Optimisation of Behind the Meter DER Generation Assets within Network Constraints: A Roadmap to Successful DR Program (Project 69)

Work Package-3 Final Report

Monash University, Melbourne

August 2023

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Acknowledgements: The project team wishes to acknowledge the data support and the feedback received from the AGL team.

Executive Summary

Demand response (DR) programs can benefit electricity consumers, distribution network service providers (DNSPs), system operators, and the energy market. However, the complexity and characteristics associated with loads connected to customer premises, the utilisation of backup generators for DR, and the baseline calculation process still require considerable research to optimise and further unlock the capabilities of DR programs. The challenges of DR programs are not limited to technical aspects, since there are several non-technical elements to consider when implementing DR programs, such as regulatory policy compliance. C4NET launched this DR research program to use the research expertise of member universities to solve some of the industry challenges concerning DR schemes and accelerate their deployment in electricity networks. This project is expected to produce potential solutions for some DR challenges associated with commercial and industrial (C&I) customers. The project consists of three work packages, and this project report outlines the summary of work completed under work package-3 (WP-3) and recommendations emanating from WP-3.

WP-3 investigates the use of battery energy storage systems (BESSs) in DR programs to benefit C&I customers in terms of electricity cost savings and return on investment (ROI). Under WP-3, standard and BESS trial network tariffs for four DNSPs are reviewed. Four C&I sites are selected, and a BESS optimising algorithm is developed for these C&I sites. Simulation studies are conducted to explore how selected sites are impacted if they are provided with different BESS sizes and charged under considered C&I tariff structures. Five financial scenarios are executed for each C&I customer with different BESS sizes, which include the consideration of unvaried existing tariff structures, reduction in tariff structures to receive the target payback period (PBP), reduction in capital expenditure (CapEx) and subsequent operation expenditure (OpEx) to attain the target PBP, increase in the BESS coulomb (C) rating with decreased capacity, and decrease in the BESS C rating with increased capacity. WP-3 also investigates the network impact studies of BESS at C&I sites using a representative distribution network.

This study has drawn the following three general recommendations to increase the uptake of batteries in DR programs:

1) ***Reforming Energy Tariffs for Batteries –***

- From the analyses in this project, it is evident that tariffs designed for batteries, e.g., trial tariffs introduced by Evo Energy, Essential Energy, SA Networks, and AusGrid, have the potential to provide higher benefits for C&I customers in comparison to standard tariffs. Therefore, it is recommended to design specific tariffs for batteries.
- Tariff reforms such as introducing a larger gap between peak and off-peak prices as well as solar soak times could help customers achieve more savings that would ultimately promote higher uptake of batteries.

2) ***Reducing Battery Costs –***

- From the project analyses, the payback period for C&I customers could be long due to the high CapEx and OpEx associated with batteries. Therefore, in order to achieve the targeted payback

period, dedicated grants and incentives to reduce battery deployment costs could be considered. While it is anticipated that batteries will provide various market and network services, the reduction in prices will help to make C&I batteries financially viable.

3) ***Ensuring Network Integrity*** –

- Deployment of a large number of behind-the-meter batteries by C&I customers can potentially result in violations of network constraints, such as voltage or thermal rating. In order to effectively deploy behind-the-meter batteries at C&I facilities while safeguarding the integrity of the network, it is recommended to explore the adoption of concepts such as the dynamic operating envelope (DOE). Insights and learnings from trials such as Project EDGE can be utilised to design and implement DOEs to ensure network integrity in the presence of a large number of behind-the-meter batteries.

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Acronyms and Terminologies

- **AER:** Australian Energy Regulator
- **C&I:** Commercial and Industrial
- **DER:** Distributed Energy Resource
- **DR:** Demand Response
- **PV:** Photovoltaic
- **BESS**: Battery Energy Storage System
- **SOC**: State of Charge
- **DNSP:** Distribution Network Service Provider
- **¢**: Cents
- **kW**: Kilowatt
- **kWh**: Kilowatt Hour
- **AU$**: Australian Dollar
- **ToU**: Time of Use
- **FiT**: Feed in Tariff
- **C Rating:** Coulomb Rating
- **CapEx**: Capital Expenditure
- **OpEx**: Operational Expenditure
- **ROI**: Return on investment
- **PBP**: Payback Period
- **PU**: Per Unit
- **BAU**: Business as Usual

- **Standard Tariff:** The standard network tariff as per business as usual, without considering the uptake of batteries.
- **BESS Trial Tariff:** The network tariff introduced to encourage the uptake of batteries.
- **Peak Period:** The period in which a C&I customer is charged at the peak ToU price.
- **Shoulder Period:** The period in which a C&I customer is charged at the shoulder ToU price.
- **Off-peak Period:** The period in which a C&I customer is charged at the off-peak ToU price.
- **Peak Demand Period:** The period in which a C&I customer is charged at the peak ToU price and also pays a demand charge for the maximum peak demand.
- **Excess Solar:** The difference between on-site solar PV generation and load demand, where solar PV generation is higher than load demand.
- **Unmet Demand:** The difference between load demand and solar PV generation, where load demand is higher than solar PV generation.
- **Solar Charge:** The situation in which a battery is charged from solar PV.
- **Grid Charge:** The situation in which a battery is charged from energy suppliers at the ToU price.

- **Cost Saving:** The amount of money saved by the update of batteries.
- **Battery PBP:** The number of years required to receive battery investment return.

1. Project Overview

RMIT and Monash University were engaged by C4NET to provide a roadmap for successful demand response (DR) programs for commercial and industrial (C&I) customers. In response to the C4NET request and in collaboration with AGL, the RMIT and Monash team proposed a project with three work packages, which are as follows:

- **Work Package-1:** Machine learning for C&I customers' baseline improvement,
- **Work Package-2:** Unlocking the potential of participation of backup generators in DR,
- **Work Package-3:** Identify tariffs that can incentivise the uptake of batteries.

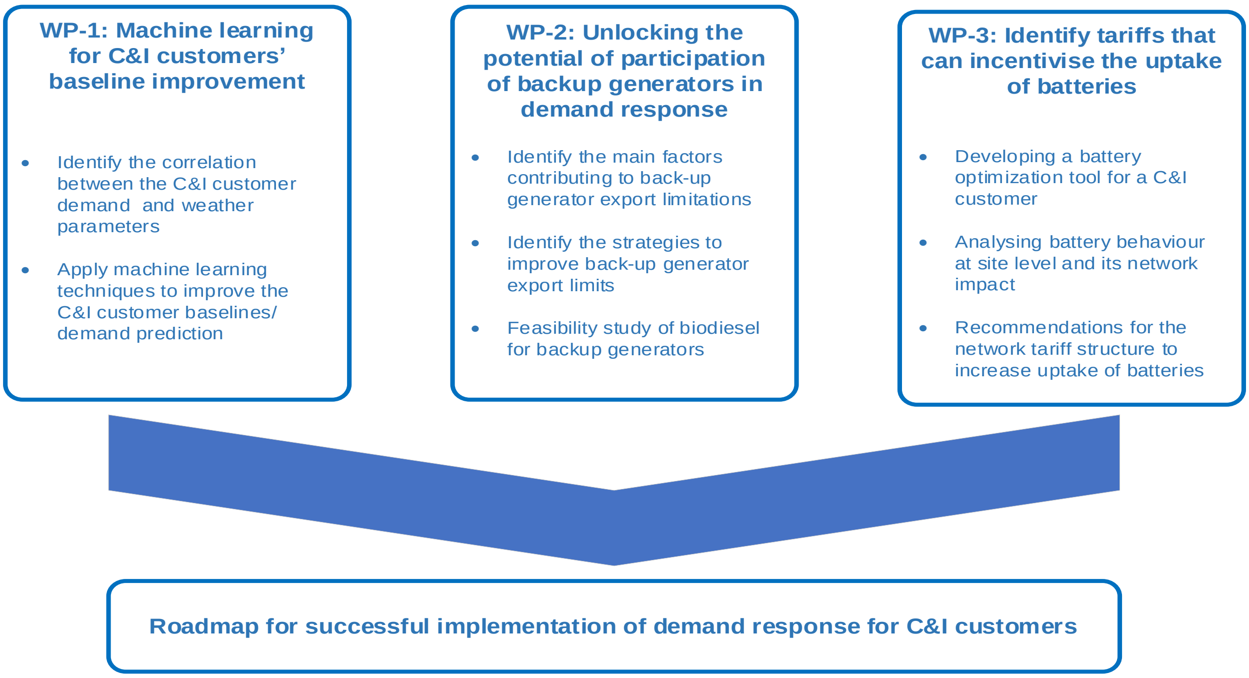


Fig. 1.1. Aims and objectives of project work packages.

The WP-1 will apply machine learning techniques to unlock the potential of demand response schemes, with a particular focus on improving the baselines used in DR. WP-2 will focus on unlocking the potential of using backup generators and other embedded generators of C&I customers in DR programs. It will also explore possible solutions to overcome the regulatory and technical barriers to using backup generators in DR programs. Lastly, WP-3 will explore the role of network tariffs in DR programs, which can incentivise the uptake of batteries.

The project team has engaged with the Victorian distribution network service providers (DNSPs) to understand better the technical and regulatory barriers to deploying backup generators for C&I customers in DR programs, such as water utilities. Moreover, the project team expects to obtain feedback from the Victorian DNSPs on the project outcomes and recommendations.

Finally, this project aims to create a roadmap for successful implementation of DR for C&I customers. It is envisaged that more C&I customers will sign up for the DR programs in the future after implementing the recommendations of the project.

2. Scope of Work Package-3

WP-3 aims to investigate the use of BESS in DR programs to benefit C&I customers in terms of electricity cost savings and ROI. DR is one of the most cost-efficient ways to add flexible capacity to the electricity grid, as adding a peaking plant or gas turbine generator, for example, would cost millions of dollars and take years to recover the investment.

In brief, this study has undertaken the following research activities:

1. Reviewing existing network tariff structures for C&I customers.
2. Selecting a set of network tariff structures in consultation with the AGL.
3. Developing a BESS optimiser for C&I customers.
4. Analysing the financial viability of the developed BESS optimiser under various case studies.
5. Conducting the network deployment assessment of the developed BESS optimiser.
6. Proposing recommendations to increase the uptake of batteries in DR programs.

The rest of the report is organised as follows:

Chapter 3 explains the methodology utilised in WP-3.

Chapter 4 reviews different network tariff structures without and with BESS trials.

Chapter 5 provides an overview of solar PV and load profiles for selected C&I customers.

Chapter 6 provides the functional description of the developed BESS optimiser.

Chapter 7 investigates how C&I sites are benefited by the application of the developed BESS optimiser under considered tariff structures and various financial case studies.

Chapter 8 contains an overview of a representative distribution network and investigates how network voltages and line loading are impacted by the application of the BESS.

Chapter 9 provides recommendations to increase the uptake of batteries in DR programs.

3. Work Package-3 Methodology

The methodology, shown in Fig. 3.1, has been followed in WP-3 to demonstrate the work package objectives.

In the first step, the project team reviewed a number of existing network tariff structures. Then, a set of network tariff structures, namely Evo Energy, Essential Energy, SA Network, and AusGrid tariff structures, were selected in consultation with AGL. In particular, two aspects of these tariff structures were considered: 1) the standard tariff (without BESS trial) and 2) the BESS trial tariff. Next, four selected C&I customers, whose profiles were provided by AGL, were chosen, and the project team developed a BESS optimiser for these customers. Afterwards, a financial viability analysis was conducted by the project team to explore how the consideration of different BESS sizes and network tariff structures can impact C&I customers financially. Specifically, each C&I customer has been tested with five financial scenarios, such as the consideration of unvaried existing tariff structures, reduction in tariff structures to receive the target PBP, reduction in CapEx to attain the target PBP, increase in the BESS C rating with decreased capacity, and decrease in the BESS C rating with increased capacity. Besides, the project team has performed a distribution network compatibility study of the developed BESS optimiser to demonstrate its operational impacts on network voltages and line loading. Finally, after carefully analysing the simulation results, the project team proposed several recommendations to expedite the uptake of batteries in DR programs.

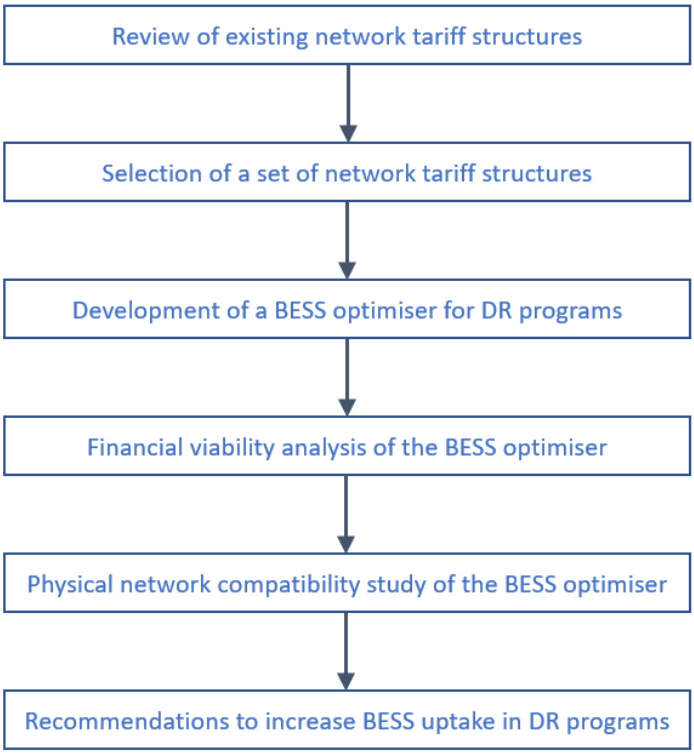


Fig. 3.1. Work package-3 methodology.

4. Review of Existing Network Tariff Structures

Electricity tariff structures are often utilised to evaluate the economic viability of energy transfer to customers-end [1]. For C&I customers, it typically comprises time of use (ToU) charges ─ that include peak, off-peak, and shoulder ToU charges based on the kilowatt-hour (kWh) usage during peak, off-peak, and shoulder periods, demand and capacity charges based on the peak demand recorded within a specified period, e.g., daily, or monthly, and a fixed supply charge (also called a network charge) to recover the costs incurred while transferring energy. Solar photovoltaic (PV) feed in tariff (FiT) is also included in some network tariff structures [2]. In Australia, network tariff structures are reviewed yearly by the Australian Energy Regulator (AER) [3].

The network tariff structures of four DNSPs are selected, namely Evo Energy, Essential Energy, SA Network, and AusGrid. In particular, two aspects of these network tariff structures are considered: 1) standard network tariff (without BESS trial), and 2) BESS trial network tariff. While standard network structures represent the business as usual (BAU) rates assigned for C&I customers, BESS trial network tariff structures denote reduced rates introduced to encourage them to install batteries at their premises [4].

Table 4.1 provides the tariff structure of Evo Energy without and with the BESS trial. According to the standard network tariff, peak (from 7 am to 5 pm), off-peak (from 10 pm to 7 am), and shoulder (from 5 pm to 10 pm), ToU rates are 8.85 ¢/kWh, 3.32 ¢/kWh, and 5.31 ¢/kWh, respectively. The FiT rate, demand charge, capacity charge, and supply charge are capped at 4.1 ¢/kWh, 21.22 ¢/kW/day, 21.22 ¢/kW/day, and 59.818 ¢/day, respectively. While ToU prices, FiT rate, and supply charge remain the same in the BESS trial tariff, both demand charge and capacity charge are reduced to 18.95 ¢/kW/day and 18.29 ¢/kW/day, respectively [5].

Table 4.1. Tariff structure of Evo Energy without and with BESS trial [5].

Tariff component	Without BESS trial	With BESS trial
ToU prices	8.85 ¢c/kWh (peak: 7 am to 5 pm) 3.32 ¢/kWh (off-peak: 10 pm to 7 am) 5.31 ¢/kWh (shoulder: 5 pm to 10 pm)	8.85 ¢/kWh (peak: 7 am to 5 pm) 3.32 ¢/kWh (off-peak: 10 pm to 7 am) 5.31 ¢/kWh (shoulder: 5 pm to 10 pm)
FiT rate	4.1 ¢/kWh	4.1 ¢/kWh
Demand charge	21.22 ¢/kW/day	18.95 ¢/kW/day
Capacity charge	21.22 ¢/kW/day	18.29 ¢/kW/day
Supply charge	59.818 ¢/day	59.818 ¢/day

The tariff structure of Essential Energy without and with the BESS trial is illustrated in Table 4.2. In both cases, peak (from 5 pm to 8 pm), off-peak (from 10 pm to 7 am), and shoulder (from 8 pm to 10 pm, from 7 am to 10 am, and 2 pm to 5 pm) rates are considered as 4.41 ¢/kWh, 2.785 ¢/kWh, and 3.79 ¢/kWh, respectively. However, the BESS trial tariff allows C&I customers to charge BESS from the power grid (which also includes load demand consumption) free of charge between 10 am and 2 pm while without the BESS trial, the rate is 4.195 ¢/kWh. Besides, both tariffs consider the same rates for

FiT and supply charge, figuring at 4.76 ¢/kWh and 15.808 AU$/day, respectively. Furthermore, three rates of demand charges are applied in both tariffs (rates are the same without and with the BESS trial) throughout a day. For instance, peak, off-peak, and shoulder demand charges (subject to the same periods as ToU) are capped at 33.634 ¢/kW/day, 7.585 ¢/kW/day, and 30.430 ¢/kW/day, respectively.

Table 4.2. Tariff structure of Essential Energy without and with BESS trial [6].

Tariff component	Without BESS trial	With BESS trial
ToU prices	4.41 ¢/kWh (peak: 5 pm to 8 pm) 2.785 ¢/kWh (off-peak: 10 pm to 7 am) 3.79 ¢/kWh (shoulder: 8 pm to 10 pm and 7 am to 5 pm)	4.41 ¢/kWh (peak: 5 pm to 8 pm) 2.785 ¢/kWh (off-peak: 10 pm to 7 am) 3.79 ¢/kWh (shoulder: 8 pm to 10 pm 7 am to 10 am, and 2pm to 5 pm)
FiT rate	4.76 ¢/kWh	4.76 ¢/kWh
Demand charge	33.634 ¢/kW/day (peak) 7.585 ¢/kW/day (off-peak) 30.430 ¢/kW/day (shoulder)	33.634 ¢/kW/day (peak) 7.585 ¢/kW/day (off-peak) 30.430 ¢/kW/day (shoulder)
Supply charge	15.808 AU$/day	15.808 AU$/day

Table 4.3. Tariff structure of SA Network without and with BESS trial [7, 8].

Tariff component	Without BESS trial	With BESS trial
ToU prices	5.33 ¢/kWh (peak: 7 am to 9 pm) 3.9 ¢/kWh (off-peak: 9 pm to 7 am)	5.33 ¢/kWh (peak: 7 am to 9 pm) 3.9 ¢/kWh (off-peak: 9 pm to 7 am)
FiT rate	5 ¢/kWh	5 ¢/kWh
Demand charge	9.589 c/kW (5 pm to 9 pm) 85.855 ¢/day (fixed)	4.795 ¢/kWh (5 pm to 9 pm) 42.927 ¢/day (fixed)
Supply charge	2.739 AU$/day	2.739 AU$/day

The tariff structure of the SA network without and with the BESS trial is depicted in Table 4.3. In this tariff structure (with and without the BESS trial), C&I customers are charged at 5.33 ¢/kWh and 3.9 ¢/kWh during peak period (from 7 am to 9 pm) and off-peak periods (from 9 pm to 7 am), respectively. The same supply charge and FiT rate are also applied with and without the BESS trial, figuring at 2.739 AU$/day and 5 ¢/kWh, respectively. Besides, the SA network tariff structure contains two components of demand charge, such as: fixed (applicable everyday) and varying (applicable from 5 pm to 9 pm). Each of the demand charge component is cut down by 50% in the BESS trial tariff [7, 8].

Table 4.4 demonstrates the tariff structure of AusGrid. In the standard tariff structure, 15.33 ¢/kWh, 2.078 ¢/kWh, and 4.52 ¢/kWh are imposed on C&I customers during peak (from 2 pm to 8 pm), off-peak (from 10 pm to 7 am), and shoulder (from 7 am to 2 pm, and from 8 pm to 10 pm) periods, respectively. Also, C&I customers pay 4.769 ¢/kW/day and 146.973 ¢/day as demand and supply charges. They receive FiT at 5 ¢/kWh for excess solar export. On the contrary, in the community BESS trail tariff, 1.6 ¢/kWh and 141 ¢/kWh are added, along with the same standard ToU prices, for charging BESS during off-peak and peak periods, respectively. Moreover, 0.75 ¢/kWh is paid to the C&I

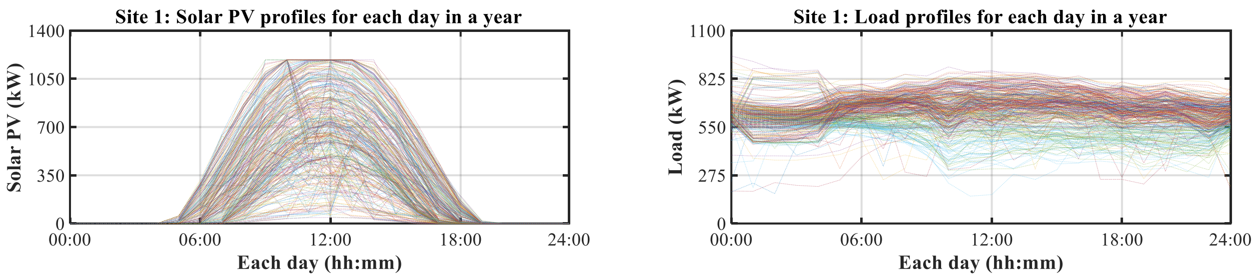
customers for exporting BESS discharge into the power grid during peak hours while completely calling off the demand charge and keeping the supply charge unvaried [9, 10].

Table 4.4. Tariff structure of AusGrid without and with BESS trial [9, 10].

Tariff component	Without BESS trial	With BESS trial
ToU prices	15.33 ¢/kWh (peak: 2pm to 8 pm) 2.078 ¢/kWh (off-peak: 10 pm to 7 am) 4.52 ¢/kWh (shoulder: 7 am to 2 pm and 8 pm to 10 pm)	15.33 ¢/kWh (peak: 2pm to 8 pm) 2.078 ¢/kWh (off-peak: 10 pm to 7 am) 4.52 ¢/kWh (shoulder: 7 am to 2 pm and 8 pm to 10 pm) 1.6 ¢/kWh (off-peak charge) 141 ¢/kWh (peak demand charge)
FiT rate	5 ¢/kWh	5 ¢/kWh 0.75 ¢/kWh (peak discharge)
Demand charge	4.769 ¢/kW/day	0 ¢/kW/day
Supply charge	146.973 ¢/day	146.973 ¢/day

5. Overview of Solar PV and Load Profiles of Representative C&I Customers

Four different C&I customers are selected and labelled as Site 1, Site 2, Site 3, and Site 4, respectively. Site 1 and Site 2 indicate a cold storage warehouse and a manufacturing plant in the Melbourne metropolitan area, respectively. Whereas Site 3 and Site 4 represent a shopping centre and a supermarket in regional Victoria, respectively.

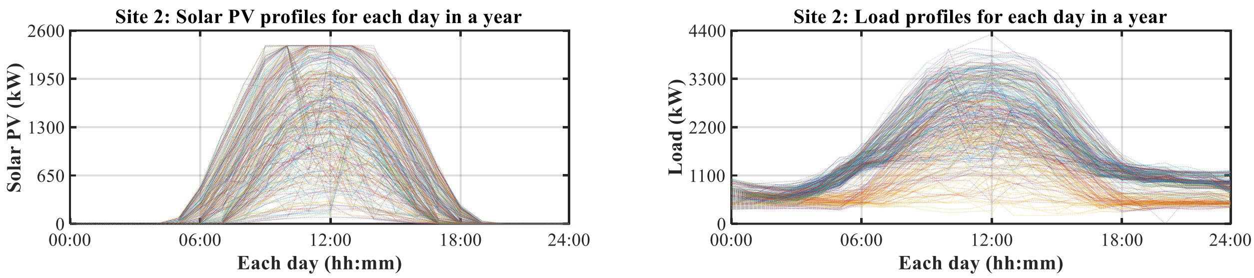


(a) (b)

Fig. 5.1. Solar PV and load profiles of Site 1.

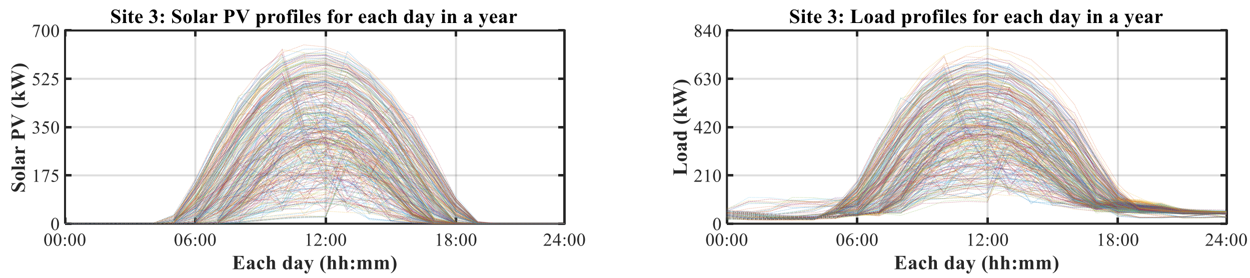
Each C&I customer is equipped with a solar PV system. The rated solar PV capacities of Site 1, Site 2, Site 3, and Site 4 are 1500 kW, 3000 kW, 745 kW, and 400 kW, respectively. The daily solar PV profiles of them for a given year are demonstrated in Fig. 5.1(a), Fig. 5.2(a), Fig. 5.3(a), and Fig. 5.4(a), respectively. As illustrated in these figures, all sites have solar PV generation between around 5:30 am and 6:30 pm. Site 2 has the most solar PV generation, while Site 4 has the least.

Each day's load profiles, over the course of a year, of Site 1, Site 2, Site 3, and Site 4 are provided in Fig. 5.1(b), Fig. 5.2(b), Fig. 5.3(b), and Fig. 5.4(b), respectively. These figures illustrate that Site 2 has the maximum load demand, followed by Site 1, Site 3, and Site 4.



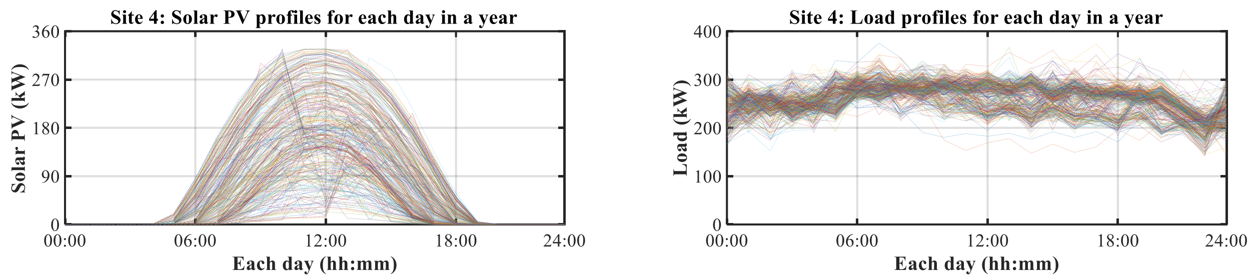
(a) (b)

Fig. 5.2. Solar PV and load profiles of Site 2.



(a) (b)

Fig. 5.3. Solar PV and load profiles of Site 3.



(a) (b)

Fig. 5.4. Solar PV and load profiles of Site 4.

6. Development of a Battery Optimiser for C&I Customers

A BESS optimiser controls charging and discharging operations of the battery based on the tariff structure to benefit battery owners [11]. Three inputs are considered to operate the BESS, such as: solar PV and load demand profiles of C&I customers, BESS specifications ─ that include kWh capacity, kW power, charging and discharging efficiencies, state-of-charge (SOC), CapEx, operational expenditure (OpEx), and tariff structures. The developed BESS optimiser generates three main outputs, namely optimum charging and discharging schedules, annual electricity cost savings estimation, and ROI with subsequent PBP analysis.

Fig 5.1 demonstrates the flowchart for operating BESS in six different steps. In **Step 1**, the solar PV and load demand profiles of C&I customers are recorded to determine their net profile. If the net profile is zero, i.e., solar PV is equal to the load demand, then a BESS customer becomes solar PV-energy sufficient, i.e., no BESS charging/discharging is required. If the net profile is not zero, then two cases can be possible:

- The net profile is negative, i.e., solar PV generation is higher than load demand. The difference between solar PV generation and load demand is termed as excess solar, by which BESS can be charged in **Step 2**.
- The net profile is positive, i.e., load demand is higher than solar PV generation. The difference between load demand and solar PV generation is termed unmet demand, which can be satisfied by the BESS discharge in **Step 5.**

In **Step 2**, excess solar is used to charge BESS, subject to the availability of excess solar and BESS constraints, including kW and kWh ratings, SOC, and charging efficiency. If excess solar is more than available BESS charging capacity, the extra amount (excess solar – available BESS charging capacity) is exported to the grid at the FiT rate in **Step 3**. However, if the opposite is true, i.e., BESS has more charging capacity and excess solar, the deficient amount (available BESS charging capacity – excess solar) is taken from the grid at the off-peak rate in the next step (**Step 4).** Note that grid charging is scheduled based on peak and shoulder demand requirements to avoid unnecessary BESS degradation.

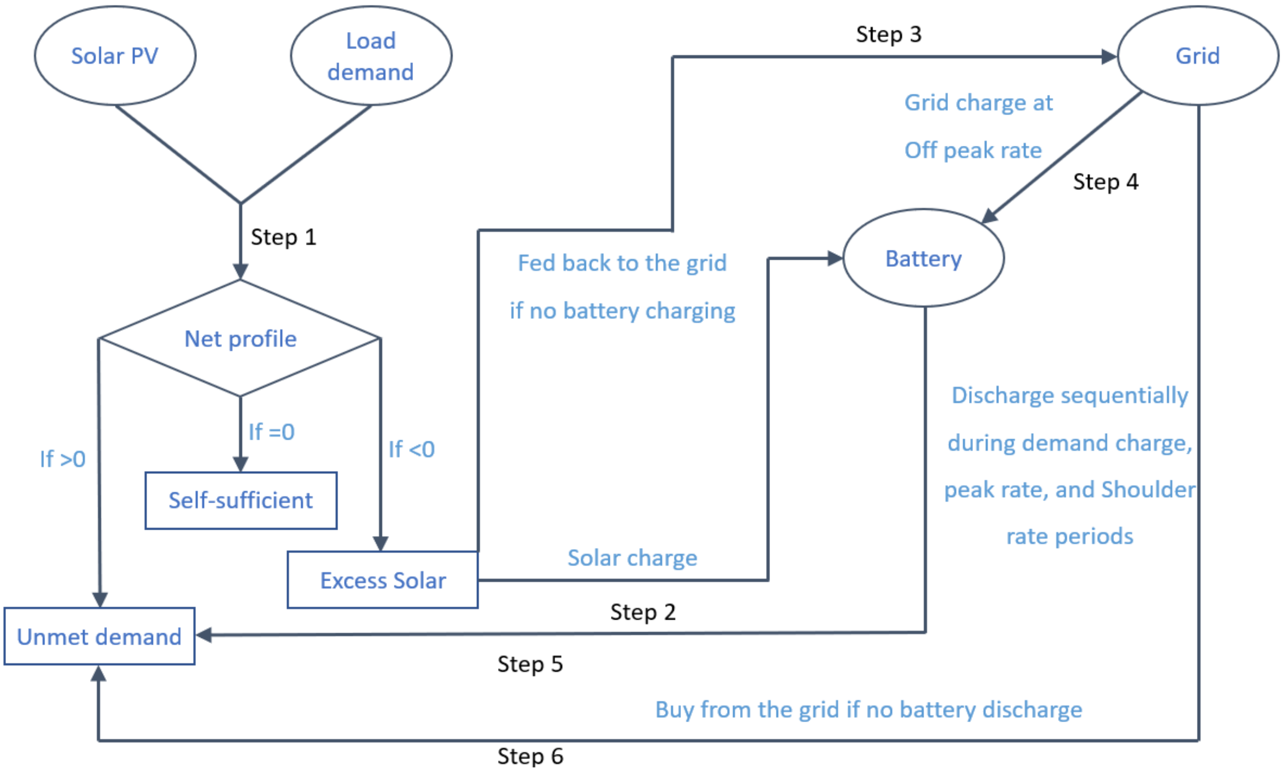


Fig. 6.1. Flowchart of optimising BESS operation.

As for managing unmet demand, firstly, BESS discharge is used in **Step 5**. The BESS is directed to discharge sequentially in accordance with the demand charge, peak rate, and shoulder rate periods, conforming to the considered tariff structure, to reduce the electricity purchasing cost and PBP optimally. BESS discharge is also bounded by the available BESS discharge capacity, SOC, and discharging efficiency. If available BESS discharge capacity is lower than unmet demand, the deficient amount (unmet demand - available BESS discharge capacity) is imported from the grid at the ToU rate in **Step 6**.

Using the BESS charge and discharge, grid export and import, and BESS trial tariffs, the BESS trial electricity cost of each C&I customer is calculated and compared with the standard electricity cost, which is calculated considering no BESS charge and discharge and by applying standard tariffs. The difference between standard and BESS trial electricity costs is termed the electricity cost savings. Adopting the mathematical relation between the cost saving, BESS degradation cost, CapEx, and OpEx, the ROI and PBP are computed. The detailed mathematical formulations are provided in the Appendix.

7. Financial Case Studies for C&I Customers with Battery

Five financial scenarios are considered for each C&I customer under different tariff structures, namely Evo Energy, Essential Energy, SA Network, and AusGrid tariff structures and BESS sizes. These scenarios include the consideration of unvaried existing tariff structures, reduction in tariff structures to receive the target PBP, reduction in CapEx and subsequent OpEx to attain the target PBP, increase in the BESS C rating with decreased capacity, and decrease in the BESS C rating with increased capacity. In total, forty financial case studies are demonstrated to assess the economic viability of the BESS for C&I customers. An overview of these case studies is illustrated in Table 7.1.

Table 7.1. Overview of financial case studies.

Financial case study	Site No.	Tariff Structure	BESS Size	C rating
Case Study F1	1	Unvaried	200 kW, 520 kWh	0.39
Case Study F2	1	Unvaried	500 kW, 1040 kWh	0.48
Case Study F3	1	Reduced tariff	200 kW, 520 kWh	0.39
Case Study F4	1	Reduced tariff	500 kW, 1040 kWh	0.48
Case Study F5	1	Reduced CapEx	200 kW, 520 kWh	0.39
Case Study F6	1	Reduced CapEx	500 kW, 1040 kWh	0.48
Case Study F7	1	Increase in C rating	200 kW, 252 kWh	0.79
Case Study F8	1	Increase in C rating	500 kW, 505 kWh	0.99
Case Study F9	1	Decrease in C rating	200 kW, 1040 kWh	0.19
Case Study F10	1	Decrease in C rating	500 kW, 1560 kWh	0.32
Case Study F11	2	Unvaried	200 kW, 520 kWh	0.39
Case Study F12	2	Unvaried	500 kW, 1040 kWh	0.48
Case Study F13	2	Reduced tariff	200 kW, 520 kWh	0.39
Case Study F14	2	Reduced tariff	500 kW, 1040 kWh	0.48
Case Study F15	2	Reduced CapEx	200 kW, 520 kWh	0.39
Case Study F16	2	Reduced CapEx	500 kW, 1040 kWh	0.48
Case Study F17	2	Increase in C rating	200 kW, 252 kWh	0.79
Case Study F18	2	Increase in C rating	500 kW, 505 kWh	0.99
Case Study F19	2	Decrease in C rating	200 kW, 1040 kWh	0.19
Case Study F20	2	Decrease in C rating	500 kW, 1560 kWh	0.32

Case Study F21	3	Unvaried	200 kW, 520 kWh	0.39
Case Study F22	3	Unvaried	500 kW, 1040 kWh	0.48
Case Study F23	3	Reduced tariff	200 kW, 520 kWh	0.39
Case Study F24	3	Reduced tariff	500 kW, 1040 kWh	0.48
Case Study F25	3	Reduced CapEx	200 kW, 520 kWh	0.39
Case Study F26	3	Reduced CapEx	500 kW, 1040 kWh	0.48
Case Study F27	3	Increase in C rating	200 kW, 252 kWh	0.79
Case Study F28	3	Increase in C rating	500 kW, 505 kWh	0.99
Case Study F29	3	Decrease in C rating	200 kW, 1040 kWh	0.19
Case Study F30	3	Decrease in C rating	500 kW, 1560 kWh	0.32
Case Study F31	4	Unvaried	200 kW, 520 kWh	0.39
Case Study F32	4	Unvaried	500 kW, 1040 kWh	0.48
Case Study F33	4	Reduced tariff	200 kW, 520 kWh	0.39
Case Study F34	4	Reduced tariff	500 kW, 1040 kWh	0.48
Case Study F35	4	Reduced CapEx	200 kW, 520 kWh	0.39
Case Study F36	4	Reduced CapEx	500 kW, 1040 kWh	0.48
Case Study F37	4	Increase in C rating	200 kW, 252 kWh	0.79
Case Study F38	4	Increase in C rating	500 kW, 505 kWh	0.99
Case Study F39	4	Decrease in C rating	200 kW, 1040 kWh	0.19
Case Study F40	4	Decrease in C rating	500 kW, 1560 kWh	0.32

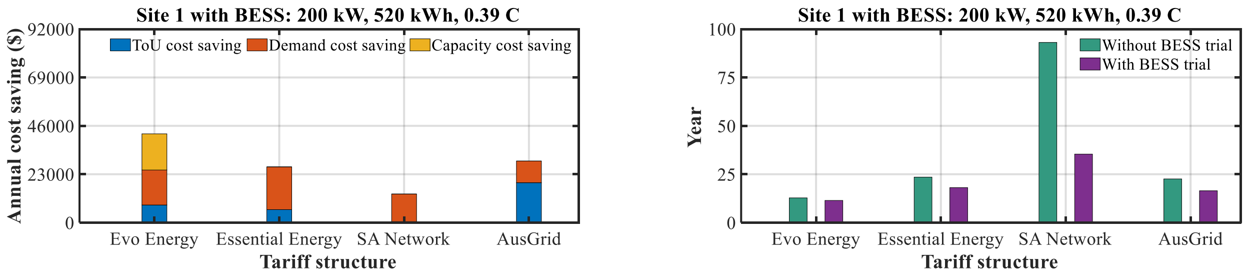
Table 7.2. Overall costs associated with different BESS sizes.

BESS size	**CapEx (AU$/kWh)**	**OpEx (% of CapEx)**	**Cost**
BESS: 200 kW, 520 kWh, 0.39 C	860	1%	451672 AU$
BESS: 500 kW, 1040 kWh, 0.48 C	860	1%	903344 AU$
BESS: 200 kW, 252 kWh, 0.79 C	1100	1%	279972 AU$
BESS: 500 kW, 505 kWh, 0.99 C	1080	1%	550854 AU$
BESS: 200 kW, 1040 kWh, 0.19 C	760	1%	798304 AU$
BESS: 500 kW, 1560 kWh, 0.32 C	790	1%	1244724 AU$

The CapEx of BESS: 200 kW, 520 kWh, 0.39 C; BESS: 500 kW, 1040 kWh, 0.48 C; BESS: 200 kW, 252 kWh, 0.79 C; BESS: 500 kW, 505 kWh, 0.99 C; BESS: 200 kW, 1040 kWh, 0.19 C; and BESS: 500 kW, 1560 kWh, 0.32 C are 860 AU$/kWh; 860 AU$/kWh; 1100 AU$/kWh; 1080 AU$/kWh; 760 AU$/kWh; and 790 AU$/kWh, respectively. The OpEx is 1% of the CapEx. The overall costs associated with different BESS sizes are depicted in Table 7.2.

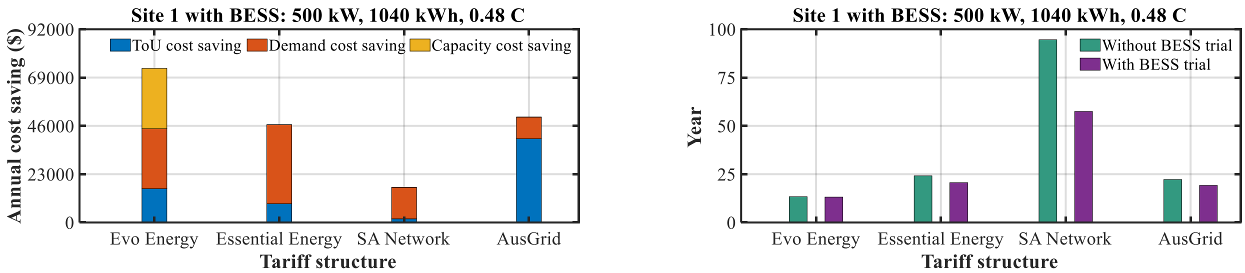
7.1. Financial Case Studies for Site 1

In *Case Study F1*, Site 1 is provided with a BESS size of 200 kW, 520 kWh, and 0.39 C. The cost savings ─ calculated from the electricity cost differences between the consideration of BESS (charged at the BESS trial tariff) and without BESS (charged at the standard tariff), and the PBPs of Site 1 under the considered tariff structures without any variation in existing rates are depicted in Fig. 7.1(a) and Fig. 7.1(b), respectively. As is observed from these figures, the Evo Energy tariff structure is more profitable for Site 1, resulting in a lower PBP compared to the Essential Energy, SA Network, and AusGrid tariff structures. Also, PBPs with the BESS trial tariff are always lower than those with the standard (without the BESS trial) tariff, indicating the BESS trial tariff is beneficial for Site 1.



(a) (b)

Fig. 7.1. Cost saving and PBP analysis of Site 1 considering unvaried tariff structure with BESS: 200 kW, 520 kWh, 0.39 C (Case Study F1).

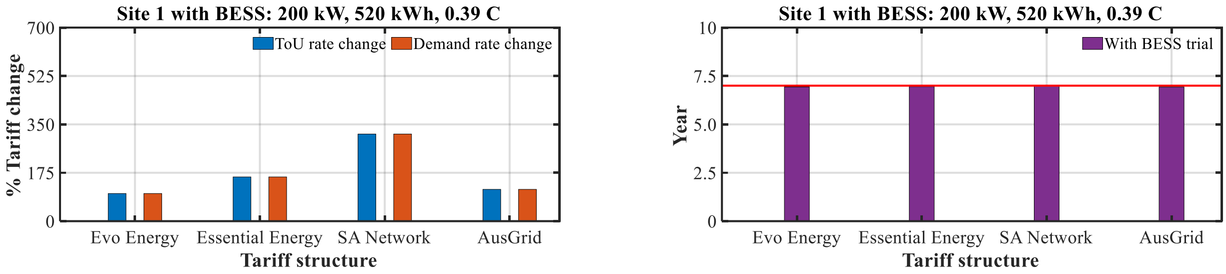


(a) (b)

Fig. 7.2. Cost saving and PBP analysis of Site 1 considering unvaried tariff structure with BESS: 500 kW, 1040 kWh, 0.48 C (Case Study F2).

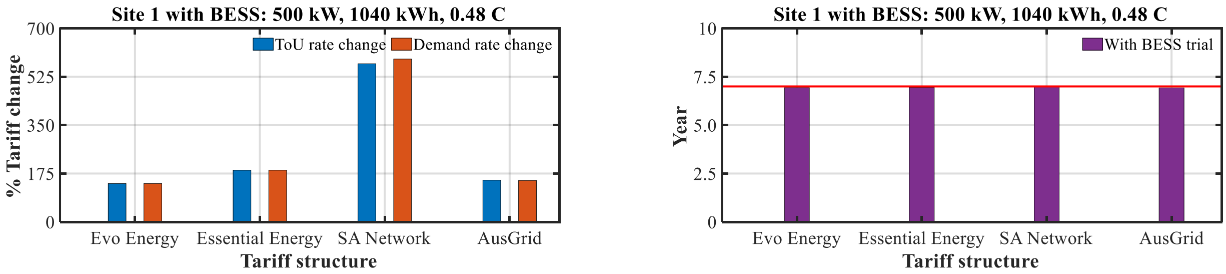
Case Study F2 is similar to *Case Study F1* except for the consideration of a higher BESS size of 500 kW, 1040 kWh, and 0.48 C. According to Fig. 7.2(a), it is evident that cost savings increase with an increase in BESS size for Site 1. However, PBP also increases, subject to the CapEx and OpEx of the considered BESS. The PBP increase of Site 1 is captured in Fig. 7.2(b).

To keep the PBP of Site 1 within the target 7 years (see Fig. 7.3(b) and Fig. 7.4(b)), based on *Case Study F3* and *Case Study F4*, Evo Energy tariff rates need to be decreased between 100% (see Fig. 7.3(a)) and 139% (see Fig. 7.4(a)). The PBP of Site 1 can also be kept within the target 7 years by reducing the CapEx and subsequent OpEx. According to Fig. 7.5(a) and Fig. 7.6(a), CapEx needs to be decreased between 40% and 50%, respectively, with Evo Energy tariff structure to achieve the target PBP (see Fig. 7.5(b) and Fig. 7.6(b)).



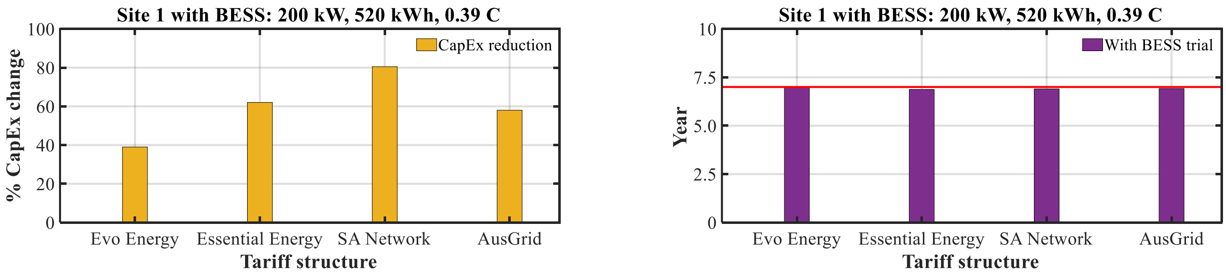
(a) (b)

Fig. 7.3. Cost saving and PBP analysis of Site 1 considering reduction in tariff structure with BESS: 200 kW, 520 kWh, 0.39 C (Case Study F3).



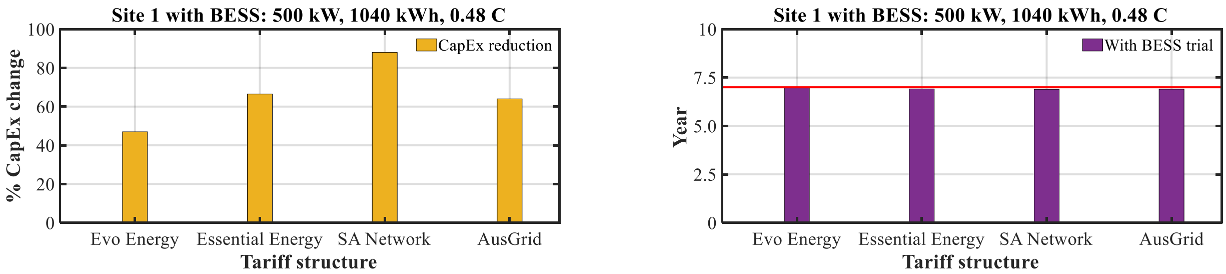
(a) (b)

Fig. 7.4. Cost saving and PBP analysis of Site 1 considering reduction tariff structure with BESS: 500 kW, 1040 kWh, 0.48 C (Case Study F4).



(a) (b)

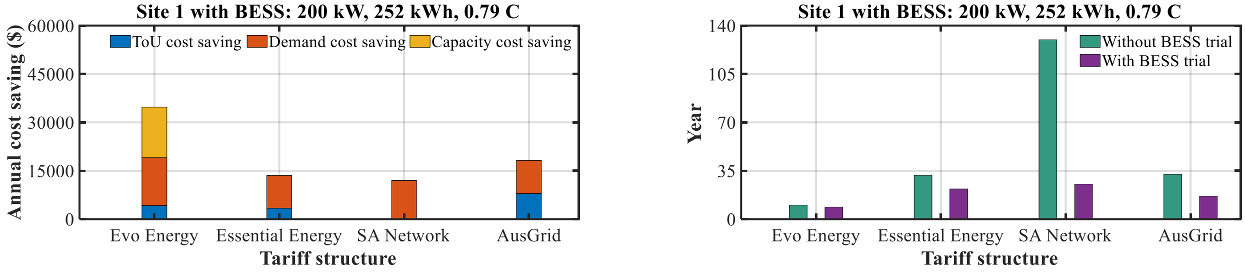
Fig. 7.5. Cost saving and PBP analysis of Site 1 considering reduction in CapEx with BESS: 200 kW, 520 kWh, 0.39 C (Case Study F5).



(a) (b)

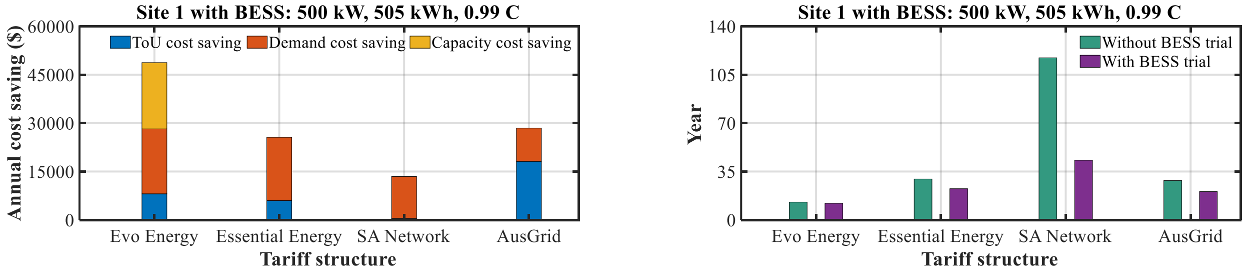
Fig. 7.6. Cost saving and PBP analysis of Site 1 considering reduction in CapEx with BESS: 500 kW, 1040 kWh, 0.48 C (Case Study F6).

Case Study F7 and *Case Study F8* deal with the increase in the BESS C ratings, i.e., from 0.39 C to 0.79 C and from 0.48 C to 0.99 C, respectively, while keeping the BESS kW ratings unchanged, i.e., 200 kW and 500 kW.



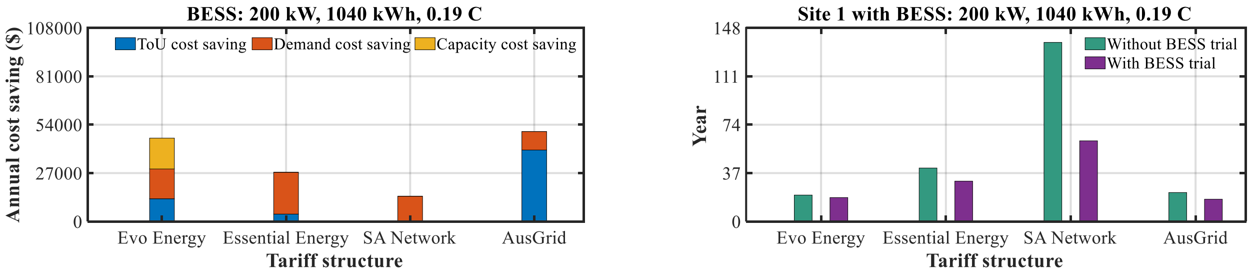
(a) (b)

Fig. 7.7. Cost saving and PBP analysis of Site 1 considering increase in C rating with BESS: 200 kW, 252 kWh, 0.79 C (Case Study F7).



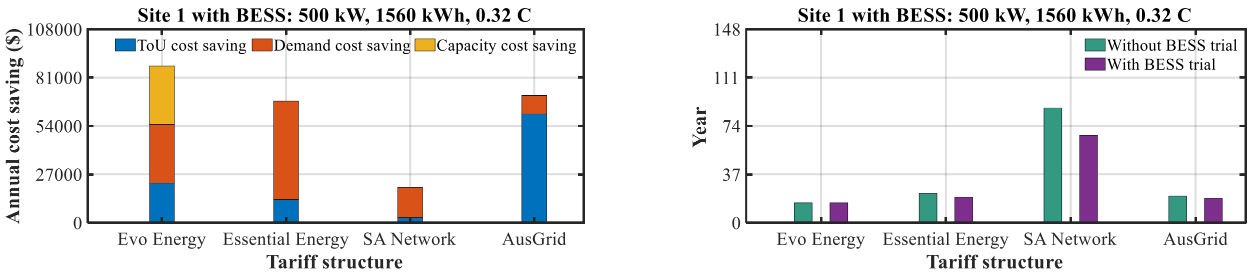
(a) (b)

Fig. 7.8. Cost saving and PBP analysis of Site 1 considering increase in C rating with BESS: 500 kW, 505 kWh, 0.99 C (Case Study F8).



(a) (b)

Fig. 7.9. Cost saving and PBP analysis of Site 1 considering decrease in C rating with BESS: 200 kW, 1040 kWh, 0.19 C (Case Study 9).



(a) (b)

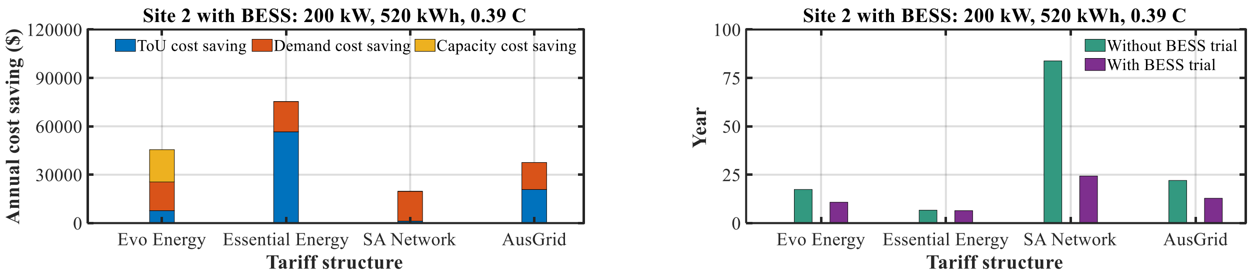
Fig. 7.10. Cost saving and PBP analysis of Site 1 considering decrease in C rating with BESS: 500 kW, 1560 kWh, 0.32 C (Case Study F10).

The cost savings of Site 1 in *Case Study F7* and *Case Study F8* are displayed in Fig. 7.7(a) and Fig. 7.8(a), respectively. Fig. 7.7(b) and Fig. 7.8(b) show the PBPs, respectively. Based on these figures, cost savings are decreased compared to *Case Study F1* because of the lesser BESS charging and discharging caused by the reduced BESS kWh capacities.

In contrast, the decrease in the BESS C ratings, i.e., from 0.39 C to 0.19 C and from 0.48 C to 0.32 C, while keeping the BESS kW ratings unchanged, i.e., 200 kW and 500 kW, are demonstrated in *Case Study F9* and *Case Study F10*, respectively. Fig. 7.9(a) and Fig. 7.10(a) exhibit the cost savings of Site 1, while PBPs are captured in Fig. 7.9(b) and Fig. 7.10(b), respectively. These figures suggest that cost savings are increased in comparison with *Case Study F1* due to higher BESS charging and discharging capacities.

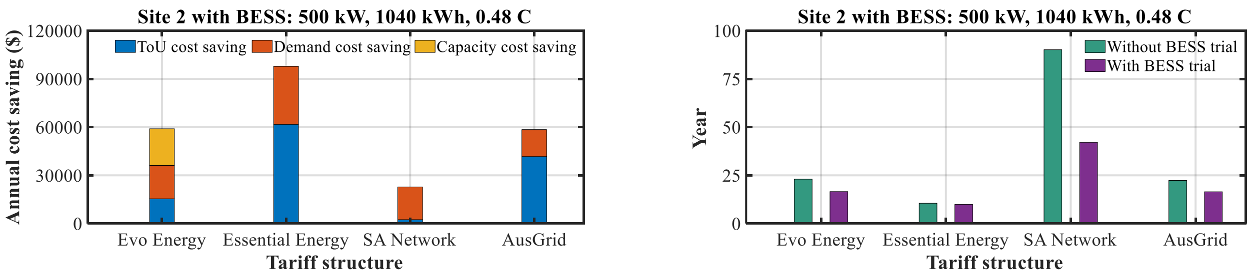
7.2. Financial Case Studies for Site 2

In *Case Study F11*, Site 2 is provided with a BESS size of 200 kW, 520 kWh, and 0.39 C. The cost savings and PBPs of Site 2 under considered tariff structures without any variation in existing rates are depicted in Fig. 7.11(a) and Fig. 7.11(b), respectively. As is noticed from these figures, the Essential Energy tariff structure is more profitable for Site 2, resulting in a lower PBP compared to Evo Energy, SA Network, and AusGrid tariff structures. Also, PBPs with the BESS trial tariff are always lower than those with the standard (without the BESS trial) tariff, indicating the BESS trial tariff is beneficial for Site 2, similar to Site 1.



(a) (b)

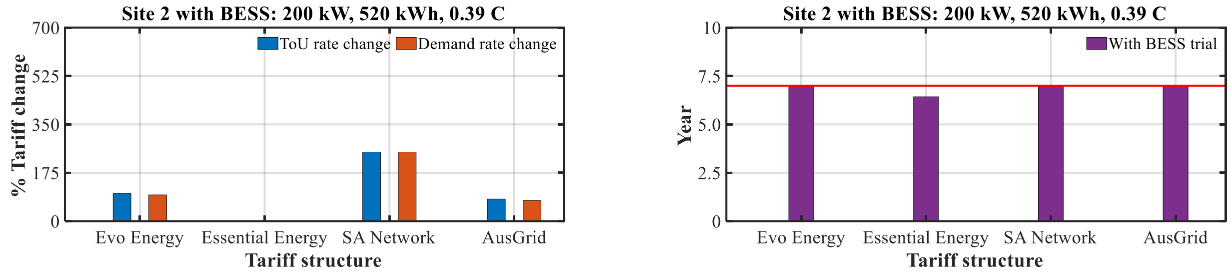
Fig. 7.11. Cost saving and PBP analysis of Site 2 considering unvaried tariff structure with BESS: 200 kW, 520 kWh, 0.39 C (Case Study F11).



(a) (b)

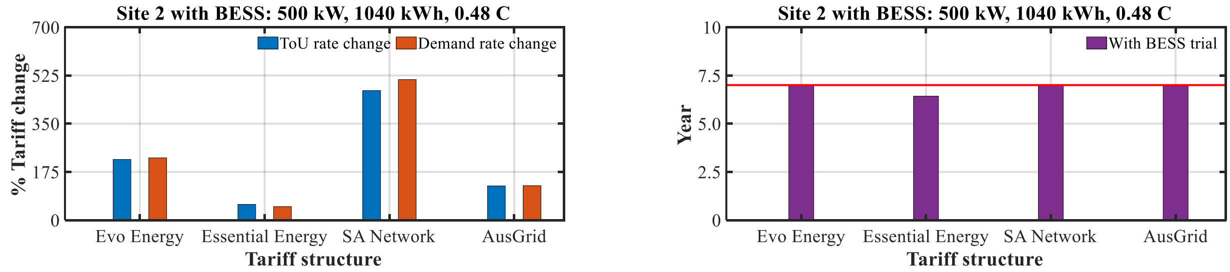
Fig. 7.12. Cost saving and PBP analysis of Site 2 considering unvaried tariff structure with BESS: 500 kW, 1040 kWh, 0.48 C (Case Study F12).

Case Study F12 is similar to *Case Study F11* except for the consideration of a higher BESS size of 500 kW, 1040 kWh, and 0.48 C. According to Fig. 7.12(a), it is evident that cost savings increase with an increase in BESS size for Site 2 (similar to Site 1). However, PBP also increases, subject to the CapEx and OpEx of the considered BESS. The PBP increase of Site 2 is captured in Fig. 7.12(b).



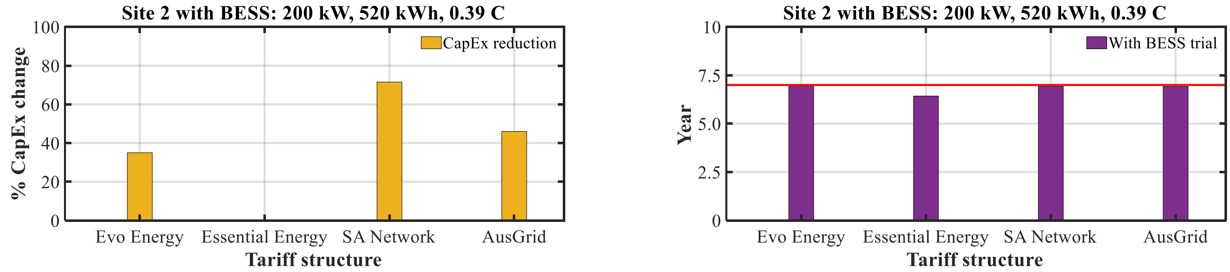
(a) (b)

Fig. 7.13. Cost saving and PBP analysis of Site 2 considering reduction in tariff structure with BESS: 200 kW, 520 kWh, 0.39 C (Case Study F13).



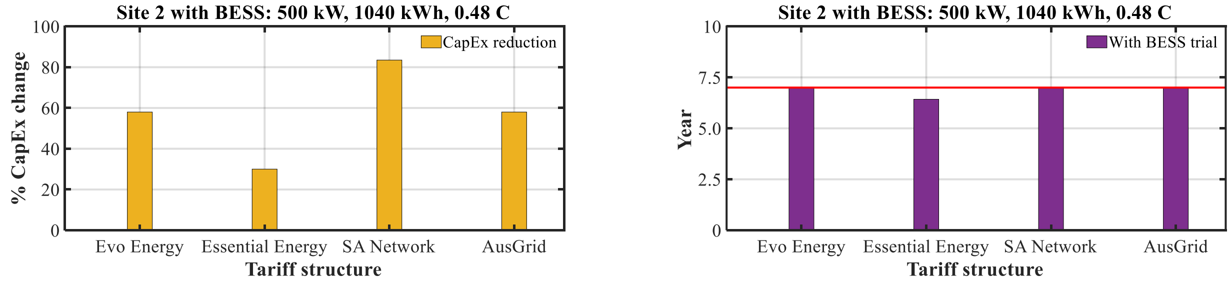
(a) (b)

Fig. 7.14. Cost saving and PBP analysis of Site 2 considering reduction tariff structure with BESS: 500 kW, 1040 kWh, 0.48 C (Case Study F14).



(a) (b)

Fig. 7.15. Cost saving and PBP analysis of Site 2 considering reduction in CapEx with BESS: 200 kW, 520 kWh, 0.39 C (Case Study F15).

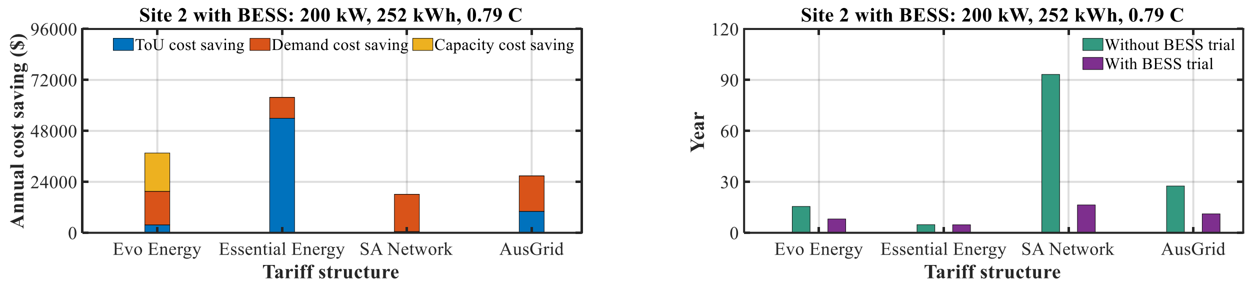


(a) (b)

Fig. 7.16. Cost saving and PBP analysis of Site 2 considering reduction in CapEx with BESS: 500 kW, 1040 kWh, 0.48 C (Case Study F16).

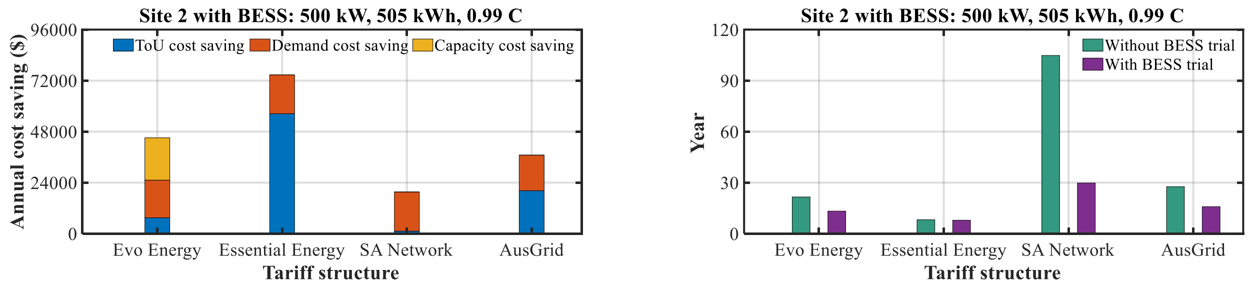
To keep the PBP of Site 2 within the target 7 years (see Fig. 7.13(b) and Fig. 7.14(b)), based on *Case Study F13* and *Case Study F14*, Essential Energy tariff rates need to be decreased between 0% (see Fig.

7.13(a)) and 60% (see Fig. 7.14(a)). The PBP of Site 2 can also be kept within the target 7 years by reducing the CapEx and subsequent OpEx. According to Fig. 7.15(a) and Fig. 7.16(a), CapEx needs to be decreased between 0% and 30% (as per *Case Study F15* and *Case Study F16)*, respectively, with the EvoEnergy tariff structure to achieve the target PBP (see Fig. 7.15(b) and Fig. 7.16(b)).



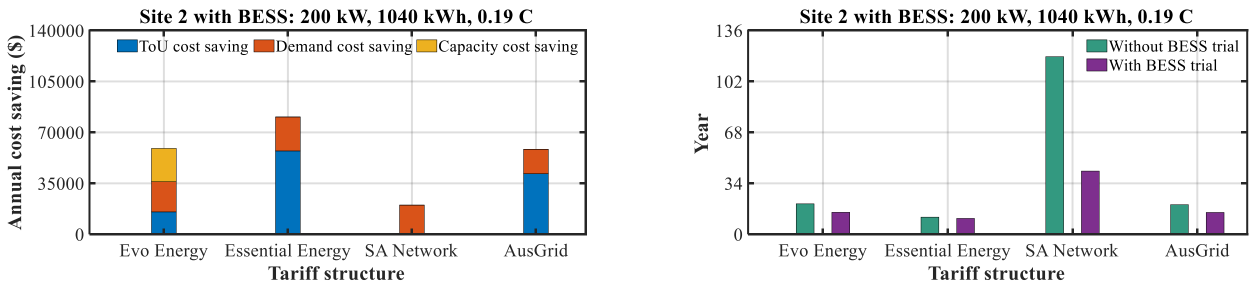
(a) (b)

Fig. 7.17. Cost saving and PBP analysis of Site 2 considering increase in C rating with BESS: 200 kW, 252 kWh, 0.79 C (Case Study F17).



(a) (b)

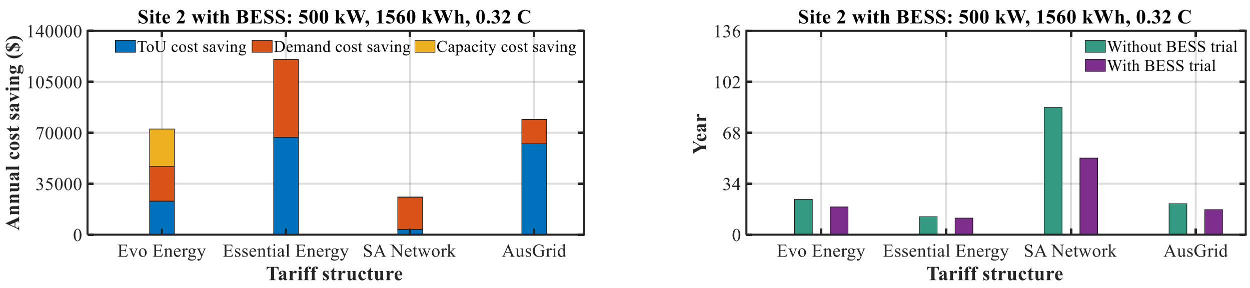
Fig. 7.18. Cost saving and PBP analysis of Site 2 considering increase C rating with BESS: 500 kW, 505 kWh, 0.99 C (Case Study F18).



(a) (b)

Fig. 7.19. Cost saving and PBP analysis of Site 2 considering decrease in C rating with BESS: 200 kW, 1040 kWh, 0.19 C (Case Study F19).

Case Study F17 and *Case Study F18* deal with the increase in the BESS C ratings, i.e., from 0.39 C to 0.79 C and from 0.48 C to 0.99 C, respectively, while keeping the BESS kW ratings unchanged, i.e., 200 kW and 500 kW. The cost savings of Site 2 are displayed in Fig. 7.17(a) and Fig. 7.18(a), respectively. Fig. 7.17(b) and Fig. 7.18(b) show the PBPs of Site 2, respectively. Based on these figures, cost savings are decreased compared to *Case Study F11* because of the lesser BESS charging and discharging caused by the reduced BESS kWh capacities.



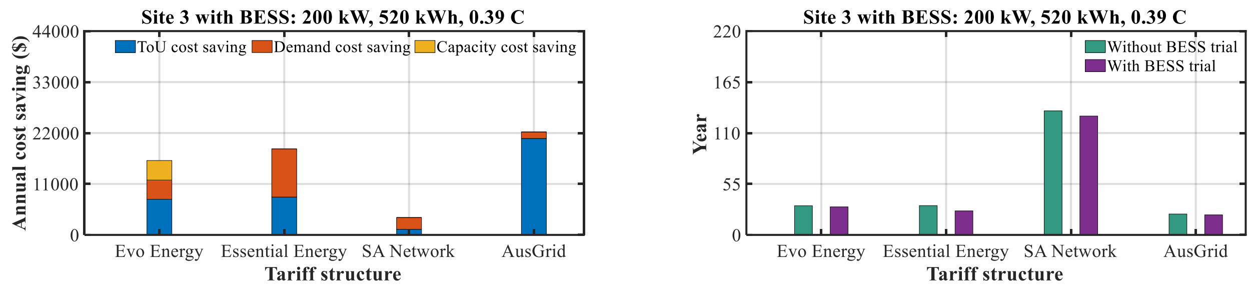
(a) (b)

Fig. 7.20. Cost saving and PBP analysis of Site 2 considering decrease in C rating with BESS: 500 kW, 1560 kWh, 0.32 C (Case Study F20).

In contrast, the decrease in the BESS C ratings, i.e., from 0.39 C to 0.19 C and from 0.48 C to 0.32 C, while keeping the BESS kW ratings unchanged, i.e., 200 kW and 500 kW, are demonstrated in *Case Study F19* and *Case Study F20*, respectively. Fig. 7.19(a) and Fig. 7.20(a) exhibit the cost savings of Site 2, while PBPs are captured in Fig. 7.19(b) and Fig. 7.20(b), respectively. These figures suggest that cost savings are increased in comparison with *Case Study F11* due to higher BESS charging and discharging capacities.

7.3. Financial Case Studies for Site 3

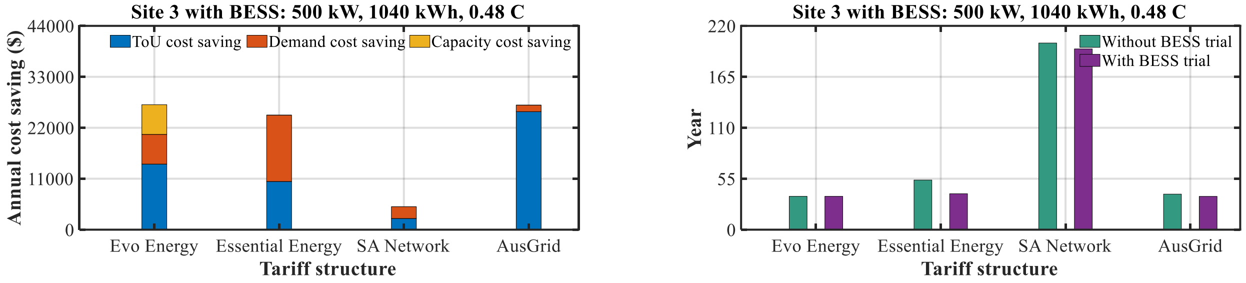
In *Case Study F21*, Site 3 is provided with a BESS size of 200 kW, 520 kWh, and 0.39 C. The cost savings and PBPs of Site 3 under considered tariff structures without any variation in existing rates are depicted in Fig. 7.21(a) and Fig. 7.21(b), respectively. As is noticed from these figures, the AusGrid tariff structure is more profitable for Site 3, resulting in a lower PBP compared to Evo Energy, Essential Energy, and SA Network tariff structures. Also, PBPs with the BESS trial tariff are always lower than those with the standard (without the BESS trial) tariff, indicating the BESS trial tariff is beneficial for Site 3, similar to Site 1 and Site 2.



(a) (b)

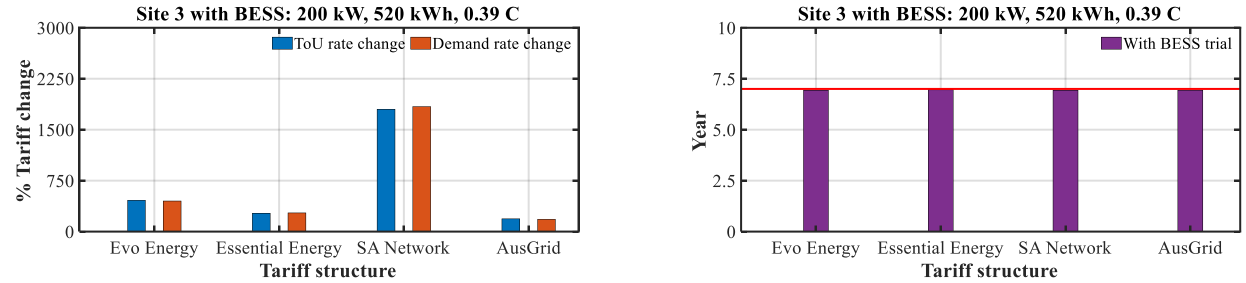
Fig. 7.21. Cost saving and PBP analysis of Site 3 considering unvaried tariff structure with BESS: 200 kW, 520 kWh, 0.39 C (Case Study F21).

Case Study F22 is similar to *Case Study F11* except for the consideration of a higher BESS size of 500 kW, 1040 kWh, and 0.48 C. Fig. 7.22(a) suggests that cost savings increase with an increase in BESS size for Site 3 (similar to Site 1 and Site 2). However, PBP also increases, subject to the CapEx and OpEx of the considered BESS. The PBP increase is captured in Fig. 7.22(b). To keep the PBP within the target 7 years (see Fig. 7.23(b) and Fig. 7.24(b)), based on *Case Study F23* and *Case Study F24*, AusGrid tariff rates need to be decreased between 180% and 344% (see Fig. 7.23(a) and Fig. 7.24(a)).



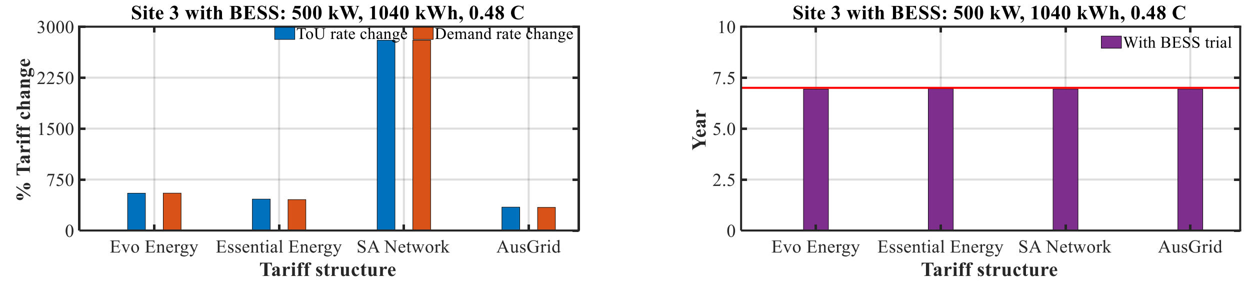
(a) (b)

Fig. 7.22. Cost saving and PBP analysis of Site 3 considering unvaried tariff structure with BESS: 500 kW, 1040 kWh, 0.48 C (Case Study F22).



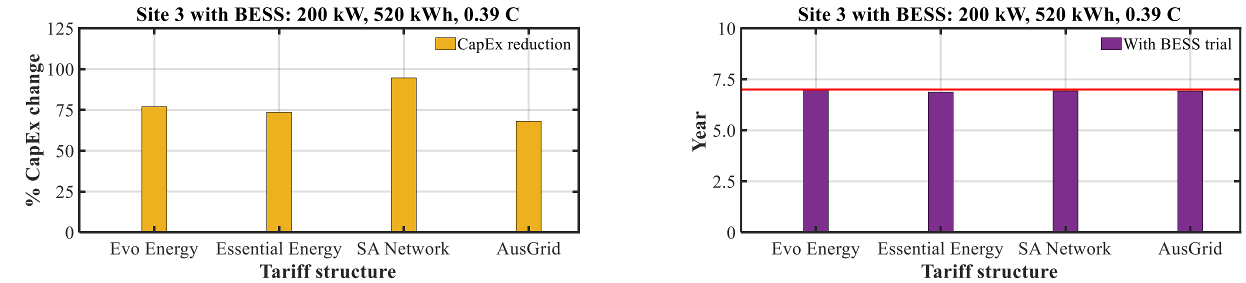
(a) (b)

Fig. 7.23. Cost saving and PBP analysis of Site 3 considering reduction in tariff structure with BESS: 200 kW, 520 kWh, 0.39 C (Case Study F23).



(a) (b)

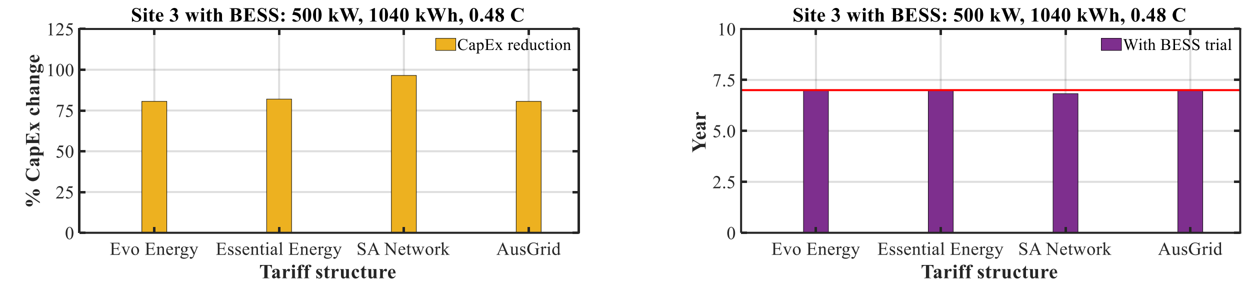
Fig. 7.24. Cost saving and PBP analysis of Site 3 considering reduction tariff structure with BESS: 500 kW, 1040 kWh, 0.48 C (Case Study F24).



(a) (b)

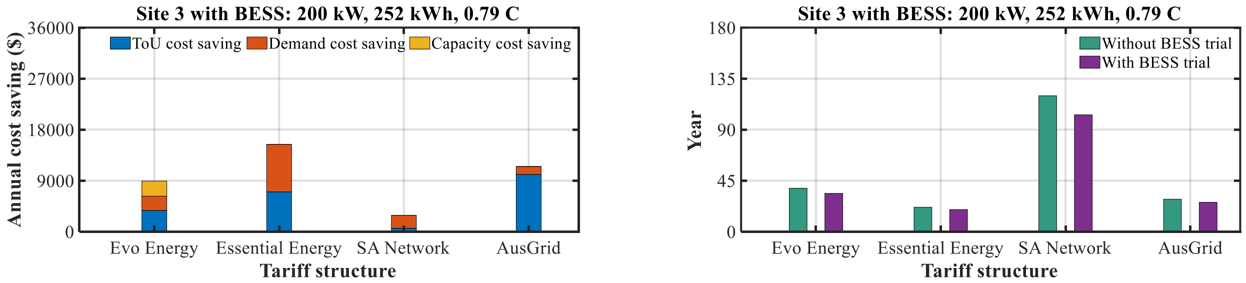
Fig. 7.25. Cost saving and PBP analysis of Site 3 considering reduction in CapEx with BESS: 200 kW, 520 kWh, 0.39 C (Case Study F25).

The PBP of Site 3 can also be kept within the target 7 years by reducing the CapEx and subsequent OpEx. According to Fig. 7.25(a) and Fig. 7.26(a), CapEx needs to be decreased between 70% and 80% (as per *Case Study F25* and *Case Study F26)*, respectively, with AusGrid's tariff structure to achieve the target PBP (see Fig. 7.52(b) and Fig. 7.26(b)).



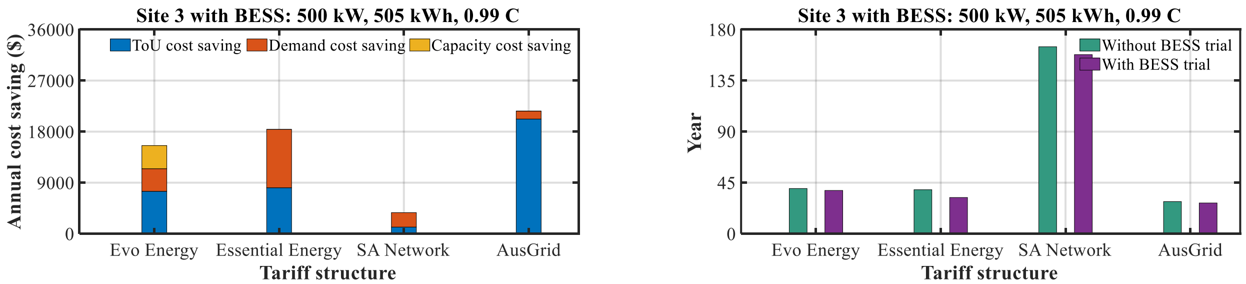
(a) (b)

Fig. 7.26. Cost saving and PBP analysis of Site 3 considering reduction in CapEx with BESS: 500 kW, 1040 kWh, 0.48 C (Case Study F26).



(a) (b)

Fig. 7.27. Cost saving and PBP analysis of Site 3 considering increase in C rating with BESS: 200 kW, 252 kWh, 0.79 C (Case Study F27).

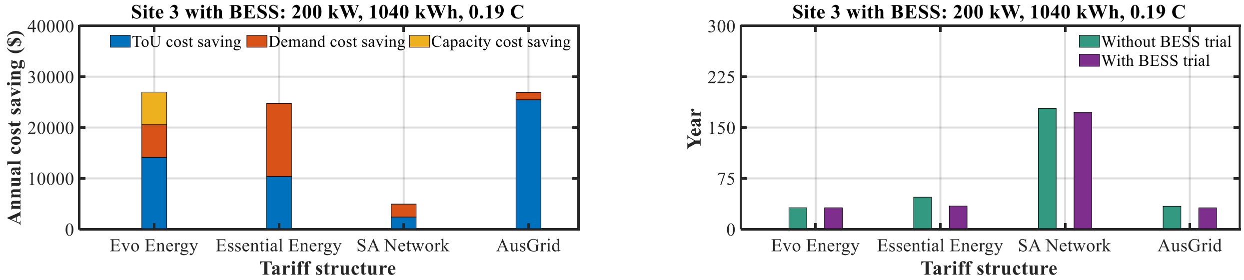


(a) (b)

Fig. 7.28. Cost saving and PBP analysis of Site 3 considering increase C rating with BESS: 500 kW, 505 kWh, 0.99 C (Case Study F28).

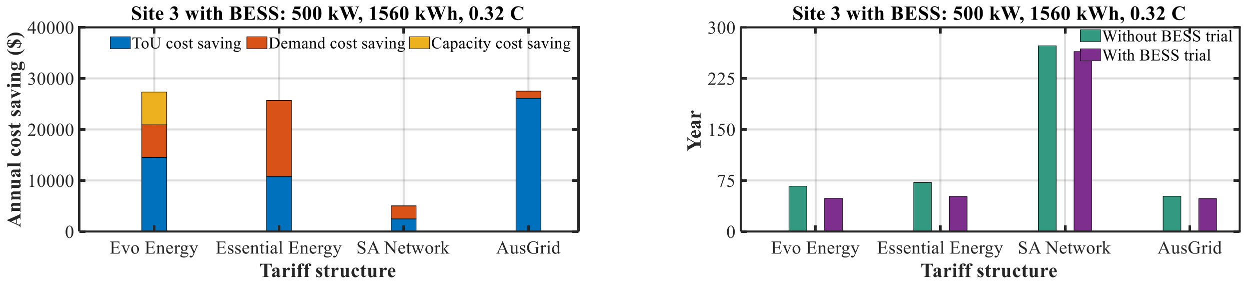
Case Study F27 and *Case Study F28* deal with the increase in the BESS C ratings, i.e., from 0.39 C to 0.79 C and from 0.48 C to 0.99 C respectively, while keeping the BESS kW ratings unchanged, i.e., 200 kW and 500 kW. The cost savings of Site 3 in *Case Study F27* and *Case Study F28* are displayed in Fig. 7.27(a) and Fig. 7.28(a), respectively. Fig. 7.27(b) and Fig. 7.28(b) show the PBPs, respectively. Based on these figures, cost savings are decreased compared to *Case Study F21* because of the fact of lesser BESS charging and discharging caused by the reduced BESS kWh capacities.

In contrast, the decrease in the BESS C ratings, i.e., from 0.39 C to 0.19 C and from 0.48 C to 0.32 C, while keeping the BESS kW ratings unchanged, i.e., 200 kW and 500 kW, are demonstrated in *Case Study F29* and *Case Study F30*, respectively. Fig. 7.29(a) and Fig. 7.30(a) exhibit the cost savings of Site 3, while PBPs are captured in Fig. 7.29(b) and Fig. 7.30(b), respectively. These figures suggest that cost savings are increased in comparison with *Case Study F21* due to higher BESS charging and discharging capacities.



(a) (b)

Fig. 7.29. Cost saving and PBP analysis of Site 3 considering decrease in C rating with BESS: 200 kW, 1040 kWh, 0.19 C (Case Study F29).



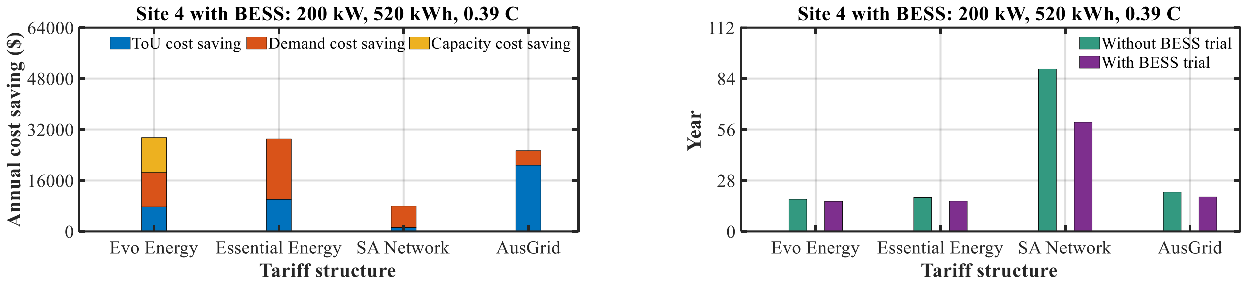
(a) (b)

Fig. 7.30. Cost saving and PBP analysis of Site 3 considering decrease in C rating with BESS: 500 kW, 1560 kWh, 0.32 C (Case Study F30).

7.4. Financial Case Studies for Site 4

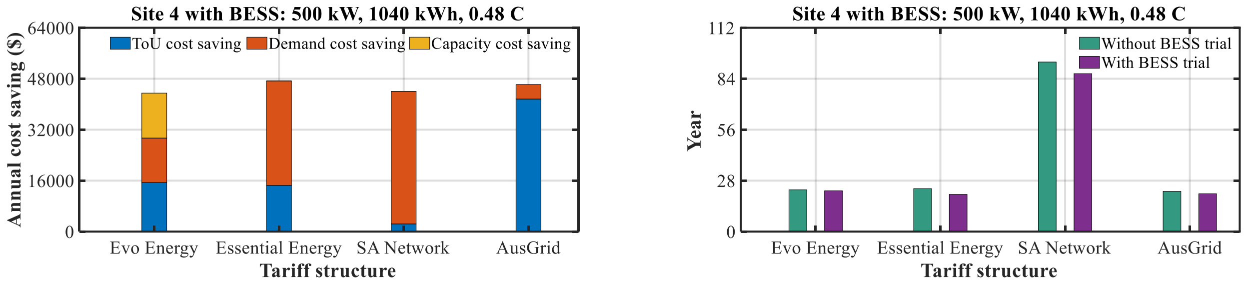
In *Case Study F31*, Site 4 is provided with a BESS size of 200 kW, 520 kWh, and 0.39 C. The cost savings and PBPs of Site 4 under considered tariff structures without any variation in existing rates are depicted in Fig. 7.31(a) and Fig. 7.31(b), respectively. As is noticed from these figures, the Essential Energy tariff structure is more profitable for Site 4, resulting in a lower PBP compared to Evo Energy, SA Network, and AusGrid tariff structures. Also, PBPs with the BESS trial tariff are always lower than those with the standard (without the BESS trial) tariff, indicating the BESS trial tariff is beneficial for Site 4, similar to Site 1, Site 2, and Site 3.

Case Study F32 is similar to *Case Study F31* except for the consideration of a higher BESS size of 500 kW, 1040 kWh, and 0.48 C. According to Fig. 7.32(a), it is evident that cost savings increase with an increase in BESS size for Site 4 (similar to Site 1, Site 2, and Site 3). However, PBP also increases, subject to the CapEx and OpEx of the considered BESS. The PBP increase of Site 4 is captured in Fig. 7.32(b).



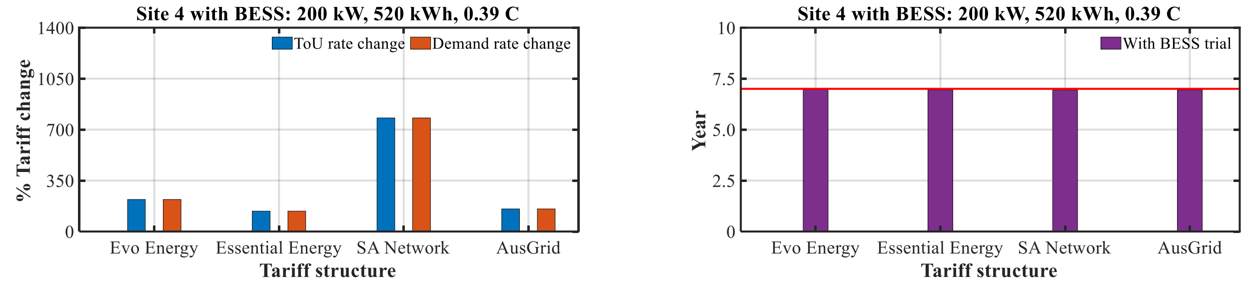
(a) (b)

Fig. 7.31. Cost saving and PBP analysis of Site 4 considering unvaried tariff structure with BESS: 200 kW, 520 kWh, 0.39 C (Case Study F31).



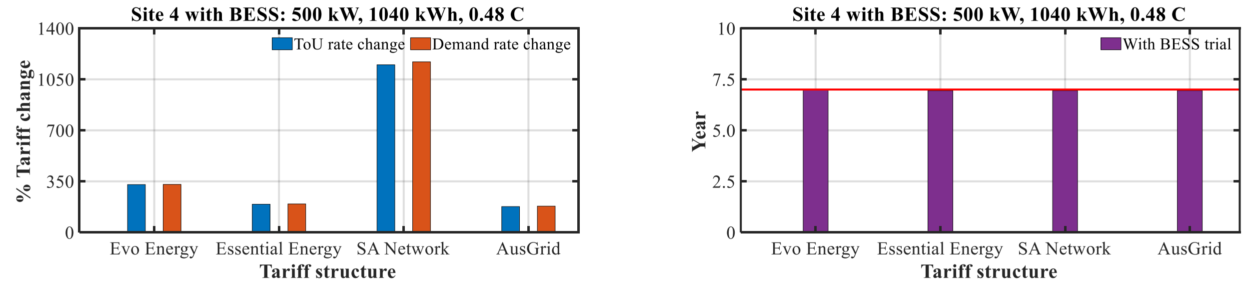
(a) (b)

Fig. 7.32. Cost saving and PBP analysis of Site 4 considering unvaried tariff structure with BESS: 500 kW, 1040 kWh, 0.48 C (Case Study F32).



(a) (b)

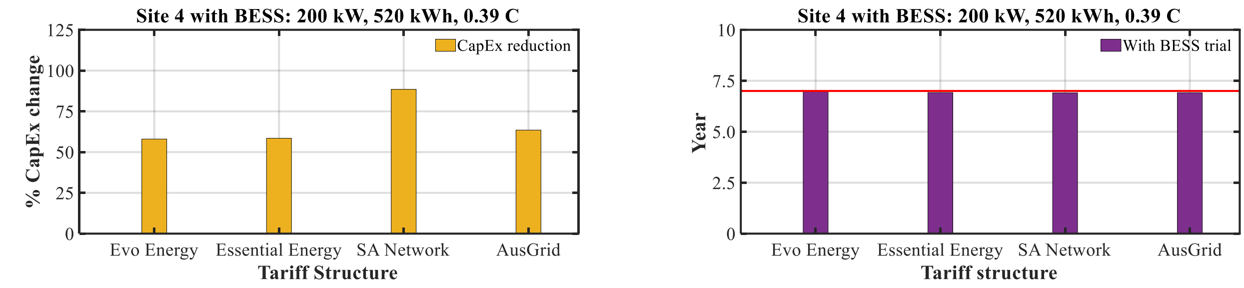
Fig. 7.33. Cost saving and PBP analysis of Site 4 considering reduction in tariff structure with BESS:200 kW, 520 kWh, 0.39 C (Case Study F33).



(a) (b)

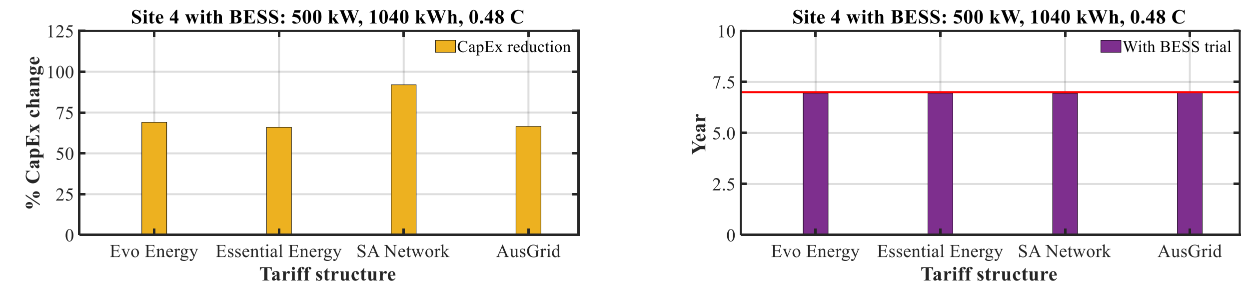
Fig. 7.34. Cost saving and PBP analysis of Site 4 considering reduction tariff structure with BESS: 500 kW, 1040 kWh, 0.48 C (Case Study F34).

To keep the PBP of Site 4 within the target 7 years (see Fig. 7.33(b) and Fig. 7.34(b)), based on *Case Study F33* and *Case Study F34*, Essential Energy tariff rates need to be decreased between 140% (see Fig. 7.33(a)) and 200% (see Fig. 7.34(a)). The PBP of Site 4 can also be kept within the target 7 years by reducing the CapEx and subsequent OpEx. According to Fig. 7.35(a) and Fig. 7.36(a), CapEx needs to be decreased between 60% and 60% (as per *Case Study F35* and *Case Study F36)*, respectively, with the Essential Energy tariff structure to achieve the target PBP (see Fig. 7.35(b) and Fig. 7.36(b)).



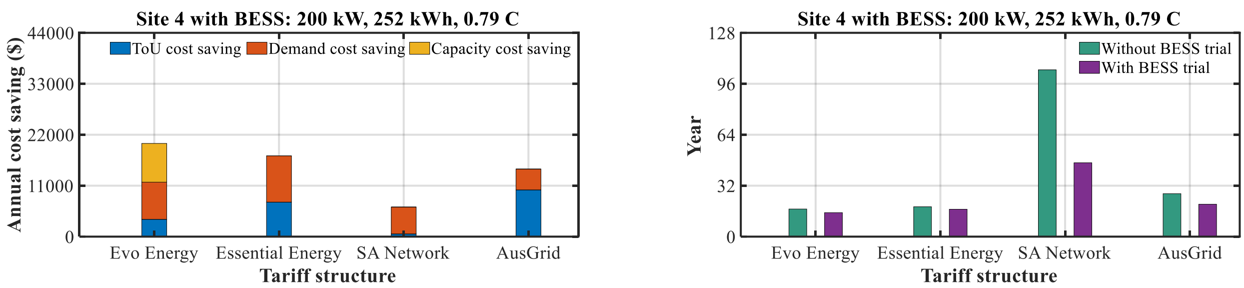
(a) (b)

Fig. 7.35. Cost saving and PBP analysis of Site 4 considering reduction in CapEx with BESS: 200 kW, 520 kWh, 0.39 C (Case Study F35).



(a) (b)

Fig. 7.36. Cost saving and PBP analysis of Site 4 considering reduction in CapEx with BESS: 500 kW, 1040 kWh, 0.48 C (Case Study F36).

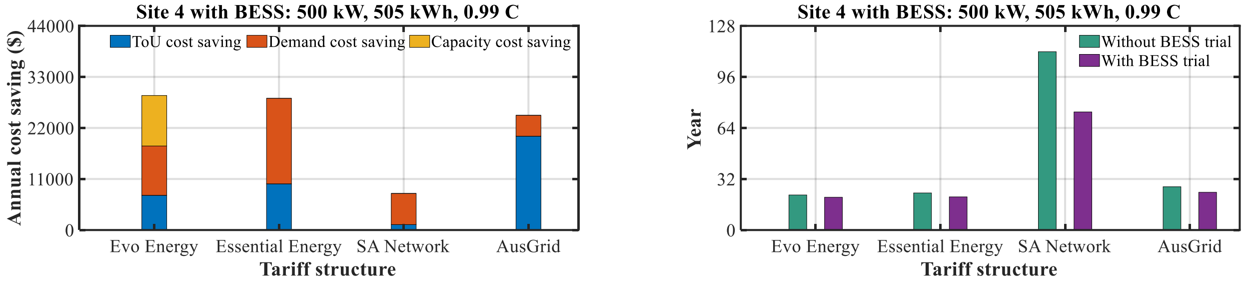


(a) (b)

Fig. 7.37. Cost saving and PBP analysis of Site 4 considering increase in C rating with BESS: 200 kW, 252 kWh, 0.79 C (Case Study F37).

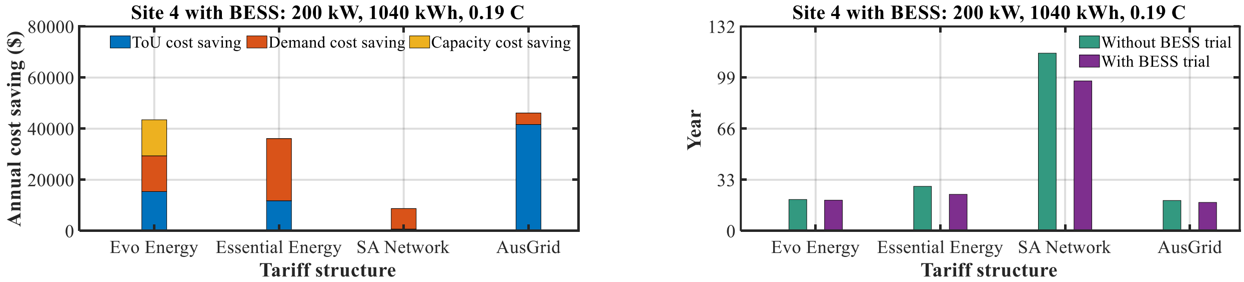
Case Study F37 and *Case Study F38* deal with the increase in the BESS C ratings, i.e., from 0.39 C to 0.79 C and from 0.48 C to 0.99 C, respectively, while keeping the BESS kW ratings unchanged, i.e., 200 kW and 500 kW. The cost savings of Site 4 in *Case Study F37* and *Case Study F38* are displayed in Fig. 7.37(a) and Fig. 7.38(a), respectively. Fig. 7.37(b) and Fig. 7.38(b) show the PBPs, respectively. Based on these figures, cost savings are decreased compared to *Case Study F31* because of the lesser

BESS charging and discharging caused by the reduced BESS kWh capacities. In contrast, the decrease in the BESS C ratings, i.e., from 0.39 C to 0.19 C and from 0.48 C to 0.32 C while keeping the BESS kW ratings unchanged, i.e., 200 kW and 500 kW, are demonstrated in *Case Study F39* and *Case Study F40*, respectively. Fig. 7.29(a) and Fig. 7.30(a) exhibit the cost savings of Site 4, while PBPs are captured in Fig. 7.29(b) and Fig. 7.30(b), respectively. These figures suggest that cost savings are increased in comparison with *Case Study F31* due to higher BESS charging and discharging capacities.



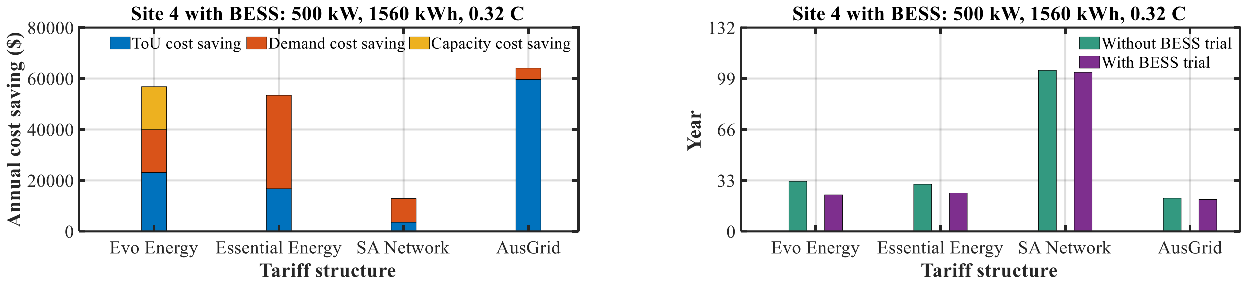
(a) (b)

Fig. 7.38. Cost saving and PBP analysis of Site 4 considering increase C rating with BESS: 500 kW, 505 kWh, 0.99 C (Case Study F38).



(a) (b)

Fig. 7.39. Cost saving and PBP analysis of Site 4 considering decrease in C rating with BESS: 200 kW, 1040 kWh, 0.19 C (Case Study F39).



(a) (b)

Fig. 7.40. Cost saving and PBP analysis of Site 4 considering decrease in C rating with BESS: 500 kW, 1560 kWh, 0.32 C (Case Study F40).

7.5. Summary of Key Findings with Battery

1) The cost saving, calculated from the electricity cost difference between the consideration of BESS (charged at the BESS trial tariff) and without BESS (charged at the standard tariff), for a C&I customer increases with BESS size.

2) The PBP increases with the increase in BESS size, subject to CapEx and OpEx of the BESS.
3) The PBP with the BESS trial tariff is always lower than that of the standard (without the BESS trial) tariff, indicating the BESS trial tariff is beneficial for a C&I customer.
4) Different tariff structures are beneficial for different C&I customers. For instance, the Evo Energy tariff structure is profitable for Site 1 (with considerable high load and solar PV configurations). The Essential Energy tariff structure is profitable for Site 2 (with high load and solar PV configurations). The AusGrid tariff structure is profitable for Site 3 (with low load and solar PV configurations). For Site 4 (with low load and solar PV configurations), the Evo Energy tariff structure is profitable if a smaller BESS size is considered. With the increase in BESS size, Essential Energy's tariff structure becomes profitable. However, the SA Network tariff structure is not profitable for any of these considered C&I customers.
5) A higher difference between peak and off-peak prices, as noticed from AusGrid's tariff structure, allows BESS to charge from the power grid during off-peak hours, subject to solar charging constraints, at a cheaper price and discharge during peak hours, resulting in greater ToU cost savings and lower PBPs for C&I customers. On the contrary, a lower difference between peak and off-peak prices, as noticed from the SA Network tariff structure, causes lesser ToU cost savings and higher PBPs for C&I customers.
6) A higher solar soak period increases ToU cost savings and decreases PBPs, as observed from the Essential Energy tariff structure.
7) Higher demand and capacity charges lead to greater ToU cost savings and reduced PBPs, as seen from the EvoEnergy tariff structure.
8) A significant reduction in tariff rates enables C&I customers to attain the target PBP. For example, to get ROI within 7 years under different BESS sizes, tariff rates need to be decreased between 100% and 139% (for Site 1 with the Evo Energy tariff structure), between 0% and 60% (for Site 2 with the Essential Energy tariff structure), between 180% and 344% (for Site 3 with the AusGrid tariff structure), and between 140% and 200% (for Site 4 with the Essential Energy tariff structure).
9) Reduction in CapEx also facilitates C&I customers to achieve the target PBP. For instance, CapEx needs to be decreased between 40% and 50% (for Site 1 with the Evo Energy tariff structure), between 0% and 30% (for Site 2 with the Essential Energy tariff structure), between 70% and 80% (for Site 3 with the AusGrid tariff structure), and between 60% and 70% (for Site 4 with the Essential Energy tariff structure) to enable C&I customers to receive ROI within 7 years under different BESS sizes.
10) An increase in the BESS C rating while keeping the BESS kW rating unchanged decreases cost savings and enhances PBPs due to lesser BESS charging and discharging caused by the reduced BESS kWh capacity.
11) A decrease in the BESS C rating while keeping the BESS kW rating unchanged increases cost savings and reduces PBPs due to greater BESS charging and discharging caused by the increased BESS kWh capacity.

8. Network Impact Analysis with Battery

The impact of installing BESS at the customers'-end on any representative power network can be analysed by following the below steps:

Step 1: Extract load values from the representative power network.

Step 2: Extract commercial site profiles with BESS under the considered tariff structures ─ used in the financial analysis.

Step 3: Select a bus from the representative power network and replace the load profile of the bus with a commercial site profile with BESS under a tariff structure.

Step 4: Repeat **Step 3** for all considered tariff structures.

Step 5: Repeat **Step 4** for all considered BESS sizes.

Step 6: Incorporate bus voltage and line loading limits.

Step 7: Perform time series power flow for all structures considered in **Step 3, Step 4** and **Step 5**.

Step 8: Record bus voltages and line loading and check the network's integrity.

8.1. Overview of Representative Power Network

In this case study, a benchmark power system, i.e., an IEEE 33 bus test distribution network, is used. The single-line diagram of this representative power network is exhibited in Fig. 8.1. The network has 33 buses. Bus 1 indicates the distribution substation, and other buses are load buses containing one C&I customer at each bus. All the buses are connected through 32 distribution lines [12]. The detailed line data and rated load values can be found in [13]. The supply voltage is considered 11 kV in accordance with the Australian electricity supply standard [14]. According to IEC Standard 61000.3, the bus voltage limits of the representative power network are maintained in the range of 0.9 to 1.06 per-unit (pu) under steady-state conditions [15].

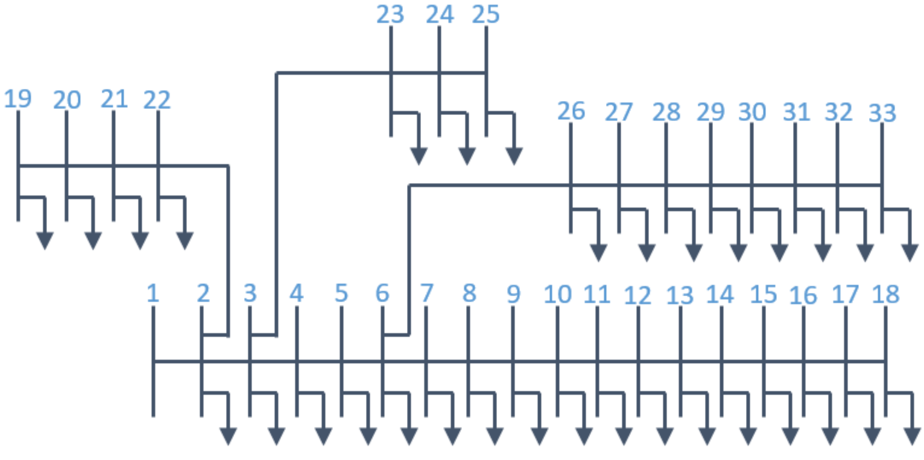
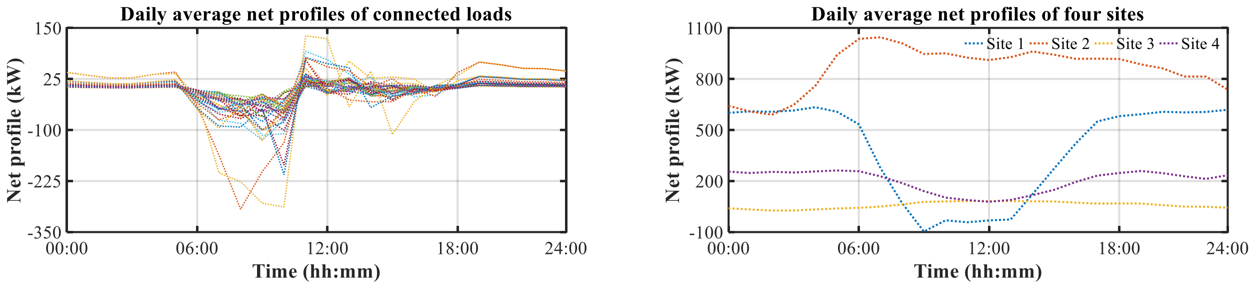


Fig. 8.1. Single-line diagram of the representative power network.



(a) (b)

Fig. 8.2. Net profiles of the representative network loads and selected four sites.

It is assumed that all the C&I customers of the representative network have solar PV with rated ratings between 1 and 2 times higher than their rated load demand. The daily average net profiles of the representative network are given in Fig. 8.2(a). The daily average net profiles of the four sites considered for the financial analysis are illustrated in Fig. 8.2(b). As is observed in Fig. 8.2(b), the daily average net profiles of Site 2, Site 3, and Site 4 are always positive, indicating load demand are always higher than solar PV generation. In contrast, Site 1 has more solar PV generation than its load demand during some solar PV hours. Therefore, Site 1 (higher solar PV generation) and Site 2 (higher load demand) are chosen to connect to the 11 kV distribution network shown in Fig. 8.1.

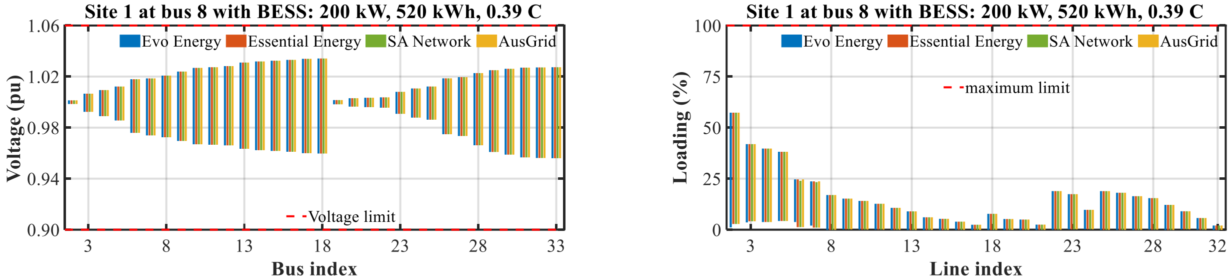
8.2. Network Case Studies with C&I Sites at Different Locations

Eight network case studies are conducted to investigate the impacts of incorporating BESS in Site 1 and Site 2 on bus voltages and line loading under considered tariff structures, namely EvoEnergy, Essential Energy, SA Network, and Ausgrid BESS trial tariff structures. An overview of these case studies is demonstrated in Table 8.1.

Table 8.1. Overview of physical network case studies.

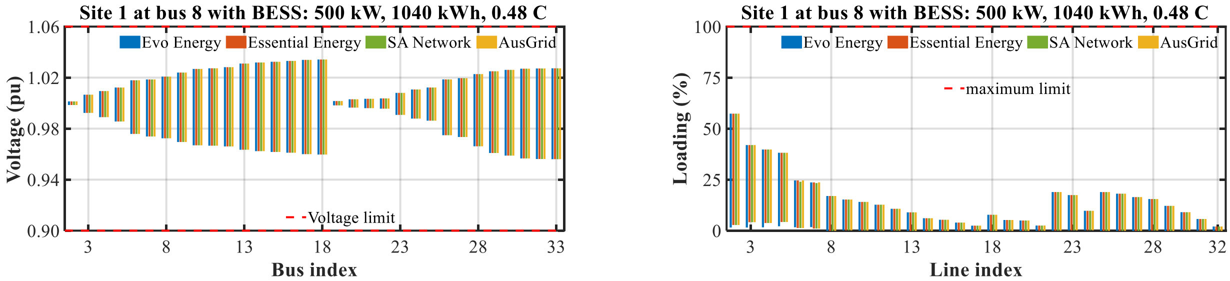
Physical network case study	Site No.	BESS Size	C rating	Bus location
Case Study P1	1	200 kW, 520 kWh	0.39	8
Case Study P2	1	500 kW, 1040 kWh	0.48	8
Case Study P3	1	200 kW, 520 kWh	0.39	18
Case Study P4	1	500 kW, 1040 kWh	0.48	18
Case Study P5	2	200 kW, 520 kWh	0.39	6
Case Study P6	2	500 kW, 1040 kWh	0.48	6
Case Study P7	2	200 kW, 520 kWh	0.39	32
Case Study P8	2	500 kW, 1040 kWh	0.48	32

In *Case Study P1*, daily average net profiles at bus 8 of the representative network are replaced with daily average net profiles of Site 1, with BESS: 200 kW, 520 kWh, and 0.39 C, under considered tariff structures. The impacts of *Case Study P1* on daily average network voltages and line loading are provided in Fig. 8.3(a) and Fig. 8.3(b), respectively. As is seen from these figures, insignificant variations in daily average bus voltages and line loading are found under Evo Energy, Essential Energy, SA Network, and AusGrid tariff structures. More importantly, both bus voltages and line loading are within the prescribed limits. Fig. 8.4(a) and Fig. 8.4(b) display daily average bus voltages and line loading in *Case Study P2*, respectively, considered tariff structures, in which Site 1, connected to bus 8, is provided with the increased BESS size of 500 kW, 1040 kWh, 0.48 C. It is noticed from Fig. 8.4(a) and Fig. 8.4(b) that daily average bus voltages and line loading do not vary substantially if there is an increase in BESS size.



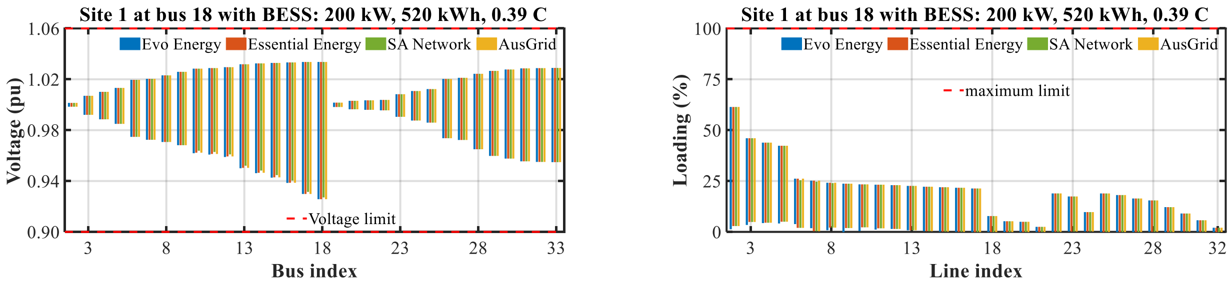
(a) (b)

Fig. 8.3. Bus voltages and line loading under considered tariff structures if Site 1 with BESS: 200 kW, 520 kWh, 0.39 C is connected to bus 8 (Case Study P1).



(a) (b)

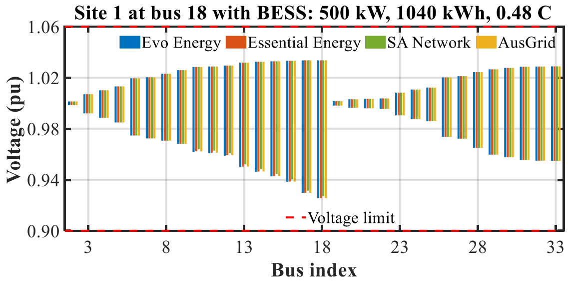
Fig. 8.4. Bus voltages and line loading under different tariff structures if Site 1with BESS: 500 kW, 1040 kWh, 0.48 C is connected to bus 8 (Case Study P2).



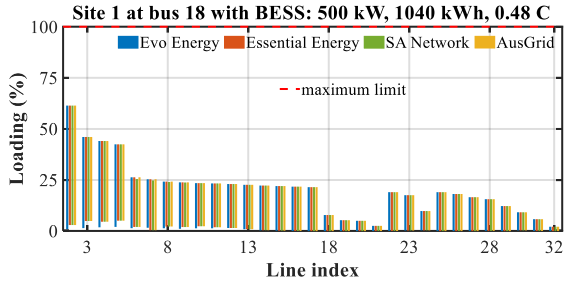
(a) (b)

Fig. 8.5. Bus voltages and line loading under different tariff structures if Site 1 with BESS: 200 kW, 520 kWh, 0.39 C is connected to bus 18 (Case Study P3).

Case Study P3 and *Case Study P4* are similar to *Case Study P1* and *Case Study P2*, respectively, except the physical network location of Site 1. In *Case Study P3* and *Case Study P4*, Site 1 is connected to bus 18. Fig. 8.5(a) and Fig. 8.6(a) suggest that this can result in greater voltage drops over the course of 24 hours on average, compared to Fig. 8.3(a) and Fig. 8.4(a), respectively, as power flows through more lines to satisfy the load demand of Site 1. Due to the same reason, Fig. 8.5(b) and Fig. 8.6(b) show more line loading contrasting to Fig. 8.3(b) and Fig. 8.4(b), respectively.

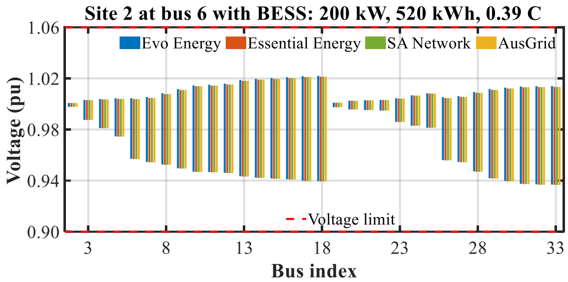


(a)

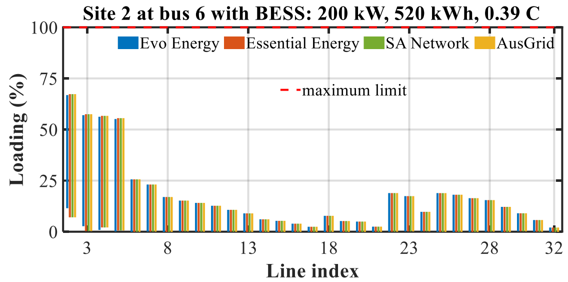


(b)

Fig. 8.6. Bus voltages and line loading under different tariff structures if Site 1 with BESS: 500 kW, 1040 kWh, 0.48 C is connected to bus 18 (Case Study P4).

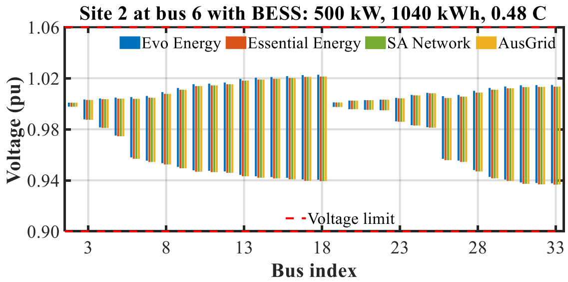


(a)

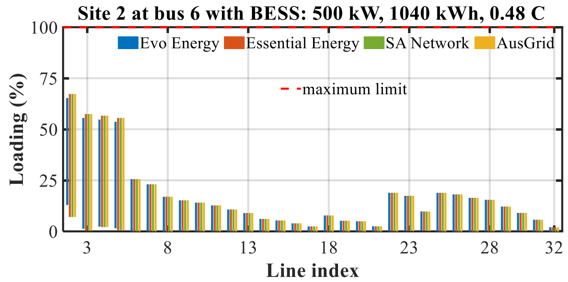


(b)

Fig. 8.7. Bus voltages and line loading under different tariff structures if Site 2 with BESS: 200 kW, 520 kWh, 0.39 C is connected to bus 6 (Case Study P5).



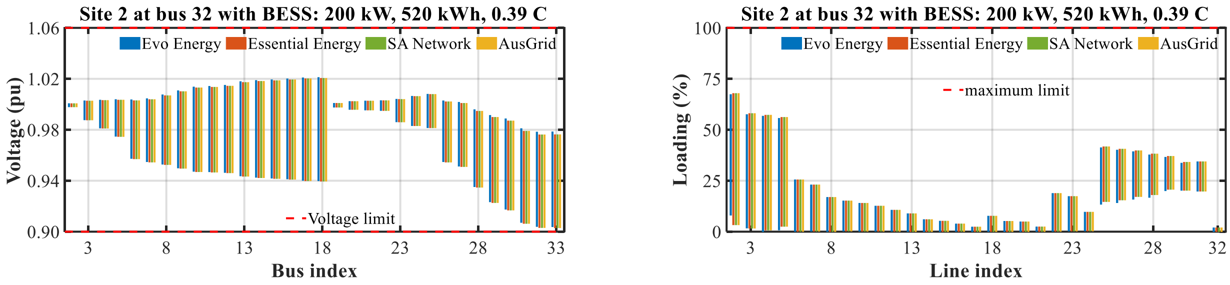
(a)



(b)

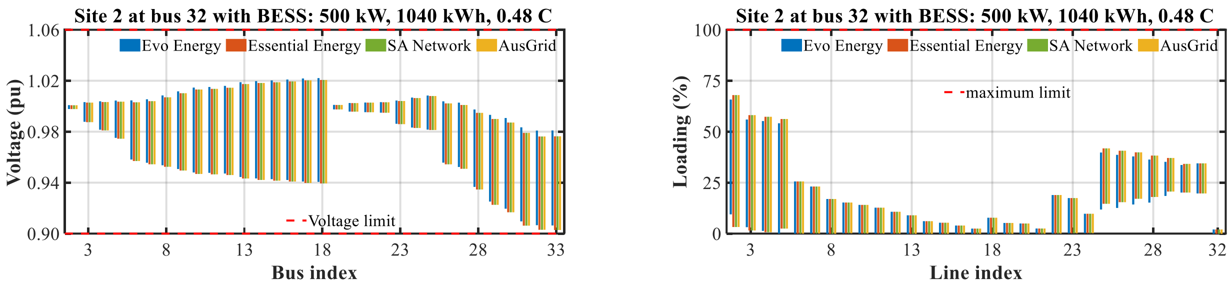
Fig. 8.8. Bus voltages and line loading under different tariff structures if Site 2 with BESS: 500 kW, 1040 kWh, 0.48 C is connected to bus 6 (Case Study P6).

Fig. 8.7(a) and Fig. 8.7(b) depict daily average bus voltages and line loading, respectively, in *Case Study P5*, in which net profiles at bus 6 of the representative network are replaced with net profiles of Site 2, with BESS: 200 kW, 520 kWh, 0.39 C, under considered tariff structures. Since Site 2 has a larger load demand in comparison with Site 1, greater voltage drops and line congestion are observed compared to Fig. 8.3(a) and Fig. 8.3(b), respectively. The same results are also found in *Case Study P6* (considering a greater BESS size contrasting to Case Study P5) if Fig. 8.8(a) and Fig. 8.8(b) are compared with Fig. 8.4(a) and Fig. 8.4(b), respectively.



(a) (b)

Fig. 8.9. Bus voltages and line loading under different tariff structures if Site 2 with BESS: 200 kW, 520 kWh, 0.39 C is connected to bus 32 (Case Study P7).



(a) (b)

Fig. 8.10. Bus voltages and line loading under different tariff structures if Site 2 with BESS: 500 kW, 1040 kWh, 0.48 C is connected to bus 32 (Case Study P8).

Case Study P7 and *Case Study P8* consider that Site 2 is connected to bus 32 of the representative network with BESS: 200 kW, 520 kWh, 0.39 C, and BESS: 500 kW, 1040 kWh, 0.48 C, respectively, under considered tariff structures. The bus voltages of both case studies are captured in Fig. 8.9(a) and Fig. 8.10(a), respectively, which suggest that noticeable voltage drops are caused in contrast with Fig. 8.7(a) and Fig. 8.8(a), respectively. This is because power flows to an increased number of lines to reach bus 32 to meet the higher load demand of Site 2. Owing to the same reason, increased amounts of line loading are found in Fig. 8.9(b) and Fig. 8.10(b) compared to 8.7(b) and Fig. 8.8(b), respectively. However, both bus voltages and line loading still abide by the defined limits.

8.3. Summary of Network Analysis with Battery

1) The consideration of BESS at the C&I sites does not create network issues, such as voltage violations and line congestion, in the test distribution network. This is because BESS prevents local export during solar PV hours through its charging operation. Also, it discharges to satisfy the load demand of C&I sites during peak demand periods, requiring less supply from the power grid.
2) Bus voltages and line loading do not vary significantly when different BESS trial tariff structures are considered, e.g., Evo Energy, Essential Energy, SA Network, and AusGrid tariff structures.
3) Bus voltages and line loading do not vary significantly if there is a moderate increase in BESS sizes.
4) More voltage drops and line congestion are found if sites are located at the end of the distribution feeder, as greater amounts of power need to flow through more lines to satisfy the load demand

of sites. In this study, sites have more load demand compared to the load profiles of the test network.

5) Improved voltage profiles are observed for Site 1 in contrast with Site 2, as Site 2 has more load demand than Site 1.

9. Recommendations to Increase the Uptake of Batteries in DR Programs

This study has drawn the following three general recommendations to increase the uptake of batteries in DR programs:

4) ***Reforming Energy Tariffs for Batteries –***

- From the analyses in this project, it is evident that tariffs designed for batteries, e.g., trial tariffs introduced by Evo Energy, Essential Energy, SA Networks, and AusGrid, have the potential to provide higher benefits for C&I customers in comparison to standard tariffs. Therefore, it is recommended to design specific tariffs for batteries.
- Tariff reforms such as introducing a larger gap between peak and off-peak prices as well as solar soak times could help customers achieve more savings that would ultimately promote higher uptake of batteries.

5) ***Reducing Battery Costs –***

- From the project analyses, the payback period for C&I customers could be long due to the high CapEx and OpEx associated with batteries. Therefore, in order to achieve the targeted payback period, dedicated grants and incentives to reduce battery deployment costs could be considered. While it is anticipated that batteries will provide various market and network services, the reduction in prices will help to make C&I batteries financially viable.

6) ***Ensuring Network Integrity*** –

- Deployment of a large number of behind-the-meter batteries by C&I customers can potentially result in violations of network constraints, such as voltage or thermal rating. In order to effectively deploy behind-the-meter batteries at C&I facilities while safeguarding the integrity of the network, it is recommended to explore the adoption of concepts such as the dynamic operating envelope (DOE). Insights and learnings from trials such as Project EDGE can be utilised to design and implement DOEs to ensure network integrity in the presence of a large number of behind-the-meter batteries.

10. Appendix

The mathematical formulation of the BESS optimiser is explained in this section. Let $ci \in CI$ be the index of each C&I customer, whose set is denoted by CI. Let $L(ci, tm)$ and $G(ci, tm)$ be average daily load demand and solar PV generation of each C&I customer at a time instant $tm \in TM$, where TM represents the set of all time instants.

The net profile $Nt(ci, tm)$ and subsequent excess solar $EG(ci, tm)$ and unmet demand $UL(ci, tm)$ can be calculated as [16]:

$$Nt(ci, tm) = L(ci, tm) - G(ci, tm), \forall ci \in CI, tm \in TM \quad (1)$$
$$EG(ci, tm) = -\min\{Nt(ci, tm), 0\}, \forall ci \in CI, tm \in TM \quad (2)$$
$$UL(ci, tm) = \max\{Nt(ci, tm), 0\}, \forall ci \in CI, tm \in TM \quad (3)$$

Assume $up(tou, sd), up(fit, sd), up(dc, sd)$, and $up(cc, sd)$ are average daily ToU price, FiT rate, demand charge, and capacity charge of a standard C&I tariff (without the BESS trial). $up(tou, sd)$ comprises peak, off-peak, and shoulder ToU prices. Under this tariff, the electricity cost can be calculated as:

$$AUD_{sd}(ci) = \sum_{tm \in TM} [(-EG(ci, tm) \times up(fit, sd)) + (UL(ci, tm) \times up(tou, sd))] +$$
$$[\max\{UL(ci)\} \times up(dc, sd)] + [\max\{UL(ci)\} \times up(cc, sd)], \forall ci \in CI \quad (4)$$

Let $C(ci, tm)$ and $D(ci, tm)$ be BESS charged and discharged power at a time instant $tx \in TM$. These are bounded by the charging and discharging capacities, $Ccap(ci, tm)$ and $Dcap(ci, tm)$, respectively. The BESS storage operation is also maintained by the SOC $S(ci, tm)$, which is also limited by the maximum SOC capacity $Scap(ci, tm)$. The BESS operation can be mathematically represented as follows [17, 18]:

$$S(ci, tm) = S(ci, tm - 1) + (CE \times C(ci, tm) \times \Delta tm)$$
$$-(\frac{D(ci, tm) \times \Delta tm}{DE}), \forall ci \in CI, tm \in TM \quad (5)$$
$$0 \leq S(ci, tm) \leq Scap(ci, tm), \forall ci \in CI, tm \in TM \quad (6)$$
$$0 \leq (C(ci, tm) \times \Delta tm) \leq Ccap(ci, tm), \forall ci \in CI, tm \in TM \quad (7)$$
$$0 \leq (D(ci, tm) \times \Delta tm) \leq Dcap(ci, tm), \forall ci \in CI, tm \in TM \quad (8)$$

where CE and DE denote charging and discharging efficiencies, respectively. Δtm is the length of the time instant.

$C(ci, tm)$ has two components, charged from solar PV $Cpv(ci, tm)$ and charged from the grid $Cgr(ci, tm)$, i.e., $C(ci, tm) = Cpv(ci, tm) + Cgr(ci, tm)$. While $Cpv(ci, tm)$ is free, $Cgr(ci, tm)$ is charged at the off-peak rate. Assume $up(tou, tr), up(fit, tr), up(dc, tr)$, and $up(cc, tr)$ are average daily ToU price (comprising peak, off-peak, and shoulder ToU prices), FiT rate, demand charge, and capacity charge of a BESS trial tariff.

Under the BESS trial tariff, the electricity cost can be calculated as:

$$AUD_{tr}(ci) = \sum_{tm \in TM} [(-(EG(ci,tm) - Cpv(ci,tm)) \times up(fit,tr)) + ((UL(ci,tm) - D(ci,tm)) + Cgr(ci,tm)) \times up(tou,tr))] + [\max\{UL(ci)\} \times up(dc,tr)] + [\max\{UL(ci)\} \times up(cc,tr)], \forall ci \in CI \quad (10)$$

Now, the electricity cost saving due to the application of BESS with the BESS tariff trial can be calculated as:

$$AUD_{sav}(ci) = AUD_{sd}(ci) - AUD_{tr}(ci), \forall ci \in CI \quad (11)$$

There are two types of BESS degradation cost: namely cycle degradation cost xe and calendar degradation cost xr. The combination of xe and xr is the total degradation cost xd These can be calculated as follows [19]:

$$xe(ci) = 0.021 \times e^{\left(-0.01943 \times \frac{\overline{S(ci,tm)}}{Cap(ci)} \times 100\right)} \times \left(\frac{\max\{S(ci,TM)\} - \min\{S(ci,TM)\}}{Cap(ci)} \times 100\right)^{0.7162} \times N^{0.5}, \forall ci \in CI \quad (12)$$

$$xr(ci) = 0.1723 \times e^{\left(0.007388 \times \frac{\overline{S(ci,tm)}}{Cap(ci)} \times 100\right)} \times \left(\frac{N}{30.5}\right)^{0.92}, \forall ci \in CI \quad (13)$$

$$xd(ci) = xe(ci) + xr(ci), \forall ci \in CI \quad (14)$$

where $Cap(ci)$ is the capacity of the BESS and N indicates the number of days in a year.

BESS ROI and PBP can be calculated as follows [20]:

$$ROI(ci) = \frac{AUD_{sav}(ci) \times N \times (1 - \frac{xd(ci)}{100})}{Cex + Oex}, \forall ci \in CI \quad (15)$$

$$PBP(ci) = \frac{1}{ROI(ci)}, \forall ci \in CI \quad (16)$$

where Cex and Oex denote CapEx and OpEx of the BESS, respectively.

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