Battery model description

Accompanying Appendix Four to

Understanding the value of residential solar PV and storage in New Zealand

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Contents

Disclaimer

This appendix accompanies the report “Understanding the value of residential solar PV and storage in New Zealand”. The information and results are supplied in good faith and reflect the expertise and experience of the author. The model used to derive the results is subject to assumptions and limitations referred to in the document and model specification. Any reliance on the model results is a matter for the recipient’s own commercial judgement, taking into account the inputs and assumptions given. AMCL accepts no responsibility for any loss by any person acting or otherwise as a result of reliance on this document and the results.

1 Introduction

This appendix accompanies the report "Understanding the value of residential solar PV and storage in New Zealand" and provides a brief explanation of the battery model used in the analysis presented in the report. The battery model is a proprietary ANSA® model, and is therefore not outlined in detail. Instead, a general explanation of its operation is given.

2 Model Operation

Throughout this document, export refers to the export of energy from an ICP to the network. The price for exported energy at any point in time is referred to as the export price or buyback price interchangeably. Further, in all graphs, and references to times of half-hourly periods, the time given refers to the half-hour ending. Energy reported is the energy at the half-hour ending, while power reported is the average power over the half-hour ending. In addition to this, the follow abbreviations are used.

Abbreviation	Description
ICP	Installation control point. This is a consumer's building (a house or business).
V2G	Vehicle to grid
PV	Photovoltaic, used to mean a photovoltaic solar system, comprising installed panels, wiring and inverter connected to the electricity network, with associated controls, metering, and protection.
EV	Electric vehicle

2.1 Charge and discharge prices

The battery model responds to marginal prices, being the price charged for an additional unit of charge or the price received for an additional unit of discharge. Half-hour periods throughout a day are prioritised by priority level for either charge or discharge, depending on the net load (load less solar) and price. Within each priority level prices are also ordered from lowest to highest (for charging) and highest to lowest (for discharging), with order by time preserved.

With the introduction of solar, each time period theoretically has up to four prices for charging a battery. This is explained below with reference to Figure 1, which gives load and solar in Wellington on a winter's day. The explanation is in the order of the most desirable times to charge (lowest price) to the least desirable (highest price).

1. When the ICP's original load less solar generation plus battery charge is negative and exceeds the export limit, and solar generation is therefore capped, the price for charging is zero. An example of when this occurs is between 13:00 and 15:00. Such a situation can only occur with solar capacity that exceeds the export limit. The rate of charge within this priority level is capped to the difference between the net load and the export limit. Once this is exceeded, the next priority level is entered.
2. When the ICP's original load less solar generation plus battery charge is negative and between zero and the export limit, the price for charging is the export price, since this determines the revenue forgone by charging instead of exporting. Examples of when this occurs are between 10:30 and 12:30 and 15:30 and 17:30. The rate of charge within this priority level is capped to the net load. Once this is exceeded, the next priority level is entered.
3. When the ICP's original load less solar generation plus battery charge is positive and less than the supply capacity limit, the price for charging is the retail price, since any additional load to charge the battery is paid for at the retail price. Examples of when this occurs are from 00:30 to 10:00 and 18:00 to 24:00 (i.e. all other half-hours than those in 1 and 2 above).

4. When the ICPs original load less solar generation exceeds the supply capacity limit, the price for charging is infinite. Such a situation does not exist in Figure 1, and practically this is implemented through a constraint in the battery optimisation, outlined below.

Similarly, with the introduction of solar, each time period theoretically has up to four prices for discharging a battery. These are outlined below, with reference to Figure 1, and in order of most desirable (highest price) to least desirable (lowest price).

1. When the ICP's original load less solar generation is positive and exceeds the supply capacity, the price for discharging is zero. Such a situation does not exist in Figure 1, and practically this is implemented through a constraint in the battery optimisation, outlined below.
2. When the ICP's original load less solar generation and battery discharge is positive and below the supply capacity, the discharge price is the retail price, since discharge from the battery reduces load which would otherwise have been purchased at the retail price. Such situations are from 00:30 to 10:00 and 18:00 to 24:00.
3. When the ICP's original load less solar generation and battery discharge is negative and between zero and the export limit, the price of discharge is the export price, since the energy is exported at the export price. Examples of when this occurs are between 10:30 and 12:30 and 15:30 and 17:30.
4. When the ICP's original load less solar generation and battery discharge is negative and beyond the export limit, the price is zero, since it is not permissible to exceed the export limit. Practically this is implemented through a constraint in the battery optimisation, outlined below.

From the above it can be seen that prices vary markedly between priority levels, in non-linear fashion, as the net of solar generation and load vary between net export capped at the export limit, net export within the export limit, and demand capped by the supply capacity. Priority levels are used to order the pairing of charge and discharge candidates, described below. Further, it may not be possible to access one priority level until another has been exhausted by a battery charging or discharging. Charge and discharge opportunities are paired by priority level from the highest price difference to the lowest price difference over a search horizon, practically one day. This is described in the next section.

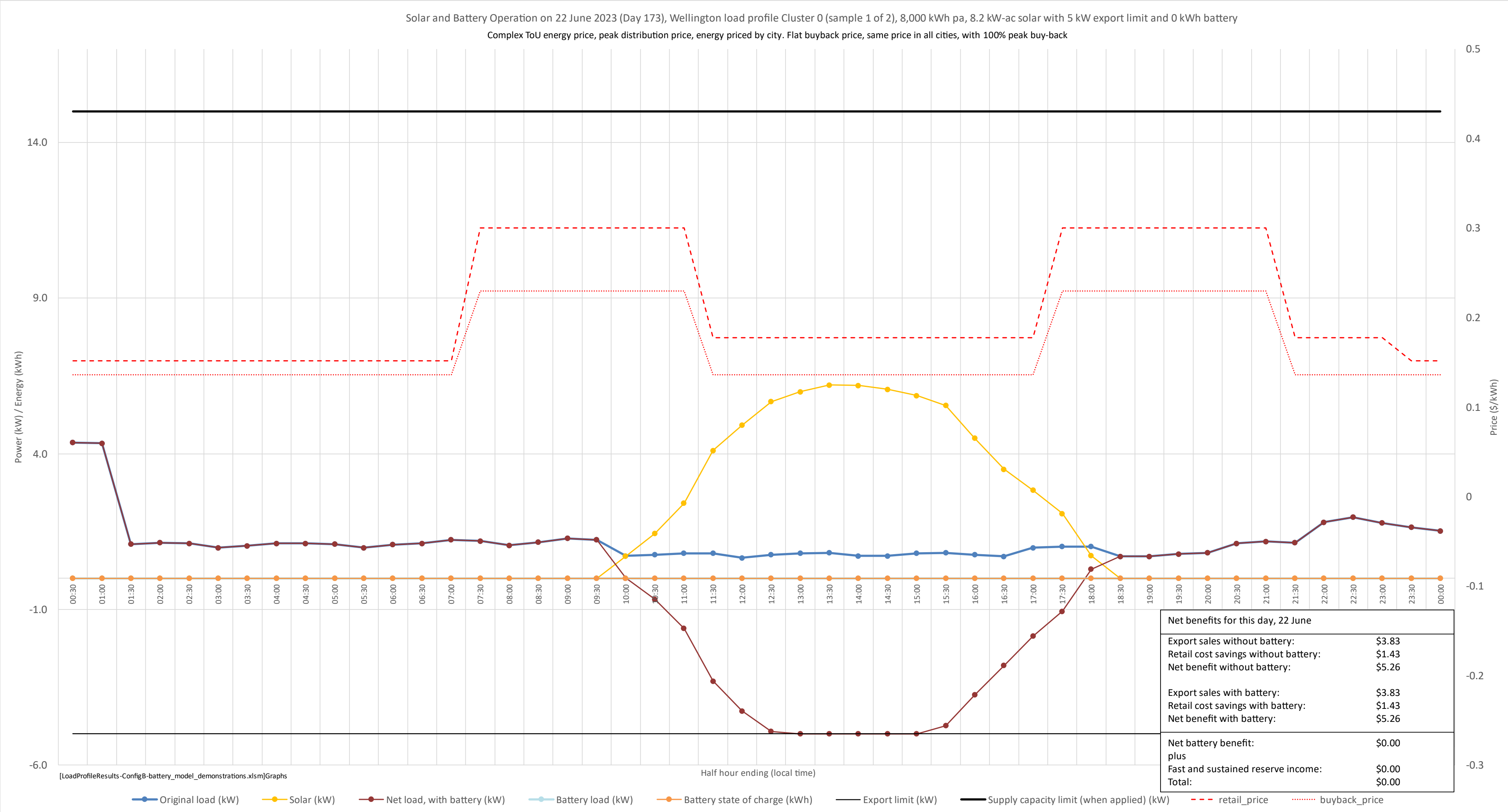

Figure 1: Load and net load after solar generation, and no battery.

2.2 Battery model operation – pairing of charge and discharge prices

Charge and discharge prices are stored for each priority level and for each half-hour of a day. The volume available from the lowest charge price is then matched with the volume available at the highest discharge price that occurs after it. This process is repeated over all charge and discharge candidates and for each day of the year within a 24-hour 'search horizon', subject to the constraints outlined below. Various search horizons were trialled, with 24 hours giving better results than most.

Because prices vary over the course of a day, the charge and discharge prices also vary. Moreover, because the ICP's original load less solar generation varies, sometimes substantially, the charge and discharge prices vary, as outlined earlier. Within the 24-hour search horizon, retail and buyback prices are known ahead of time. However, for such an algorithm to operate in real-time, solar generation and load must be forecast. The battery model assumes a perfect forecast of each by using the actual historical values of each ahead of time. Thus, the battery performance from this model represents the best performance achievable. This is considered a reasonable assumption, as accurate forecasting services available for a small fee to optimise battery performance are likely to grow as more batteries are deployed around the world.

The following constraints are also applied during the search process:

- Battery state of charge must remain within the limits of the battery's capacity and 0 kWh. In all cases the capacity stated is the battery's capacity after accounting for 70% depth of discharge.
- Battery charge rate at each half-hour must be within the system's charge capacity, equal to the PV inverter ac capacity for a battery and equal to 10 kW for V2G.
- Battery discharge rate at each half-hour capacity must be within the system's discharge capacity, equal to the PV inverter ac capacity for a battery and equal to 10 kW for V2G.
- The supply capacity of the ICP (assumed to be 15 kW single phase) must not be exceeded.
- The export limit must not be exceeded (both 5 kW and 15 kW are tested).

2.3 Operation and maintenance cost

A limit on the number of battery cycles is not added as a constraint. Instead, operation and maintenance cost is incurred based on the number of cycles exceeding the battery's limit of 11,000 cycles, at the years they are exceeded, and based on the present day cost of a battery. An alternative might have been to incur the cost of an entire battery. However, the future is so uncertain after 20 years, when the battery cycle limit is typically exceeded if at all, that incurring battery cost in small capacity increments seemed reasonable.

The cycle limit of 11,000 cycles refers to full cycles, within the full 10 kWh or 30 kWh capacity of the battery (the capacity after depth of discharge adjustment – see later discussion in Section 2.4). As demonstrated in the next section, the battery is not always fully charged or fully discharged within a day. Conversely, there may be days when it is fully charged and discharged more than once in a day. To reflect these changing conditions in the model, the actual number of cycles of the battery within each year is determined by summing the battery discharge over a year, converting it from kW to kWh, and dividing by the battery capacity after depth of discharge, and dividing it by the battery round trip efficiency.

The battery operation and maintenance model differs to that of PV, which incurs an operation and maintenance cost in every year based on the capacity. This reflects a growing cost as more panels are installed, which increases the number that may need replacing over time due to defects or damage, as well as cleaning costs and wiring maintenance as capacity increases. Inverter replacement is assumed to not be required, although over the 29 years of operation, the present cost of the typical operation and maintenance costs amounts to roughly the present-day cost of an inverter.

2.4 Battery parameters

Throughout the model a 5 kWh, 10 kWh battery, and 30 kWh V2G EV battery are used. These are the usable capacities, after 70% depth of discharge (so the 10 kWh battery's actual capacity is 14.3 kWh, and the EV's battery capacity is in excess of 43 kWh). At this depth of discharge a limit of 11,000 cycles of battery capacity is set. A round-trip-efficiency of 90% is assumed. It is possible that higher efficiencies may be achieved with DC coupled batteries and inverters. However, this analysis assumes the worst case of AC coupled batteries.

As discussed in Appendix Five, a battery cost of 1,000 $/kWh is assumed, then halved, to provide an optimistic view of installed battery cost. This is further adjusted by dividing by the depth of discharge. Hence, the 10 kWh battery cost is $14,286, but is halved to $7,143.

The V2G battery cost is not included in the battery capital cost calculation, as it is assumed that the EV is a sunk cost and that the owner is prepared to use it as a battery. The same operation and maintenance costs are applied however, based on the 10 kWh battery cost discussed earlier. A V2G capable charger/inverter is costed at $6,000. This is AC coupled with the PV inverter, with suitable monitoring of PV generation, load, and main supply to implement the battery control described earlier. This includes implementing export limits and other protection such as islanding and voltage control. Exactly how the inverter and V2G charger/inverter work together is a detail that is conveniently ignored, but is an important detail in a practical implementation. It is recommended that this be investigated further.

For simplicity, the EV is assumed to be connected and available from Sunday to Wednesday inclusive, 24 hours a day. Clearly EV availability would vary considerably from this, but this availability is chosen to illustrate V2G potential. In this model no control to ensure the EV is at a certain state of charge by a certain time of day is implemented.

The PV inverter is assumed to be battery capable.

2.5 Battery control algorithms

Because the battery model matches the lowest price charge times with the highest price discharge times within a 24 hour window, it is akin to a greedy optimisation, which seeks to find the battery dispatch that maximises profit within a day, even though there may be more optimal charge/discharge profiles over an entire a year. Such an annual optimisation would require accurate solar and load forecasts well ahead of time, which is not considered practical. This further justifies the use of a day-ahead method (24 hour search horizon).

This study has set out to use a battery control algorithm that delivers the best performance possible, to inform the results as if such battery control was possible. Description of battery control from inverters with battery capability are scarce, and anecdotally battery's are often paired with the 9pm-midnight free price structures. For this reason, the 9pm-midnight free price structure is modelled in this study, although it is unclear how long such a price structure will be available. Because of this, a more general battery model was sought for this study, that would respond to complex time-of-use retail price structures and buyback structures.

3 Battery model operation examples

Further battery operation is discussed with reference to the following figures. The initial configuration is a simple time-of-use two-rate price structure with flat buyback price. An earlier winter day than Figure 1 (21 June, a Wednesday) is used to demonstrate V2G operation later, and Christchurch load and prices are used instead. Christchurch is used to later demonstrate the response to subtle changes in price in Christchurch prices with more complex price structures (Orion's 'super off-peak' price from 3am to 5am). The round-trip-efficiency is set to 1.00 in these examples for ease of explanation.

The main report demonstrates 9pm-midnight price structure operation, and demonstrates more complex time-of-use price structures with increasingly complex buyback prices.

Cluster 0 is used for consistency with other sections.

3.1 Simple two-rate time-of-use price structure with a flat buyback price

In Figure 2 the battery charges to 9.25 kWh in the lower price period of the two-rate time-of-use price close to the transition to the higher rate period. The charge rate is limited to 5 kW at 05:30 and 06:00, equal to the inverter capacity. It then discharges completely within the entire higher price section, reducing electricity purchases at the retail price of 30.33 c/kWh. The rate of discharge matches the load, such that the net load is zero. It does not export, as the export price of 13.61 c/kWh is too close to the nigh-time retail price of 13.41 c/kWh – there being insufficient margin between the prices to justify exporting. This explains why the battery only charges to 9.25 kWh instead of 10 kWh; there is only 9.25 kWh of load energy within the daytime higher price period.

When the lower price period begins again at 10:30pm, the battery charges, with similar behaviour seen on the following day, Figure 3.

Replacing the 10 kWh battery with V2G in Figure 4, and noting that V2G is only available from Sunday to Wednesday inclusive (21 June 2023 being a Wednesday), the battery also only charges to 9.25 kWh, but does so at a higher rate due to the higher capacity V2G charger, charging in a single half-hour period at an average rate of 8.5 kW. The battery does not charge later in the evening, since it is no longer available. The V2G model is a relatively simple one, and does not model charging the EV battery to a desired capacity for the following day.

Adding 5 kW-ac solar with a 10 kWh battery, as shown in Figure 5, interestingly reduces the state of charge that the battery reaches to just 3.61 kWh. This initially seems counterintuitive, since one might expect a battery to make use of the excess solar and charge to a higher state of charge. However, the solar is sufficiently high during the winter day to not just fully meet the load between 11:00 and 17:30, but also export. This leaves less load energy required to be met by the battery, offsetting the retail price of 30.33 c/kWh and no other opportunity for the battery to receive the retail price of 30.33 c/kWh. If the battery was charged to a higher state of charge, at the night-time price of 13.41 c/kWh, its only other opportunity to use this energy is to export it at the export rate of 13.61 c/kWh, which as pointed out earlier is too close to the night-time price to justify the export.

Hence, as shown in Figure 5, the operation of the battery with solar is generally more 'timid' with the retail pricing shown.

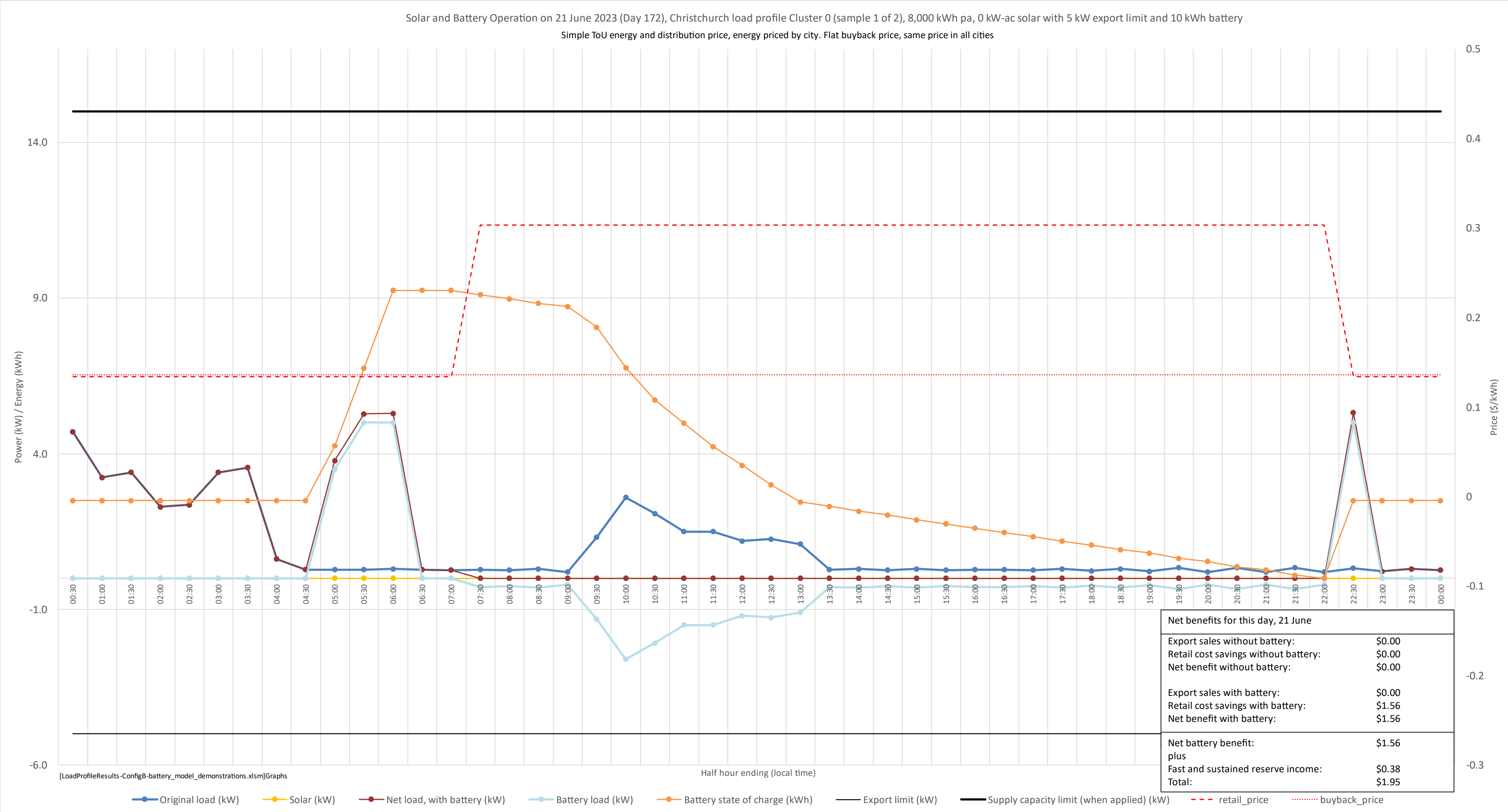

Figure 2: Battery operation with a simple time-of-use two-rate price structure with flat buyback price and no solar, 21 June.

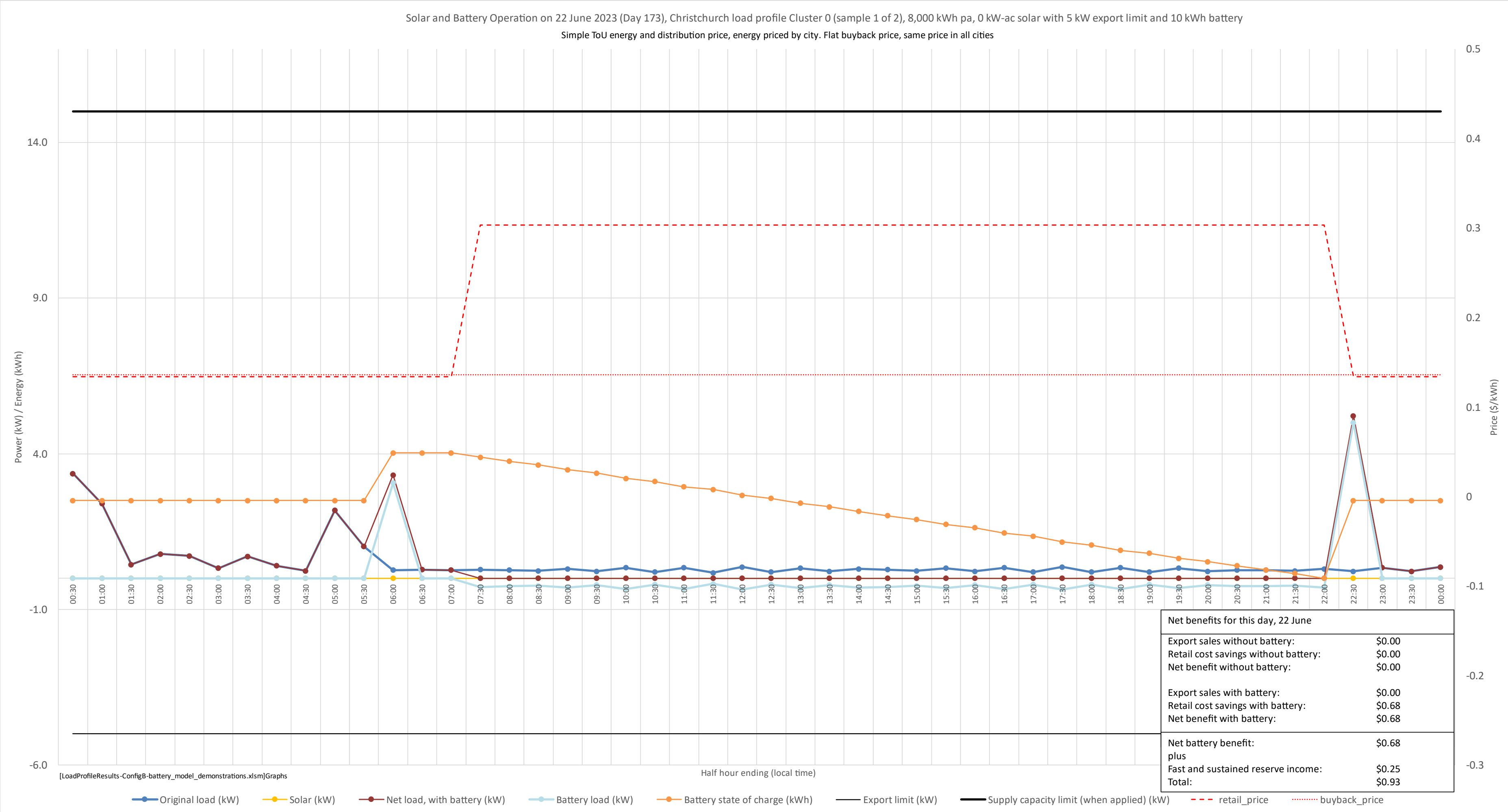

Figure 3: Battery operation with a simple time-of-use two-rate price structure with flat buyback price and no solar, 22 June.

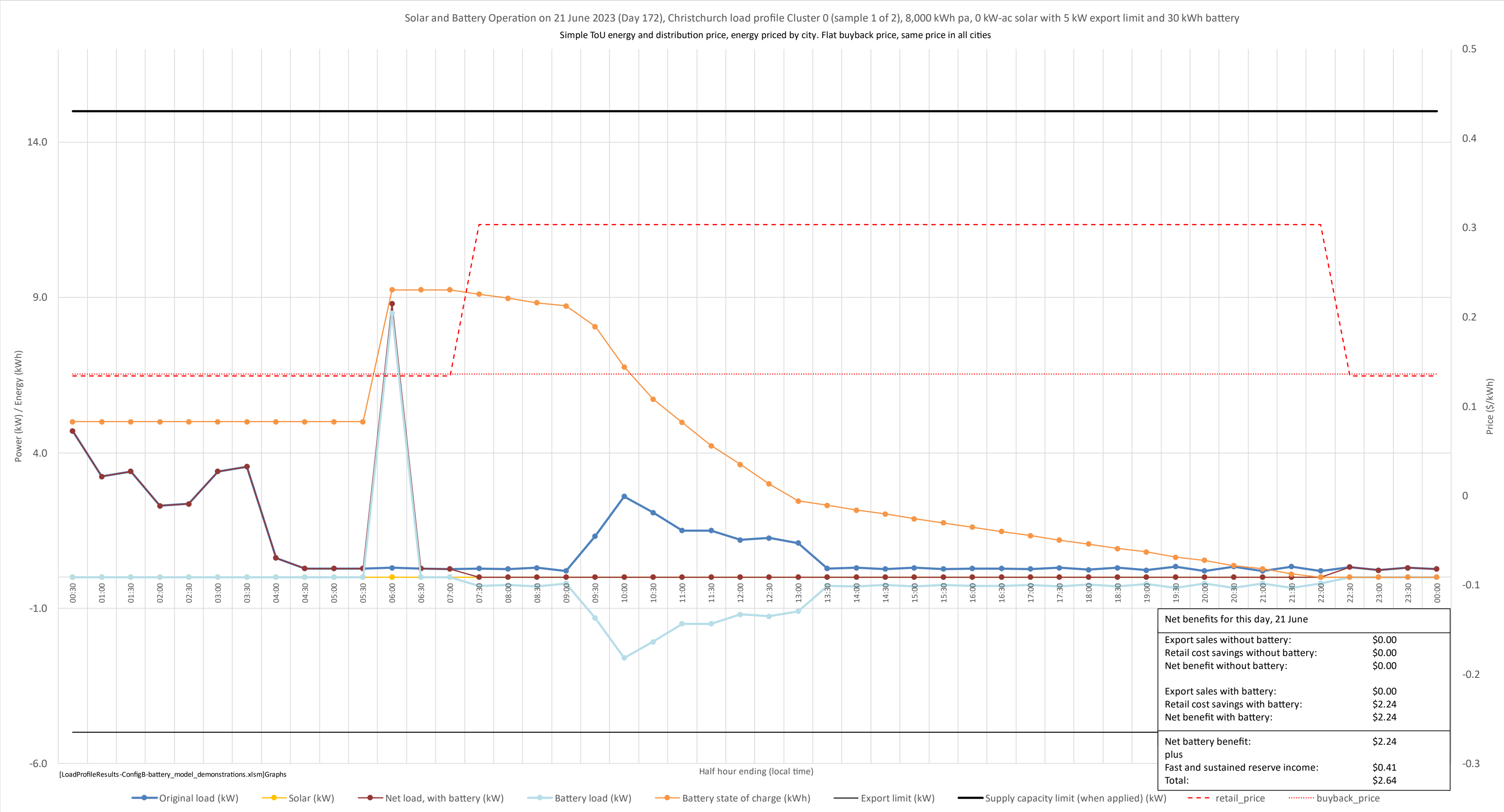

Figure 4: V2G battery operation with a simple time-of-use two-rate price structure with flat buyback price and no solar, 21 June.

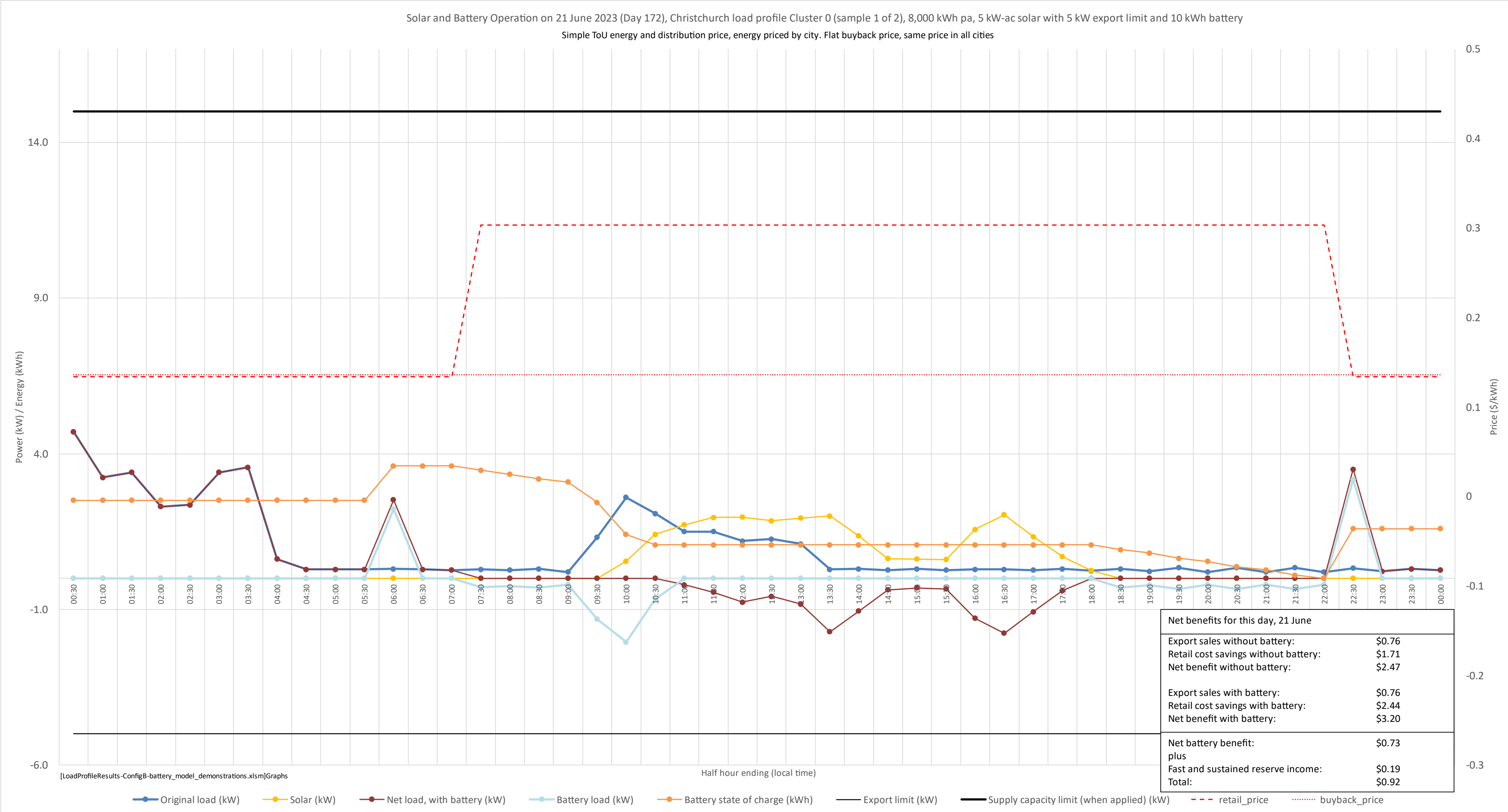

Figure 5: Battery operation with a simple time-of-use two-rate price structure with flat buyback price and 5 kW-ac solar with DC:AC ratio of 1.2, 21 June.