$

The following constraint ensures that the network export (i.e. feed-in) limit P^{max}_{feedin} is maintained at all times:

$$E_{PV-grid,h}(t) + E_{BESS-grid,h}(t) \leq P^{max}_{feedin} \cdot \triangle t \tag{7}$$

To ensure that the household cannot not simultaneously import and export electricity from the grid, the following constraints are applied using Boolean variable $B_{sell-buy,h}(t)$ and large number M.

$$M \cdot (1 - B_{sell-buy,h}(t)) \geq E_{PV-grid,h}(t) + E_{BESS-grid,h}(t) \tag{8}$$

$$M \cdot B_{sell-buy,h}(t) \geq E_{grid-load,h}(t) + E_{grid-BESS,h}(t) \tag{9}$$

The BESS operation is described using the following constraints, which also assumes 100 % depth of discharge.[5] The state-of-charge in time-step t is in energy units $E^{BESS}_{soc,h}(t)$ and incremented using:

$$\begin{aligned} E^{BESS}_{soc,h}(t) = E^{BESS}_{soc,h}&(t-1) \\ &+ \eta_c \cdot [E_{PV-BESS,h}(t) + E_{grid-BESS,h}(t)] \\ &- \frac{1}{\eta_d} \cdot [E_{BESS-load,h}(t) + E_{BESS-grid,h}(t)] \end{aligned} \tag{10}$$

with a charging efficiency of η_c and discharging efficiency of η_d. The charging and discharging energy flows must also remain within the rated power capacity of the BESS $P^{BESS}_{rated,h}$, such that:

$$B^{BESS}_{c,h}(t) \cdot P^{BESS}_{rated,h} \cdot \triangle t \geq \eta_c \cdot [E_{PV-BESS,h}(t) + E_{grid-BESS,h}(t)] \tag{11}$$

$$B^{BESS}_{d,h}(t) \cdot P^{BESS}_{rated,h} \cdot \triangle t \geq \frac{1}{\eta_d} \cdot [E_{BESS-load,h}(t) + E_{BESS-grid,h}(t)] \tag{12}$$

where the Boolean charge $B^{BESS}_{c,h}(t)$ and discharge $B^{BESS}_{d,h}(t)$ states are further constrained by (13) to ensure that the BESS cannot be in both states at the same time.

$$B^{BESS}_{c,h}(t) + B^{BESS}_{d,h}(t) \leq 1.001 \tag{13}$$

Cyclic and calendric ageing of the BESS storage capacity is factored into its operation as an energy state-of-health term $E_{soh,h}(t)$ such that:

$$E^{BESS}_{soc,h}(t) \leq E^{BESS}_{soh,h}(t) \tag{14}$$

where the state-of-health decreases in each time-step based on a constant calendric reduction term $X^{BESS}_{cal-aging}$ and time-series cyclic reduction term $X^{BESS}_{cyc-aging,h}(t)$ which are both relative to the end-of-life storage capacity percentage $X^{BESS}_{eol-capacity}$.

$$E_{soh,h}(t) = E_{soh,h}(t-1) - (1 - X^{BESS}_{eol-capacity}) \cdot [X^{BESS}_{cal-aging} + X^{BESS}_{cyc-aging,h}(t)] \tag{15}$$

The calendric reduction term is a constant value derived from the time-step $\triangle t$ relative to the overall end-of-life time span T^{BESS}_{eol} and scaled to its rated capacity.

$$X^{BESS}_{cal-aging} = \frac{\triangle t}{T^{BESS}_{eol}} \cdot E^{BESS}_{rated,h} \tag{16}$$

[5] e.g. Tesla Powerwall 2

The cyclic reduction term represents the cycles consumed in this time step relative to its end-of-life number of cycles $X^{BESS}_{eol-cycles}$ and scaled to its rated capacity.

$$X^{BESS}_{cyc-aging,h}(t) = \frac{1}{2} \cdot \frac{P^{BESS}_{abs-cd,h}(t) \cdot \triangle t}{X^{BESS}_{eol-cycles}} \tag{17}$$

where:

$$\begin{aligned} P^{BESS}_{abs-cd,h}(t) = B^{BESS}_{c,h}(t) \cdot \eta_c \cdot [E_{PV-BESS,h}(t) + E_{grid-BESS,h}(t)] \\ + B^{BESS}_{d,h}(t) \cdot \frac{1}{\eta_d} \cdot [E_{BESS-load,h}(t) + E_{BESS-grid,h}(t)] \end{aligned} \tag{18}$$

3.1.3. Outputs

In addition to the constraints, the following equations define for each household the level of self-consumption X^{SC}_h taking into account battery grid discharging:

$$X^{SC}_h = \frac{\sum_t [E^{PV}_{gen,h}(t) - E_{PV-grid,h}(t) - 1/\eta_c \cdot 1/\eta_d \cdot E_{BESS-grid,h}(t)]}{\sum_t E^{PV}_{gen,h}(t)} \tag{19}$$

the level of self-sufficiency X^{SS}_h taking into account battery grid charging:

$$X^{SS}_h = 1 - \frac{\sum_t [E_{grid-load,h}(t) + \eta_c \cdot \eta_d \cdot E_{grid-BESS,h}(t)]}{\sum_t E^{underlying}_{import,h}(t)} \tag{20}$$

the total amount of grid exports over the year $E^{total}_{exports,h}$:

$$E^{total}_{exports,h} = \sum_t [E_{PV-grid,h}(t) + E_{BESS-grid,h}(t)] \tag{21}$$

the total amount of grid imports over the year $E^{total}_{imports,h}$:

$$E^{total}_{imports,h} = \sum_t [E_{grid-load,h}(t) + E_{grid-BESS,h}(t)] \tag{22}$$

the total amount of battery charging from the grid over the year $E^{total}_{grid-BESS,h}$:

$$E^{total}_{grid-BESS,h} = \sum_t E_{grid-BESS,h}(t) \tag{23}$$

and the total amount of battery energy discharged into the grid over the year $E^{total}_{BESS-grid,h}$:

$$E^{total}_{BESS-grid,h} = \sum_t E_{BESS-grid,h}(t) \tag{24}$$

The residual load profile of each household represents the optimal import and export load profile:

$$E^{PVB}_{residual,h}(t) = E^{PVB}_{import,h}(t) - E^{PVB}_{export,h}(t) \tag{25}$$

3.2. Case study: Melbourne, Australia

To represent the household sector, 400 individual detached and semi-detached household load profiles (obtained from utility power meters) in the Jemena Electricity Network region[6] were procured from the Centre for New Energy Technologies (C4NET). The customer load data covers one year (1 April 2019 to 31 March 2020) with an hourly resolution. Due to strict data privacy laws, households remain anonymous, which precludes the disclosure of additional contextual information (e.g. number of occupants, household income, types of appliances). Across the dataset, the average household electricity consumption is 3,937 kWh. With a temperate oceanic climate in Melbourne, the average hourly seasonal load profile across all households (Fig. 3) shows an increase in heating load during winter; consistently small early morning peak and large evening peak in autumn, winter, and spring; and, minimum demand typically occurring in the hours preceding dawn. The average profile is provided in the Supplementary Data.

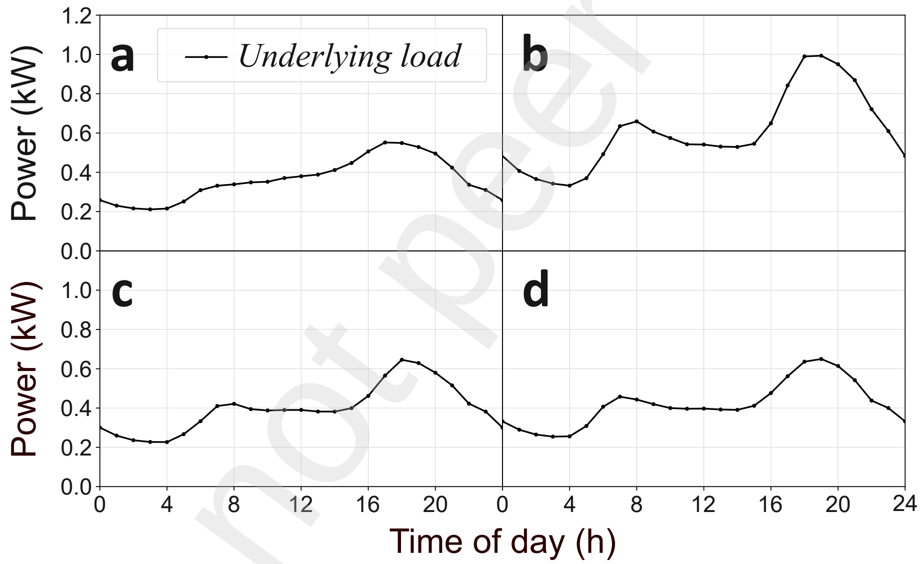

Figure 3: Average hourly seasonal underlying load profile across all households (N = 400). (a) Summer. (b) Winter. (c). Autumn. (d) Spring. Data source: C4NET (2020)

The hourly solar PV generation profile per kW_P was obtained from the National Renewable Energy Laboratory (NREL, 2021) and represents a north-facing rooftop PV system with a 22-degree slope (i.e. typical roof pitch). The resulting solar PV generation data for Melbourne, Australia has a capacity factor of 15.8 %. A 5 kW network export limit is assumed (Powercor et al., 2022). Corresponding to average installed PV and BESS sizes in Australia (AEC, 2023; Johnston, 2023), we assign each household with a 9 kW_P PV system and 12 kWh / 5 kW BESS. For the BESS, we assume an inverter efficiency of 94 %; end-of-life capacity of 70 % in 10 years or 10,000 cycles; and the option to grid charge and discharge. For the PV system, we assume a linear degradation in generation with 80 % output remaining in 25 years. Additional details are provided in Table A.1 and Table A.2.

[6]https://www.jemena.com.au/electricity/jemena-electricity-network/

The retail tariffs correspond to the 'Victorian Default Offer' (ESC, 2023a) and 'Minimum Feed-in Tariff' (ESC, 2023b), as determined by the Victorian Essential Services Commission between 1 July 2023 and 30 June 2024, with prices and structure shown in Table 1 and Figures 4 and 5 respectively. The reference scenario is F_iF_e, which corresponds to the predominant tariff regime in Australia. By counterfactually evaluating the results of the remaining three tariffs (T_iF_e, F_iT_e, T_iT_e) against the reference F_iF_e tariff scenario, we approximate different introduction pathways for time-varying tariffs, and the potential impact each may have on reshaping the residual load profile (i.e. operation demand) of PV-BESS households to counteract the worst effects of the solar duck curve. In addition, a sensitivity analysis is performed with tariff prices increased or decreased by 30 % to examine the influence of electricity price levels on the average residual load profile.

Table 1: Pricing of retail flat and time-varying import and export tariffs.

Tariff type	**Peak (AUD/kWh)**	**Off-peak (AUD/kWh)**	**Shoulder (AUD/kWh)**	**Source**
Flat import	0.331 *Always*	-	-	(ESC, 2023a)
Time-varying import	0.419 *3 pm to 9 pm*	0.269 *All other times*	-	(ESC, 2023a)
Flat export	0.052 *Always*	-	-	(ESC, 2023b)
Time-varying export	0.106 *4 pm to 9 pm*	0.039 *10 am to 2 pm*	0.055 *All other times*	(ESC, 2023b)

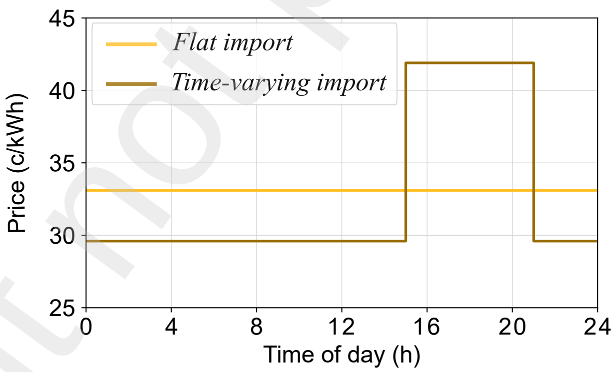

Figure 4: Structure of retail flat and time-varying import tariffs

Table 2: The four tariff scenarios evaluated.

Tariff type	F_iF_e	T_iF_e	F_iT_e	T_iT_e
Flat import	Yes	-	Yes	-
Time-varying import	-	Yes	-	Yes
Flat export	Yes	Yes	-	-
Time-varying export	-	-	Yes	Yes

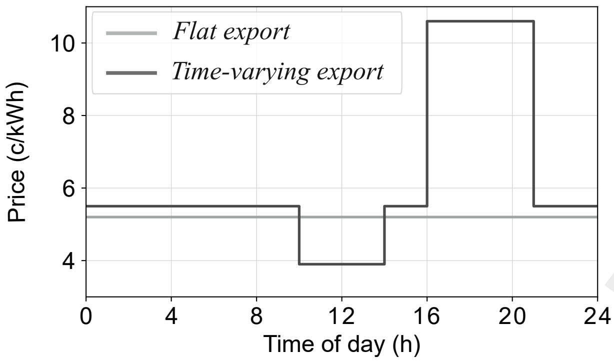

Figure 5: Structure of retail flat and time-varying export tariffs.

4. Results

The 400 PV-BESS household residual load profiles, as defined by equation (25), from each tariff scenario (Table 2) provide a range of results that we evaluate using the following perspectives (Fig. 1). First, we consider how the time-varying tariffs affect annual electricity bills and energy flows. Second, we consider the subsequent changes to the diurnal residual load profile in each season. Third, we consider their impact on BESS operation. Finally, we quantify the changes to the solar 'duck curve' as the amount of grid feed-in between 10 am and 2 pm (corresponding to low midday operational demand) and between 4 pm and 9 pm (corresponding to peak evening demand).

4.1. Changes to electricity bills and annual energy flows

At annual perspective, the residual load profile of each PV-BESS household results in an electricity bill, level of self-consumption and self-sufficiency, level of grid exports and grid imports, and level of BESS grid charging and discharging, which changes in response to each tariff scenario. Table 3 summarises the average techno-economic results across the 400 PV-BESS households.

Table 3: Average techno-economic results across 400 PV-BESS households for one year

	Unit	F_iF_e	T_iF_e	F_iT_e	T_iT_e
Electricity bill w/o PV-BESS	AUD	1,303	1,260	1,303	1,260
Electricity bill with PV-BESS	AUD	-257	-284	-397	-424
Bill savings from PV-BESS	AUD	1,560	1,544	1,700	1,684
Self-consumption	%	29.64	29.64	29.63	29.63
Self-sufficiency	%	86.99	86.99	86.97	86.97
Grid imports	kWh	512	516	513	517
Grid exports	kWh	8,713	8,713	8,455	8,455
BESS grid charging	kWh	0	34	0	34
BESS grid discharging	kWh	117	117	2,019	2,019

Without a PV-BESS, the electricity bills of households are on average 43 AUD lower under time-varying import tariffs (T_iF_e and T_iT_e). This indicates that the average household is not disadvantaged under the time-varying import tariffs of the 'Victorian Default Offer'. With a PV-BESS, the average annual electricity bill across all four tariff scenarios is negative (i.e. in credit). In addition, bill savings under the time-varying export tariffs (F_iT_e and T_iT_e) are on average 9 % higher (140 AUD) compared to the flat export tariffs. These electricity bill differences are not being driven by large changes in operational self-consumption or self-sufficiency, as these remain consistent across all four tariff scenarios at 28 % and 87 % respectively. As a result, annual grid imports per PV-BESS household are on average between 512 kWh and 517 kWh. Notably, annual grid exports are 16 to 17 times higher than annual imports, with the flat export tariff scenarios (F_iF_e and T_iF_e) exporting 8,713 kWh and the time-varying export tariff scenarios (F_iT_e and T_iT_e) exporting 2.9 % less at 8,455 kWh. This 2.9 % difference is the result of higher levels of grid exports from BESS grid discharging, which incurs additional round-trip efficiency losses. Finally, the flat import tariffs (F_iF_e and F_iT_e) do not lead to any BESS grid charging, whereas the time-varying import tariffs (T_iF_e and T_iT_e) do incentivise a relatively small amount of BESS grid charging (34 kWh) for energy arbitrage.

4.2. Changes to diurnal residual load profiles

The diurnal residual load profiles (Fig.6) represent the average hourly grid import (positive) and grid export (negative) energy flows across all 400 PV-BESS households. The four residual load profiles show the seasonal variability as driven by changes in solar PV generation and underlying demand. Between the four tariff scenarios there are two main types of optimal residual load profiles, the first consists of the flat export scenarios (F_iF_e and T_iF_e), and the second consists of the time-varying export scenarios (F_iT_e and T_iT_e). Only during the winter months, when solar PV generation is at its lowest, are the differences between time-varying and flat import tariffs evident (specifically in the evening).

The most common tariff structure F_iF_e is used as the baseline reference scenario. With flat import and export tariffs, PV-BESS households are not financially rewarded to change the timing of their electricity imports or exports. Given that there are costs associated with BESS utilisation (i.e. energy losses attributed to inverter efficiency and cyclic aging), the resulting optimal F_iF_e BESS operation is to charge with enough excess rooftop PV generation (i.e. solar generation that exceeds underlying demand) to cover the household's night-time electricity consumption. Additional PV generation is then exported to the grid, while also avoiding grid exports[7] above the 5 kW network export limit. As a result, PV-BESS households under the F_iF_e scenario consume little to no energy during the evening and overnight (Fig. 6 a,c,d) while still exporting a large amount of energy (Table 3) into the grid during midday in all seasons except winter. Peak feed-in generally occurs during noon (Fig. 6) and is on average 4.4 kW in summer and falls to 1.6 kW in winter. This suggests that PV-BESS households with flat tariffs continue to export significant energy during the day, but are capable of significantly reducing their evening and night-time energy consumption. In winter however, lower PV generation reduces the ability for PV-BESS households to be self-sufficient. As a result, their average grid imports during the evening and night are consistently above zero from 4 pm until 9 am the next morning (Fig. 6b).

The transition to time-varying import tariffs in the T_iF_e scenario does not significantly change the residual load profile of PV-BESS households (Fig. 6). It produces a similar profile to the F_iF_e scenario, with PV-BESS households continuing to export significant energy during the day (that peaks at noon), while significantly reducing their evening and night-time energy consumption (during non-winter months). However, there are differences in winter with PV-BESS households (on average) suppressing their grid imports (with their BESS) to just above zero until 9 pm due to

[7] As there is no additional value gained from exporting above this level.

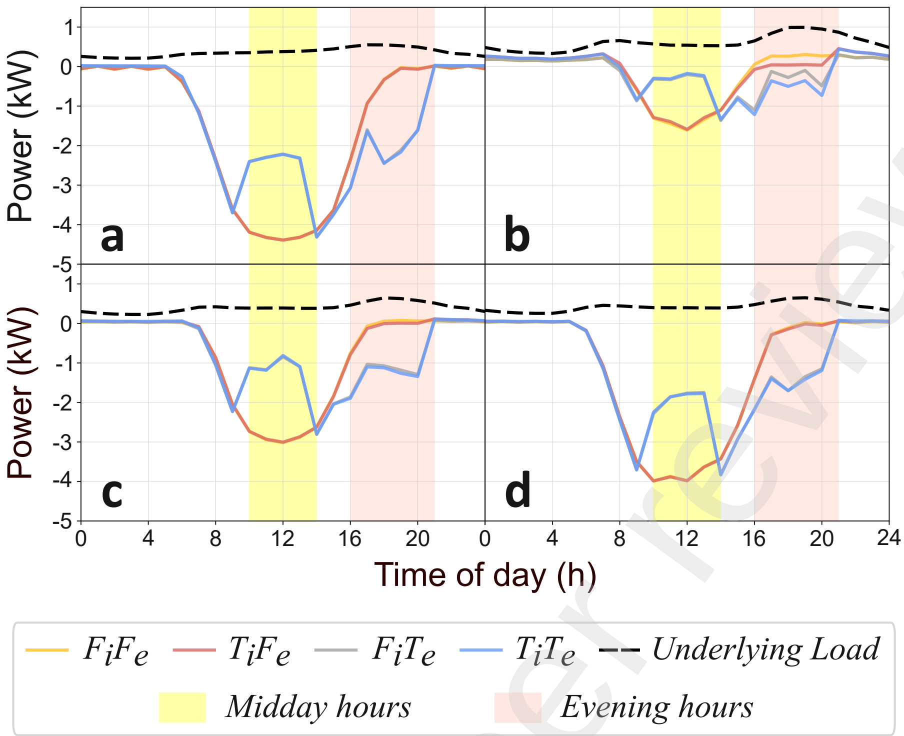

Figure 6: Average hourly underlying and residual load profiles across 400 PV-BESS households for each season and tariff scenario. (a) Summer. (b) Winter. (c) Autumn. (d) Spring.

peak import tariffs (between 3 pm and 9 pm). From 9 pm onwards the BESS' have been depleted and there is a distinct rise in grid imports above those the F_iF_e scenario until the next morning.

Comparing the F_iT_e to the reference F_iF_e scenario shows that introducing a time-varying export tariff (Fig. 5), significantly changes the residual load profile of PV-BESS households. There is a distinct reduction in grid exports between 10 am and 2 pm coinciding with off-peak feed-in tariffs. Furthermore, the 400 PV-BESS households (on average) continue to export energy to the grid throughout the evening until 9 pm which coincides with peak feed-in tariffs between 4 pm and 9 pm (Table 1). This outcome suggests that the time-varying export tariff incentivises PV-BESS households to (i) reduce their midday feed-in, and (ii) feed into the grid into the evening, which would actively reduce peak evening demand across the entire power system. This relies on the BESS' to have stored enough energy during the day to grid discharge beyond the households' underlying consumption until 9 pm. Outside of these findings, the average night-time consumption remains close to zero in all seasons except winter. In winter, there continues to remain a residual amount of night-time consumption from 9 pm onwards (Fig. 6b) that matches the F_iF_e scenario.

The use of time-varying import and export tariffs in the T_iT_e scenario, does not significantly change the residual load profile beyond the F_iT_e scenario. It still leads to a similar level of midday feed-in reduction from BESS charging, and generally the same level of evening feed-in in the summer, autumn, and spring (Fig. 6a,c,d) from BESS grid discharging. In winter, with the lower level of PV generation, the addition of peak import tariffs between 3 pm and 9 pm results in a higher level of grid feed-in until 9 pm. From 9 pm onwards, with the BESS' depleted, there is a rise in grid consumption (matching the T_iF_e scenario) until the next morning.

4.3. Changes to BESS operation

The differences in the average PV-BESS household residual load profile across each tariff scenario is reflected in how their BESS assets are utilised. The average state-of-charge (SoC) reflects the way BESS' are generally operated to minimise household electricity bills (Fig. 7). At the annual average, there are two main types of SoC profiles, (a) scenarios with flat export tariffs (F_iF_e and T_iF_e); and, (b) scenarios with time-varying export tariffs (F_iT_e and T_iT_e).

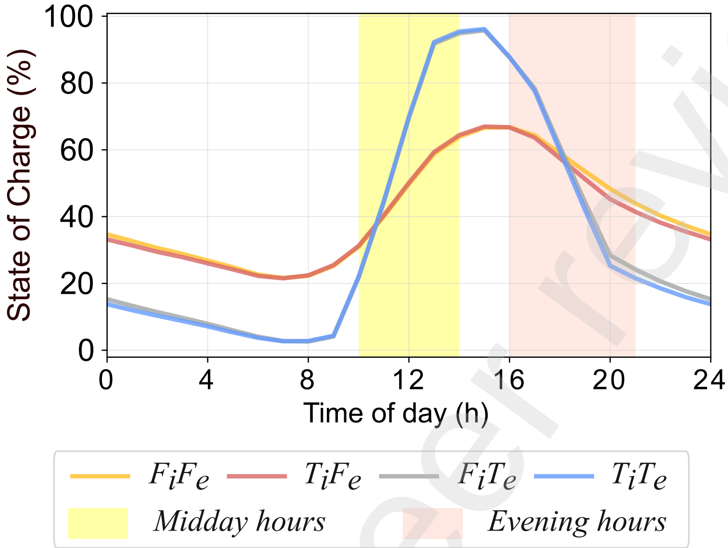

Figure 7: Average hourly battery state-of-charge across 400 PV-BESS households in each tariff scenario

Considering the F_iF_e scenario, the lowest SoC (Fig. 7) typically occurs at 7 am and rises until 4 pm, which indicates that the PV-BESS households charge their batteries across the daylight hours (from an average SoC of 22 % to 67 %) and then discharge from the early-evening until the next morning. The average change in SoC is 45 % which corresponds to 164.8 full battery cycles per year. Under the T_iF_e scenario, the SoC profile remains very similar to the F_iF_e scenario (Fig. 7), except that the PV-BESS households discharge their batteries slightly more during the peak import tariff period (between 3 pm and 9 pm) which lowers the average SoC until the next morning. This leads to a slight increase in the number of battery cycles per year to 165.8.

With the F_iT_e scenario the SoC difference (93.2 %) between the average minimum and maximum SoC (Fig. 7), at 2.6 % and 95.8 % respectively, is much larger, which indicates a much higher average battery utilisation compared to the flat export tariff scenarios (F_iF_e and T_iF_e). This also leads to a much higher number of battery cycles per year at 340.0. Furthermore, the average charging period of these PV-BESS household batteries is shifted predominantly to the time period between 10 am and 2 pm, which also corresponds to the off-peak export tariff time period (Table 1). This change in battery charging operation is responsible for reducing midday grid feed-in (Fig. 6). Furthermore, there is also a higher level of battery discharge that occurs between 4 pm and 9 pm, which corresponds to the peak export tariff time period. This change in battery discharging is responsible for the evening grid feed-in that continues past sunset. Under the T_iT_e scenario, the SoC profile remains very similar to the F_iT_e scenario, except that (and sharing similarities with the T_iF_e scenario) there is slightly more discharge during the peak import tariff time period (between 3 pm and 9 pm), which leads to a slight increase in the annual number of battery cycles to 341.2.

5. Discussion

The overall results indicate that time-varying export tariffs significantly influence the optimal residual load profile of PV-BESS households, and that time-varying import tariffs have much lower influence. The choice of tariff structure has direct implications on the resulting shape of the solar duck curve, financial benefits to PV-BESS households, and the grid and system operation. The following subsections discuss these wider implications of introducing time-varying export tariffs over existing flat export tariffs.

5.1. Implications for the solar duck curve

The changes to the solar 'duck curve' are quantified as the amount of energy fed into the grid during the midday hours between 10 am and 2 pm (Table 4), which is generally identified as the 'belly of the solar duck curve', and the amount of energy fed into the grid during the evening between 4 pm and 9 pm, which is generally identified as the 'head of the solar duck curve'. These time periods respectively correspond to the off-peak export tariff, and the overlap between the peak import and peak export tariffs (Table 1).

During midday hours (10 am to 2 pm), the introduction of the time-varying export tariff (over the flat export tariff) leads to changes in the grid feed-in profile (Fig. 6) that significantly lowers the amount of energy being fed into the grid (Table 4). On average across the year, the time-varying export tariffs lower the midday feed-in from 12.4 kWh/day to 5.5 kWh/day, which is a –55.6 % reduction and is primarily driven by delaying battery charging until 10 am. During summer, autumn, and spring, which has a relatively large amount of excess PV generation,[8] this change lowers midday grid feed-in by between 7.3 – 8.0 kWh/day. In winter months, this reduction falls to 4.6 kWh/day reflecting lower solar irradiance and greater heating load.

Table 4: Average energy per PV-BESS household (N = 400) fed into the grid daily between the midday hours of 10 am and 2 pm for flat and time-varying export tariffs.

	Flat export tariffs ($F_i F_e$ and $T_i F_e$) [kWh/day]	Time-varying export tariffs ($F_i T_e$ and $T_i T_e$) [kWh/day]	Percentage change [%]
Summer	17.2	9.2	–46.4
Autumn	11.6	4.2	–63.4
Winter	5.6	1.1	–81.3
Spring	15.5	7.7	–50.5
All	12.4	5.5	–55.6

These changes in the amount of energy and profile of grid feed-in during daytime hours show that, under time-varying export tariffs, introducing new PV-BESS households into the power system would still lead to lower minimum system demand,[9] but the marginal level of reduction would be lowered by an average of 55.6 %. If existing PV-only households (with a 9 kW_P PV system) install 12 kWh batteries to become PV-BESS households, the time-varying export tariffs would incentivise reductions in midday feed-in, which would subsequently raise minimum system

[8] i.e. higher solar irradiance in summer, and lower heating and cooling demand in autumn and spring.
[9] which typically occurs around noon (AEMO, 2023)

demand. The net result is that these time-varying export tariffs are capable of slowing the growth rate of feed-in at the 'belly of the solar duck curve'.

During evening hours (4 pm to 9 pm), flat export tariffs do not provide any financial incentive for PV-BESS households to feed into the grid. As a result, these households are incentivised to significantly reduce their grid consumption using their BESS and do not feed-in after sunset (Fig. 6 and Table 5). However, the introduction of the time-varying export tariff provides a financial incentive to continue feeding energy into the grid past sunset (until 9 pm), which leads to a further 5.5 kWh/day of grid feed-in (annual average), where these PV-BESS households not only avoid consuming energy during the evening, but actively reduce peak evening demand at the system level. The level of additional evening grid feed-in varies with the season, with the highest contribution during summer (7.2 kWh/day) and the lowest during winter (2.6 kWh/day).

Table 5: Average energy per PV-BESS household (N = 400) fed into the grid daily between the evening hours of 4 pm and 9 pm for flat and time-varying export tariffs.

	Flat export tariffs (F_iF_e and T_iF_e) [kWh/day]	Time-varying export tariffs (F_iT_e and T_iT_e) [kWh/day]	Net change [kWh/day]
Summer	3.7	10.9	+7.2
Autumn	0.9	6.6	+5.7
Winter	0.0	2.6	+2.6
Spring	1.9	7.8	+6.0
All	1.5	7.0	+5.5

Introducing PV-BESS households into the power system with time-varying export tariffs would therefore lead to reductions in peak evening demand (Fig. 6) across the distribution network. If existing PV-only households (with a 9 kW_P PV system) install 12 kWh batteries to become PV-BESS households, flat export tariffs would lead to a reduction in evening electricity imports such that they no longer worsen peak evening demand, while time-varying export tariffs would actively lead to peak evening demand reductions at the overall system level. The net result is that these time-varying export tariffs are capable of actively reducing the 'head of the solar duck curve'.

5.2. Implications for PV-BESS households

The changes to the annual electricity bill (Table3) show that the time-varying import and export tariffs (Table 1) – as provided by the Victorian Essential Services Commission (ESC, 2023a,b) – do not financially disadvantage the average PV-BESS household. Even before considering a PV-BESS, the average annual electricity bill across all households is slightly lower (by 43 AUD) under time-varying import tariffs. With a PV-BESS, the average annual electricity bill continues to be lower under time-varying import and/or export tariffs compared to flat import and export tariffs.[10] This suggests that PV-BESS households (on average) are not financially disadvantaged under the time-varying import and/or export tariffs (Table 1), while also interacting with the grid in a more system-friendly manner – especially under F_iT_e and T_iT_e tariffs. These time-varying export tariffs provide PV-BESS households with the opportunity to

[10] The T_iT_e tariff has the lowest average annual electricity bill, followed by the F_iT_e, T_iF_e, and F_iF_e tariff.

arbitrage their excess PV generation and grid imports with higher-value grid export tariffs in the evening. However, while this results in an average 106 % increase in BESS utilisation (Fig. 7) from the increased number of battery cycles per year,[11] its operation still resides within the typical residential battery warranty of 1 cycle per day.[12] Overall, the use of time-varying export tariffs does not worsen the financial outcomes for the average PV-BESS household, while providing a financial mechanism that allows these households to extract more value from their spare battery capacity.

5.3. Implications for grid and system operators

The results show that the potential changes to the solar 'duck curve' from PV-BESS households depend heavily on the type of tariffs these households face, and in particular that the time-varying export tariff has a much larger influence on the overall residual load profile when compared to the time-varying import tariff (Fig. 6).

If PV-BESS households face flat export tariffs (F_iF_e and T_iF_e), the average level of grid exports during midday hours remains comparatively high (but within the 5 kW network export limit), which means that these households are likely to continue contributing to the current level of midday reverse power flows. This will continue exacerbating network congestion problems (e.g. accelerated aging of transformers, raising voltage levels, reducing rooftop PV hosting capacity), and system-wide issues related to minimum operational demand (e.g. low system inertia, negative wholesale prices). As flat export tariffs incentivise self-consumption during evening hours, the average grid utilisation and demand from PV-BESS households is significantly reduced (and remains close to zero during non-winter months). These PV-BESS households are less likely to worsen local network congestion during the evening and do not contribute to the growth of peak diurnal demand at the system level.

If PV-BESS households face time-varying export tariffs (F_iT_e and T_iT_e), the average amount of grid exports during midday hours is further reduced by 56 % (Table 4) compared to flat export tariffs. This significantly lowers the expected amount of midday reverse power flows from each PV-BESS household, alleviating both network congestion and falling minimum operational demand. The higher feed-in tariff during evening hours raises the incentive of grid exports over self-consumption. As a result, grid exports generally continue 2 to 4 hours beyond sunset (Fig. 6) via grid discharging from the household batteries until 9 pm. Between 4 pm to 9 pm, the average level of grid feed-in per household is increased by 5.5 kWh/day (Table 5) compared to flat export tariffs. This means that PV-BESS households may become capable of actively reducing congestion in the distribution network during this time, which lowers diurnal peak demand (at the system level) and the ramp rate between midday and evening. This benefits the power system by reducing the demand for typically more expensive peaking generation and/or utility-scale battery storage that may lead to lower evening wholesale electricity prices. Therefore, the use of time-varying export tariffs adjusts the residual load profile of PV-BESS households to better match the availability of renewable energy generation in a grid with a high penetration of solar PV.

5.4. Sensitivity analysis

To assess the sensitivity of results to tariff prices, we evaluate 8 additional tariff scenarios that correspond to all tariff prices either increasing by 30 % or decreasing by 30 %. The sensitivity results (Table 6) show that raising or lowering the relative price level of the tariffs (± 30 %) does not significantly change the average amount of feed-in that occurs between the midday hours (10 am to 2 pm) and evening hours (4 pm to 9 pm) in the time-varying export scenarios (F_iT_e and T_iT_e). This is because the time-varying export tariff structure retains the same relative temporal

[11] From 165 cycles (average of F_iF_e and T_iF_e) to 341 cycles (average of F_iT_e and T_iT_e).
[12] https://www.solarquotes.com.au/battery-storage/comparison-table/

economic incentives for charging and discharging the PV-BESS battery during the midday and evening hours. As a consequence, the results and implications are unaffected.

Under the flat export tariff scenarios ($F_i F_e$ and $T_i F_e$), the export pricing constraint is relaxed, which increases the feasibility space between the hours of 10 am and 2 pm and 4 pm to 9 pm. As there is no explicit temporal cost against exporting energy at other times, this broadens the range of viable solutions, which influences the optimal solution and slightly increases the feed-in variation in the –30 % results (and further exacerbated by the 'small denominator problem'). However, the amount of feed-in during the midday and evening hours remain relatively consistent in absolute terms and overall, the annual level of self-consumption, self-sufficiency, grid imports and grid exports are near-equivalent (Table B.1 and Table B.2). Therefore, the flat export tariff results as discussed in the previous subsection remain unaffected.

Table 6: Comparison of average feed-in and percentage change across the four tariff structures and their sensitivities (10 am to 2 pm and 4 pm to 9 pm).

	Case	10 am to 2 pm [kWh/day]	4 pm to 9 pm [kWh/day]	Perc. change 10 am - 2 pm [%]	Perc. change 4 pm - 9 pm [%]
$F_i F_e$	Reference	−12.46	−1.21	0	0
	+30 %	−12.47	−1.20	+0.1	−0.7
	−30 %	−12.73	−1.11	+2.2	−8.5
$T_i F_e$	Reference	−12.42	−1.60	0	0
	+30 %	−12.45	−1.58	+0.2	−0.1
	−30 %	−12.69	−1.52	+2.2	−5.2
$F_i T_e$	Reference	−5.53	−6.76	0	0
	+30 %	−5.53	−6.75	0.0	−0.1
	−30 %	−5.53	−6.75	0.0	0.0
$T_i T_e$	Reference	−5.50	−7.15	0	0
	+30 %	−5.51	−7.15	+0.1	0.0
	−30 %	−5.50	−7.15	0.0	0.0

5.5. Caveats and areas for future research

To evaluate the operational effects of PV-BESS households under time-varying and flat import and export tariffs, we utilise a range of input data and parameters, and develop the *Electroscape* MILP optimisation model. This relies on the following key assumptions that have an influence on the interpretation of the results and discussion.

First, *Electroscape* determines the optimal PV-BESS operation with perfect foresight, which implies that future electrical demand and PV generation are completely known before operational decisions are made. As a consequence, the residual load profiles are the best-case response, and real world outcomes will be less than optimal. Future research may consider developing heuristic models (without perfect foresight) that can operate as close as possible to the economic optimal. Furthermore, *Electroscape* assumes an ideal direct current network with zero losses or the need to consider reactive power. Incorporating these into the analysis would improve the robustness of results.

Second, the overall operational objective is to maximise bill savings, which disregards the broader range of social (e.g. autarky), environmental (e.g. minimising indirect greenhouse gas emissions), and other economic (e.g. minimising wholesale electricity costs) motivations. An area of future research is to consider the broader objectives of PV-BESS households and the range of operational impacts on the power system.

Lastly, we only evaluate one PV-BESS sizing configuration across all households. While it reflects the current average installation size in Australia, it does not consider the breadth of configurations available to many different households. Further research should evaluate how a range of PV and BESS sizes may affect the results and if there exists a tipping point when time-varying export tariffs begin to have increased influence over time-varying import tariffs.

The scope of our study is centred around the PV-BESS household. Future research may also consider the upstream supply chain by incorporating the costs of retailers and distribution network owners. Understanding how these tariffs may influence operational strategies, pricing models, and overall profitability as well as network augmentation and wholesale prices would provide valuable insights for policymakers. These areas of future research may offer a more nuanced understanding of the impacts of time-varying tariffs on the power system and the range of behaviours from retailers and consumers alike.

6. Conclusions and policy implications

As a world leader of installed solar PV capacity per capita (IEA, 2023) – most of which is behind-the-meter – Australia is at the forefront of integrating rooftop PV systems into the power system. While this has helped to accelerate Australia's energy transition, the resulting solar 'duck curve' has led to operational issues in the distribution network (e.g. reverse power flows, and the fair allocation of finite hosting capacity) and at the system level (e.g. falling operational demand and system inertia during midday, and increased ramp rates toward the evening). As the adoption of residential BESS increases, there is a potential for these PV-BESS households to change their residual load profiles in order to mitigate the challenges posed by the solar 'duck curve'. Time-varying import (i.e. *Time-of-Use*) tariffs (Table1) have been proposed to disincentivise households from consuming electricity during the evening, and incentivise households to consume energy during midday. Time-varying export (i.e. *Time-of-Export*) tariffs (Table 1) have been proposed to disincentivise households from exporting energy during midday, and incentivise households to export energy during the evening and night.

Evaluating each time-varying and flat import and export tariff combination through four tariff scenarios, applied to 400 real household load profiles from Melbourne, Australia with a developed household dispatch optimisation model *Electroscape* and a 9 kW_P PV and 12 kWh / 5 kW BESS assigned to each household, we find that time-varying export tariffs (as opposed to time-varying import tariffs) have a much greater influence on the residual load profile. These differences in operational demand may have significant implications for the solar duck curve, PV-BESS households, system and market operation, and future retail electricity tariff policies.

Between the four tariff structures, there are two main outcomes with the results of the two flat export scenarios ($F_i F_e$ and $T_i F_e$) having strong similarities with each other, and similarly with the two time-varying export scenarios ($F_i T_e$ and $T_i T_e$). If rooftop PV households were to transition into PV-BESS households that only face flat export tariffs, our results show that grid feed-in continues during the day (and peaks at noon) and that households are primarily operating with self-consumption (stored from PV self-generation) through the evening and towards the next morning. Overall, this would continue to exacerbate daytime system issues around falling minimum operational demand during midday but prevent the growth of peak system demand (and network congestion) from these PV-BESS households in the evening.

However, if these same households were to face time-varying export tariffs, our results show that the lower feed-in tariff between 10 am and 2 pm lowers grid feed-in by an average of 55.6 %, which would help to slow the decline in midday operational demand. Notably, the higher feed-in tariff between 4 pm and 9 pm leads to PV-BESS households continuing to feed into the grid past sunset by an average of 5.5 kWh/day from BESS grid discharging (and PV self-generation), which actively reduces peak system demand and grid congestion. As these changes in the average PV-BESS household residual load profile actively counteract the widening difference in midday and evening operational demand arising from existing PV-only households (i.e. the 'solar duck curve'), it reduces the midday-to-evening ramp rate and system peaking generation requirements, which would likely reduce evening wholesale electricity prices and supply costs.

Given that the time-varying export tariff incentivises PV-BESS households to interact with the grid in a way that counteracts the solar 'duck curve' while increasing renewable energy penetration, policymakers of electricity systems with growing solar PV penetration should consider regulations or reforms to add a time-varying component to the retail feed-in tariff (i.e. *Time-of-Export*) – such that the incentive for midday feed-in is reduced and the incentive for evening feed-in is increased. Furthermore, a *Time-of-Export* tariff only affects households with self-generation and storage, rather than all households. Our results also show that time-varying import tariffs (i.e. *Time-of-Use*) are much less effective at counteracting the solar 'duck curve', and given that they may be regressive for those of lower socio-economic advantage (Burns and Mountain, 2021), policymakers may find *Time-of-Export* tariffs to be more socially acceptable. Furthermore, as *Time-of-Export* tariffs can be adjusted over time, they provide a means for decision and policy makers to continue improving the integration of consumer energy resources with the broader power sector and its transition. The installation of PV-BESS by households is a direct investment by households in the energy transition, but the financial returns should change as the electricity system changes. By rewarding consumers with system-friendly behaviour, time-varying export tariffs help to align system and consumer objectives and accelerate the rate of decarbonisation.

A. Scenario and technical parameters

Table A.1: Scenario parameters

Description	Value	Unit	Source
Scenario forecast period	1	year	Model assumption
Time step	1	hour	Model assumption
Number of households	400	-	Provided by C4NET (2020)
Underlying demand profile	Time series	kW	Provided by C4NET (2020)
Underlying solar profile	Time series	kW/kW_P	NREL (2021)

Table A.2: Technical parameters

Description	Value	Unit	Source
PV capacity	9	kW_P	APVI (2024)
PV initial SoH	100	%	Model assumption
PV end-of-life capacity	80	%	SolarPower Europe (2024)
PV end-of-life period	25	years	SolarPower Europe (2024)
Battery capacity	12	kWh	Johnston (2023)
BESS initial SoH	100	%	Model assumption
Max. BESS power	5	kW	Model assumption
BESS charging efficiency	93.81	%	Chadly et al. (2022)
BESS discharging efficiency	93.81	%	Chadly et al. (2022)
BESS end-of-life period	10	years	Say and John (2019)
BESS end-of-life cycles	10,000	cycles	Chadly et al. (2022)
BESS end-of-life capacity	70	%	Say and John (2019)
Network export limit	5	kW	Powercor et al. (2022)

B. Results of the sensitivity analysis

Table B.1: Sensitivity analysis +30 % – Average techno-economic results across 400 PV-BESS households

	Unit	F_iF_e	T_iF_e	F_iT_e	T_iT_e
Electricity bill w/o PV-BESS	AUD	1,694	1,638	1,694	1,638
Electricity bill with PV-BESS	AUD	-335	-369	-516	-551
Bill savings from PV-BESS	AUD	2,029	2,007	2,210	2,189
Self-consumption	%	29.64	29.64	29.63	29.63
Self-sufficiency	%	86.99	86.99	86.97	86.97
Grid imports	kWh	512	516	513	517
Grid exports	kWh	8,713	8,713	8,455	8,455
BESS grid charging	kWh	0	34	0	34
BESS grid discharging	kWh	117	117	2,019	2,019

Table B.2: Sensitivity Analysis -30 % – Average techno-economic results across 400 PV-BESS households

	Unit	F_iF_e	T_iF_e	F_iT_e	T_iT_e
Electricity bill w/o PV-BESS	AUD	912	882	912	882
Electricity bill with PV-BESS	AUD	-180	-199	-278	-296
Bill savings from PV-BESS	AUD	1,092	1,081	1,190	1,179
Self-consumption	%	29.64	29.64	29.63	29.63
Self-sufficiency	%	86.99	86.99	86.97	86.97
Grid imports	kWh	512	516	513	517
Grid exports	kWh	8,713	8,713	8,455	8,455
BESS grid charging	kWh	0	34	0	34
BESS grid discharging	kWh	117	117	2,019	2,019

CRediT author statement

Lisa Restel: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Kelvin Say**: Conceptualization, Methodology, Software, Formal analysis, Resources, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision, Project administration.

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