Me ko Māui:

Harnessing the Sun to Provide Better Outcomes for Marae and Communities

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ABSTRACT

Marae are the cultural centres of Māori communities, providing a space for important gatherings both joyful and sad. With the advent of solar energy capture technologies and rising electricity bills, many marae are becoming interested in whether a solar powered system will be beneficial for them. However, marae have unique electricity demand profiles, distinct from commonly modelled building types such as residential or commercial buildings. It is thus difficult to estimate an appropriate solar and battery system size based on annual or even monthly electricity usage data, which may be the only data readily available, requiring more in-depth analysis at a highly site-specific level to find an answer. This thesis aims to increase understanding around how solar power could benefit marae, first by investigating the characteristic electricity demand profile of marae, then by observing how proposed system configurations meet the demand. The potential community benefits arising from such a system was also investigated. Using a year's worth of half-hourly data from three marae, five characteristic day types were found in the analysis of the demand profile, namely a "Non-Event" profile that maintained a low baseload and accounted for 70% of the days in a year, a "1-Day Event" profile that lasted only a few hours, and for events spanning multiple days a "Start", "Middle" and "End" day profile that varied greatly in demand magnitude. The demand profiles were then used to develop an annual demand profile for an average marae that was broadly representative of a wide range of marae. Different configurations of solar and battery powered systems were then applied to the annual demand and a technoeconomic analysis performed to determine whether a specific configuration met the needs of the average marae or not, which then produced a range of acceptable system sizes based on the needs specified. Not many solar and battery configurations resulted in positive economic returns for the marae alone, but widening the scope of the analysis to the surrounding community allows other interests such as local grid resilience to be considered, some of which may justify a marae's decision to invest in a non-economic system to gain better community benefits. While investigating the use of peer-to-peer energy trading and community energy scenarios, sharing excess energy generated by a system with the wider community was also found to improve the economic outlook of solar for marae.

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1 INTRODUCTION

> *Maui found the days too short, for the sun moved too fast across the sky. With the assistance of his brothers he therefore made stout ropes and a noose. Then the five hid themselves far to the east, by the edge of the world whence the sun was wont to rise, building on each side a long, high clay wall with hides at each end. The noose was stretched and, when the sun rose well up into the snare, the ropes were pulled tight. Thereupon the hero rushed forward with his enchanted jawbone and belaboured the unfortunate captive so sorely that, when released, the sun could merely hobble slowly across the sky.*
>
> (McLintock, 1966)

Māori are no strangers to capturing the sun. The advent of solar energy capture technologies brings to mind the story of how Māui, a renowned hero in Polynesian mythology, once caught the sun because he moved too quickly across the sky and did not leave enough time for Māui's people to complete their work. This thesis attempts to walk in his footsteps, and once again capture the sun to benefit the people.

Solar power is an increasingly popular renewable alternative to traditional fossil fuel electricity generation methods. Most commonly seen as photovoltaic (PV) panels mounted to household rooftops or in large-scale ground-mounted arrays, this technology captures the sun's rays and converts the light into an electric DC current. This current is converted to AC through an inverter, then used to power an electrical demand or charge batteries for later use. The amount of energy available for capture is referred to as solar irradiation, and is dependent on conditions such as location, weather (cloud cover), time of day and season, with lower irradiation in winter compared to summer and no irradiation at night.

Solar powered systems have often been thought of in the context of providing energy for residential houses, commercial buildings such as offices and supermarkets, and as utilities for the national grid. However, none of these classifications are particularly applicable to marae, which are the target of this research.

Marae are the cultural centres of Māori society, containing the history of the land and people of the area, providing a home for whānau (family) to return to, and accommodating most important events in te ao Māori. They are cared for voluntarily by whānau, and maintenance and operational costs paid through koha (donations) collected during events and sometimes through paid bookings. In recent years, the climbing costs of electricity have made paying the bills difficult, and marae have started looking for alternative energy sources to help save money. One of the most popular of these sources is solar power, which is promoted as a low-cost option that provides free energy for users when the sun is shining. Coupling this with battery storage for overnight use, it seems a promising solution for marae. However, the design of such a system for marae is complicated by the variable nature of their electricity demand, with different sized events occurring at random throughout the year, each with a unique usage pattern.

The non-standard electricity demand profile of a marae means that the typical solar and battery system design methodologies are not as easily applicable and could lead to either over- or under-sizing the system and failing to meet the marae's needs. A bespoke, custom solution is thus needed for most marae, which will take longer to design and likely cost more than off-the-counter systems such as those targeted towards residential households.

Since it is difficult to estimate an appropriate system size for marae simply, it is also difficult for companies to offer quotes and explain the benefits and drawbacks for marae interested in solar technologies. This thesis aims to increase understanding around how solar power could benefit marae, first by investigating the characteristic electricity demand profile of marae, then by observing how proposed system configurations meet the demand. The potential benefits of the system to the wider community will also be explored.

The research moves beyond site-specific modelling to develop a more generalised framework for analysis and results that can be applied to most marae in New Zealand, making it a useful reference point for solar consultants and marae alike. The following chapters will provide some background to the research, an analysis of the characteristic marae demand profile and solar energy supply system, as well as an investigation into how benefits for the community could potentially be increased.

2 BACKGROUND

2.1 INTRODUCTION

This chapter will provide an overview of the literature available that is relevant to this research. In particular, the technical concepts used as a basis for the methodologies of the study as well as references to the unique aspects of a New Zealand-based project that need to be considered. Before any of that, some background on the Māori worldview and an explanation of what a marae is and their uses will be provided for future reference.

2.2 TE AO MĀORI

Māori are the tangata whenua (indigenous people) of Aotearoa New Zealand, and have their own customs, language and values separate to the wider New Zealand community.

In the Māori worldview, everything is related. People are connected with the environment through whakapapa (genealogy) and see the world as a "vast and complex whānau (family)" (Royal, 2007). Whakapapa also denotes kinship groups with other people, and Māori society is structured on these relationships. Four types of kin groups are widely recognised by Māori, namely, whānau (the family an individual is born into), hapū (subtribe, or grouping of related whānau), iwi (tribe, or grouping of related hapū) and waka (the canoe on which common ancestors migrated to New Zealand) (Taonui, 2005). This structure can be seen in the diagram below.

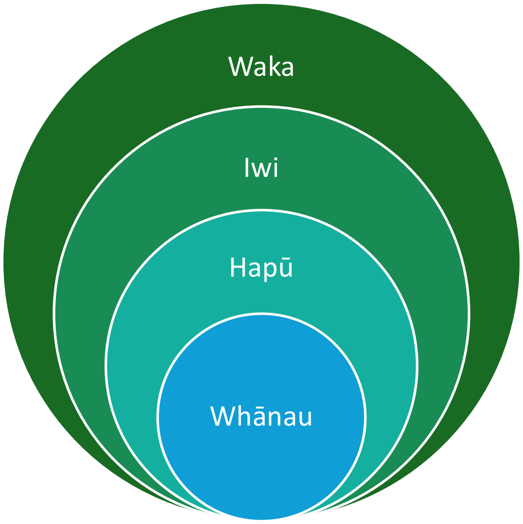

Figure 1: Māori Social Structure

Māori did not traditionally have a written language, so knowledge was passed down orally through waiata (songs) and pūrakau (stories).

Values and practices were also passed down using pūrakau, as Royal (2007) wrote: “The Māori traditions such as those relating to Māui illustrate fundamental behaviours active in Māori society and also highlight various concepts of traditional Māori culture. They were used as an educational tool to highlight and illustrate morals, principles, models and behaviours which Māori could learn to apply in everyday life.”

Using pūrakau as an educational tool, the story of Māui capturing the sun became both an inspiration and a conceptual guide for this research. Different parts of the story were used to frame the research in a way that asked the question “What would Māui do?” and helped generate solutions more in line with Māori values.

A social unit not referred to in the graph above (Figure 1) is the marae, which are typically linked to a number of whānau and/or hapū, traditionally living together in a community but in modern times often whānau members may live further away (i.e., in other towns/cities or overseas).

2.3 WHAT IS A MARAE?

Marae are the traditional meeting grounds of the Māori people and are communally owned by a number of whānau or hapū. They have significant cultural value beyond being just a complex of buildings, as one of the few remaining places where traditional art (marae are often ornately carved and painted in traditional patterns), customs and tikanga (practices) are on full display.

As one author put it most concisely:

> The marae is the hub of a Māori community, the place where people gather in times of joy and celebration, and times of stress and sadness. It generally has a wharenui (meeting house), a wharekai (dining room with attached kitchen) and a shower and toilet block. In older marae this is often a building separate from the others. In more modern marae it is attached to the meeting house. (Whaanga, 2013)

An example layout is shown below (Figure 2).

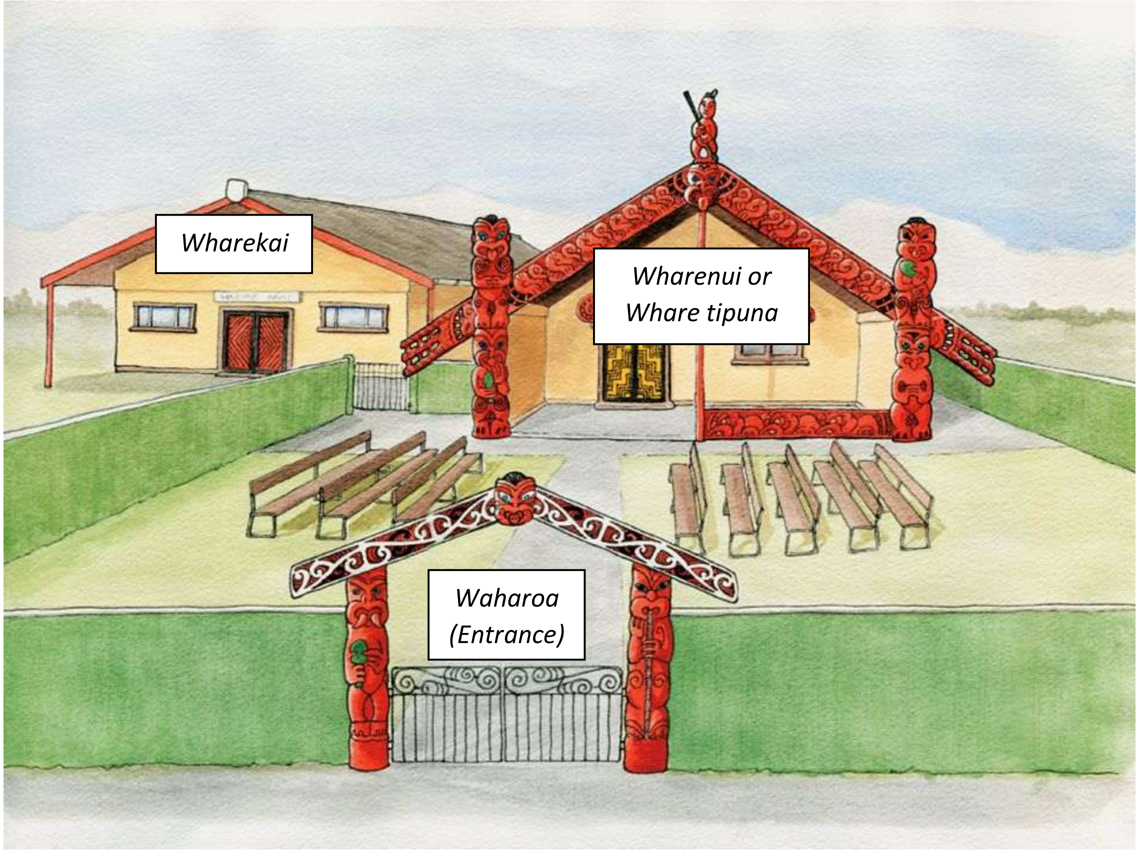

Figure 2: Example Marae Layout (Macfarlane, 2011)

A whare tipuna is a type of wharenui where the meeting house is carved to embody an ancestor. Inside, other ancestors are carved into supporting posts, and the history of the surrounding land and people woven into wall panels and painted on the rafters. It is thus an extremely sacred building to Māori, representing their history, ancestry and connection to the land.

Manaakitanga (hospitality) is an important value to Māori (the word “marae” itself also meaning “generous” or “hospitable”), and marae take pride in their ability to cater for large numbers of guests, with commercially sized kitchens including large gas cookers and often multiple refrigerators and freezers, ablution blocks with multiple toilets and shower cubicles, and mattresses provided to sleep on in the wharenui during overnight stays. This sentiment is captured in the whakatauki (proverb) “*He tangata takahi manuhiri, he marae puehu”* translated to “A person who mistreats their guests has a dusty marae” meaning they will not be visited again.

Most important events for Māori are hosted at marae, the largest of which would usually be tangihanga or funerals. At a tangihanga, the tūpapaku (deceased’s body) would be bought to lay at the marae for a number of days (often three or more) with the whānau pani (bereaved) accompanying them. Manuhiri (guests) enter the marae in ope (groups) to pay their respects and would later be given food and drink as is custom. Some guests may stay longer or for the full duration of the tangihanga, while others leave and may return on later days. All guests present at mealtimes are fed, and the kitchen is kept busy preparing food and cleaning the dining hall each day. Many guests will stay overnight at the marae if they do not live nearby. The final day of the tangihanga is the nehu (burial) and is the day when the most guests will be present. A hākari (feast) is prepared for everyone attending, and the marae tidied once the guests have left. The total number of guests present at any time during a tangihanga can vary from less than fifty to a few hundred and even thousands at the tangihanga of prominent leaders such as at the late Māori King Tuheitia's funeral in 2024 (1News Reporters, 2024). Other events a marae may host include wānanga (educational workshops or seminars, usually over multiple days) and hui (meetings or gatherings, often only an hour or longer).

The majority of marae are run on a mix of grid-tied electricity (for lights, refrigerators and room heating/cooling) and gas bottles (for hot water and cooking), though some still use biomass boilers for hot water. A growing number of marae are investing in solar panels and batteries to provide some or all of their electricity needs (Endless Energy NZ, 2024b, 2024a; Heagney, 2024; The Lines Company, 2022), which was the original inspiration behind this research. Some of the interests of marae and Māori people in energy matters will be discussed in the following section.

2.4 MĀORI ENERGY INTERESTS

It is important to note that Māori are not a homogenous people, and values and interests will differ from place to place, hapū to hapū and even person to person. Māori interests in the energy sector are thus wide and varied, from active participation in the energy market as is the case for some iwi with geothermal resources (Tutua-Nathan, 1992), to staunch adversaries in the installation of new energy generation on sites of cultural significance (MacArthur & Matthewman, 2018).

Some key values are nonetheless widely shared, including for example kaitiakitanga (guardianship of the environment), manaakitanga (hospitality), whanaungatanga (relationships) and tino rangatiratanga (self-determination) (Harmsworth, 2005). This value system differs from the mainstream "Western" perspective in that the world is viewed holistically through relationships with people and the environment, which influences decision-making even at the corporate level. To understand this difference, Bargh (2012) suggested a set of ethical coordinates that may reflect Māori enterprise considerations based on traditional values (Figure 3).

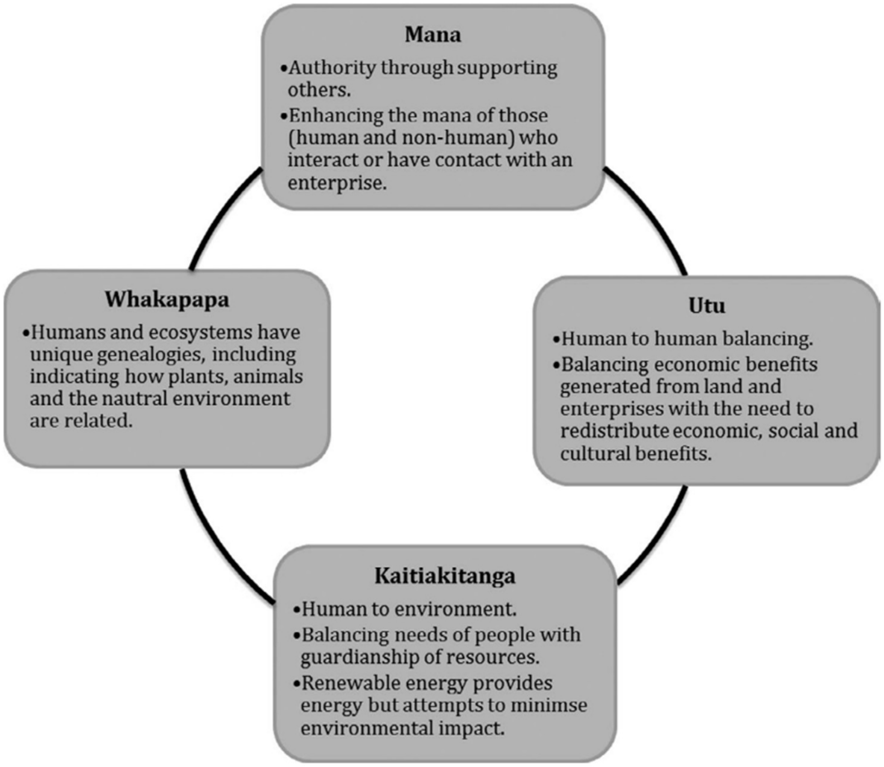

Figure 3: Māori Ethical Coordinates (Bargh, 2012)

Taking these factors into account, decisions on future investments may look very different for Māori than non-Māori, with a greater focus on preserving the natural environment and distribution of benefits to uplift the wider community and future generations rather than short-term economic gains. These values can also be seen in the project outlines of the recipients of the recently closed "Māori Housing Renewable Energy Fund", where the majority of the funded projects targeted houses of kaumātua (elders), disadvantaged families, papakāinga (communal villages) and marae (MBIE, 2023). The projects also favoured solar and battery powered systems over other renewable energy sources such as hydropower and wind, indicating a growing interest from Māori in these technologies.

It should be noted that grants and funding pools like the "Māori Housing Renewable Energy Fund" as well as other fundraising ventures are expected to be the typical methods of raising money to pay for a solar powered system. Marae have limited financial resources available for investment, with income usually coming from koha (donations) and in some cases booking charges, which are then used to pay bills (i.e., for electricity, water, insurance, etc.) and maintenance costs (Whaanga, 2013). Fundraisers and working bees are also often used to help pay for expensive upgrades and repairs. According to Whaanga (2013), "keeping a marae alive and functioning well is a huge task", and one that requires dedication and hard work from their communities. As such, many marae fall into disrepair or struggle to afford insurance without a strong community backing.

This means that it could be difficult for marae to finance larger solar projects, and even if they made enough money to afford it, the project would face greater scrutiny as the marae might find other projects such as upgrading equipment or investing in water treatment more valuable. A holistic review of the marae, its issues and desired improvement projects could be done to determine which of the projects is the most beneficial, however the results of this will vary from marae to marae and is out of scope for this research.

Another report that provided some insight into Māori views on energy was prepared by Haemata Limited (2022) for the Ministry of Business, Innovation and Employment, exploring Māori perspectives on the measurement of energy wellbeing. Key areas of interest were identified from a series of wānanga or discussions with different Māori groups, and suggestions made on how to respond to these concerns. In terms of methodology, researchers were encouraged to make good use of existing data, to actually talk to the communities they were analysing, and understand the value of incorporating the Māori worldview and traditional narratives into their work. Issues such as high electricity prices, poor insulation and a desire for better energy information availability were also discussed, and ideas around Māori energy sovereignty and the future of energy shared.

The issues raised in Haemata Limited's (2022) report as well as the values systems described by Bargh (2012) and Harmsworth (2005) are useful in understanding the drivers behind marae energy initiatives, and can be used to help shape a range of solutions that are more acceptable or appealing to Māori. Other factors to consider can come from an analysis of similar projects internationally, especially considering other indigenous peoples. This will be explored in the next section.

2.5 INDIGENOUS COMMUNITY ENERGY PROJECTS

Māori are not wholly unique in their values systems, as caring for the natural environment and working for the benefit of their communities rather than the individual are values shared by many other indigenous cultures world-wide. These indigenous peoples often also face the same challenges as Māori, with historic injustices resulting in modern inequities (Smith, 2021), most relevant to this research are indigenous communities facing energy hardship and lack of reliable energy supply (Graff et al., 2021). Taking inspiration from energy projects implemented with indigenous people in other countries and noting the challenges identified is thus a valuable method of understanding key concepts required for the success of similar endeavours in New Zealand.

A review of current literature surrounding indigenous community energy projects was conducted for this purpose, with the term “community energy” referring specifically to energy initiatives organised “by the people, for the people” in a specified community, though the term is used much more broadly in most of the literature. This refined definition aligns more closely with the intended outcomes of a marae-based solar energy installation, and so helped filter the available literature on the subject.

Interestingly, many of the identified studies found in this category were associated with Canada and relations with the First Nations, reflecting the country’s commitment to reconciliation. For example, Leonhardt et al. (2023) focussed on the government instruments supporting or hindering community energy projects in Northern and Indigenous communities, while Zapata (2024) looked at the impact of renewable energy projects on the well-being of remote Indigenous communities in Canada. Hoicka & MacArthur (2018) compared community energy projects occuring in Canada with those happening in New Zealand, mentioning that both countries contained a form of community energy including Indigenous peoples participation. Australia’s “First Nations Clean Energy Strategy”, prepared by The Department of Climate Change, Energy, the Environment and Water (2024), also referred to studies from both New Zealand and Canada along with local projects in their case studies.

These and other reports identified common themes in terms of the benefits and issues arising from community energy initiatives, for example noting that the positive impacts of community energy projects reached beyond economic or technical benefits (i.e., savings on power bills or increased energy resilience) to include aspects such as community well-being, education and employment as benefits (Hoicka & MacArthur, 2018). Along with the benefits, many issues were also noted, including regulatory challenges, limited funding, and sometimes a lack of meaningful engagement with the community (The Department of Climate Change, 2024).

One of the most prevalent concepts referred to in these reports was a desire for self-determination, or an increase in the ability to manage and provide for their own people. In terms of energy, this means self-sufficiency and control over their energy resources, reducing reliance on outside sources and supply (Stefanelli et al., 2019).

Community education was specified as both a benefit (The Department of Climate Change, 2024) and a challenge (Krupa, 2012), as gaining the technical expertise to install and manage a community energy system was valuable to the self-determination goals of the community, but that level of expertise was also difficult to obtain with limited resources.

Community engagement had a similarly mixed reaction, with projects that prioritised proactive community engagement and involved people from the very beginning received favourably, but projects that researched a community without engaging with it eliciting a negative response. Meaningful engagement can lead to benefits outside of the project, such as providing employment opportunities and education that could have transformative impacts on the community, while also increasing community support and acceptance for the project (The Department of Climate Change, 2024).

Securing funding for community energy projects was often a key barrier in their uptake, with the Australian Department of Climate Change, Energy, the Environment and Water (2024) mentioning that many of the representative bodies involved in a community energy project operated with small balance sheets and limited access to finance. As mentioned in the previous section, this is also a pressing issue for many marae.

Regulatory challenges varied from country to country, but New Zealand was not immune. Abaunza (2020), for example, wrote a thesis on the law for active electricity consumers including regulations surrounding community energy in New Zealand, Colombia and the Netherlands, and recommended simplified licensing and procedures were needed for small prosumers (electricity consumers that also supply some energy back to the grid).

Krupa (2012) ultimately summarised the challenges faced by Indigenous-led community energy projects as the “Four Cs” of “cash”, “capacity”, “clarity”, and “circumstances” and the “Two Ls” of “lack of legitimacy” and “lack of equality”.

The success of a community energy project could thus be defined as one that overcomes these barriers, has full community engagement, increases the capacity of the community for self-determination, and provides wider benefits to the community including better education and well-being.

Apart from the cultural and community needs specified in the above sections, the technical limitations around solar and battery powered systems also need to be known to design an achievable solution for marae, which will be discussed next.

2.6 TECHNICAL CONCEPTS

There are many important considerations needed in the technical analysis of a solar and battery system for marae. This section will outline the literature on methodologies for characterising electricity demand and modelling solar power systems, the concepts used in energy trading, as well as the data sources used in the analysis.

2.6.1 Modelling Solar and Battery Powered Systems

Solar energy has been a hot topic in the renewable energy space for many years now, so there is a wealth of methods available on PV and battery system design and modelling (Khatib et al., 2013). Two of the main techniques used to design and size these systems are economic analyses and supply reliability analyses, where system sizes are optimised to meet selected design parameters such as percentage of electricity demand met (Kaushika et al., 2005). This is usually done either intuitively using simplified assumptions, numerically by simulating the energy balance in a specified time period, or analytically by defining the size of the system as a function of supply reliability.

Short et al. (1995) working with the National Renewable Energy Laboratory (NREL) developed a manual of the key analytical techniques for the economic evaluation of renewable energy systems, which can be used as a basis for technoeconomic studies. EECA presented a similar guide for the New Zealand context, focused on commercial scale solar and the techniques required for financial performance analysis by businesses looking to install on-site solar (Miller & Gretton, 2021), while another report was prepared for MBIE in regards to the economics of utility-scale solar in New Zealand (Miller, 2020).

Both of these reports are useful for analyses in their respective categories, especially when looking at the assumptions and estimates used for the New Zealand context rather than internationally. For example, Miller & Gretton (2021) included a costing curve for solar by capacity in New Zealand, which differs from international estimates in similar studies (Figure 4).

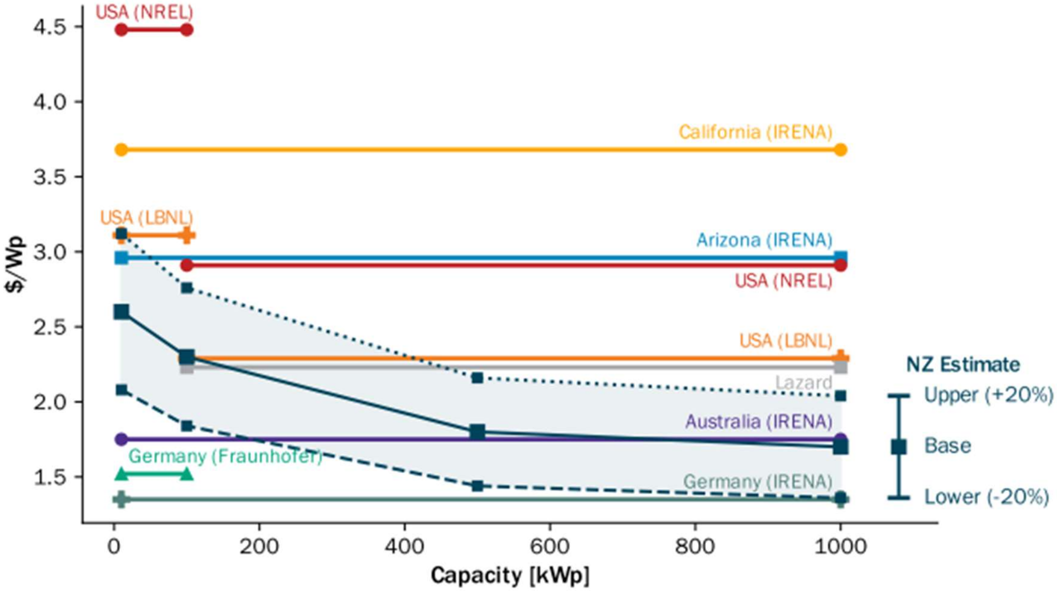

Figure 4: Per unit capital cost (NZD) at 2021 versus system size for commercial rooftop solar installations (Miller & Gretton, 2021)

These reports focused only on solar PV; separate reports are available focusing only on batteries which together can give a more complete view of the entire system. One such report was written by Transpower, the New Zealand grid owner and system operator, which dove into the potential value added by batteries to the grid (Transpower New Zealand Limited, 2017). The assumptions used in this report were similarly good starting points for economic analyses in the New Zealand context.

2.6.2 Data Sources

To perform numerical technical analyses on solar powered systems two main datasets are required: the electrical demand to be fulfilled and the solar irradiation at the specified location (Khatib et al., 2013).

NIWA, the National Institute for Water and Atmospheric Research, produced a map of hourly irradiance data averaged over a ten-year period for all of New Zealand which was used in this research (NIWA, 2019). Many other irradiation datasets exist such as NASA's MERRA dataset and are often embedded in software such as Renewables.ninja (Pfenninger & Staffell, 2016; Rienecker et al., 2011). The NIWA dataset was selected because it was made specifically for New Zealand and was based on measured data that took into account clouds blocking the sun as well as a model of the landscape at the location selected rather than calculated purely from the sun's position or using meteorological data to derive, so was assumed to provide a satisfactory view of the situation.

A characteristic electricity demand profile for marae will be developed in this research, so a more thorough review of the relevant literature will be provided in the following section.

2.6.3 Demand Profiling

The electricity demand profile is an important aspect required in the design and sizing of a solar PV and battery system. Given an average profile of how much electricity is being used at what times, the system can be adjusted to fit the demand and ensure a reliable electricity supply via power supply probability analyses. Usually this is unique to a building and requires an in-depth analysis to come up with a bespoke solution to the demand but in some cases the demand profile for a building type is already well known.

Averaged household demand profiles have been extensively developed both in New Zealand (Anderson et al., 2018; Isaacs & HEEP Team, 2002) and internationally (Wang et al., 2023), which has led to an increase in “Residential” sized ready-made systems entering the market that can fulfil most houses needs without requiring a comprehensive survey at an additional cost. Businesses, industrial sites and schools similarly have a large number of studies done on defining an appropriate demand profile, with BRANZ for example creating a method of estimating non-residential building energy use based on area and thermal simulation models (Amitrano et al., 2014).

Marae are unique energy users that belong in a category of their own, having a low typical electricity demand when it is not in use, but high, variable demand when it is in use. Not much work has been done on developing a characteristic demand curve for marae, although previous studies on designing renewable energy systems for specific marae have attempted to bridge this gap for the intended sites. In the absence of measurable data, Apperley & Toki (2023) synthesised a representative demand profile for a marae on Aotea (Great Barrier Island) based on household demand profiles, with additional loads added for hui based on community suggestions. Curd (2017) explored the energy demand of Parihaka, a papakāinga in Taranaki that included 10 residential houses (representative of wider community) and three marae. The gas, electricity and biomass usage of the community was estimated by taking individual analyses of each building over a 12-month period, noting difficulties with accurately measuring energy use from wood burning appliances and portable LPG appliances. A trade-off between accuracy, data processing labour intensity and cost of equipment installation was also mentioned as a problem common in these types of studies.

2.6.4 Energy Trading

The simplest way to sell excess electricity generated by a small solar PV and battery system in New Zealand is to enter into a buy-back agreement with an electricity provider. In this case, an analysis will be carried out on the local grid to ensure it is capable of carrying the extra electricity added by the system, and if no problems arise the electricity can be sold to the provider at a specified rate. The income generated in this way will appear as a credit on future electricity bills, offsetting what would usually be paid in full for the usage. This arrangement works well for owners whose solar PV systems only partially fulfil their needs as it increases their savings, however for off-grid owners who would not usually have an electricity bill, the "credit" aspect of the arrangement means they would not receive any benefit from the sale. Another issue is that the buy-back rates of most electricity providers are lower than the market rate for electricity (buy-back rates are currently between 8-17 c/kWh, while standard electricity prices are between 20-30 c/kWh (Power Compare, 2025)), so it is more economical to use the generated electricity as much as possible to gain greater savings than it is to sell the electricity for income in this way.

An emerging solution to these problems is Peer-to-Peer Trading, where the electricity is sold to specified neighbouring buildings at a rate lower than their usual bills but optionally higher than the expected buy-back rate, resulting in greater income rates for the owner and savings for the wider community (IRENA, 2020). This kind of arrangement usually requires a broker or third-party organiser to carry out the legal and technical procedures required to simplify the experience, as an electricity provider must be involved in the transfer of electricity across a property boundary (Abaunza, 2020).

The final issue is with New Zealand's aging distribution and transmission infrastructure. There may be cases where the proposed system load to be added to the network and/or grid may be greater than the current capacity, in which case upgrades to the network would be required to install it. With the current regulatory set-up, the cost for this upgrade would be borne by the user who needed it (first-mover disadvantage) and thus could add a significant cost to the project. Understanding whether this is the case or not before beginning the project is essential to know whether it is worth installing a system of the proposed size. This consideration is outside the scope of this study as the results are intended to be generalised, so locational aspects such as this become difficult to quantify. However, future work could benefit from including this.

2.7 RESEARCH GAP

From the literature review carried out around marae-based solar energy systems, three main research gaps were identified that this study will attempt to cover. The first is the absence of a data-based characteristic marae electricity demand profile, which is important in the design of a solar and battery system specifically for marae. An established design methodology and approximate range of "marae-sized" solar and battery systems is the second gap needing to be filled, and the inclusion of

Māori values and perspectives in the design and selection methodology another valuable addition to literature.

2.8 CONCLUSION

The technical methodologies for designing solar and battery powered systems are well defined in literature, and when used in conjunction with standardised electricity demand profiles can be used to find the most suitable system sizes for the specified demand type. Since there has been limited research done on marae electricity demands it is relatively difficult to design appropriate solutions for them, a gap that this research seeks to address. Incorporating Māori values and perspectives in the design and selection of solar and battery powered systems for marae also allows for more valuable solutions to be developed.

3 MARAE AND COMMUNITY ENERGY DEMAND PROFILING

3.1 INTRODUCTION

No matter which of his adventures, Māui was always prepared before beginning it. He would ask questions and seek to understand the problem and situation, then devise a plan and prepare any necessary equipment before setting off. Before capturing the sun, Māui first observed the issues his people were facing, struggling to work productively with limited daylight hours, and decided the best way to help them would be to slow down the sun. The same principles can be applied in this research: before attempting to solve the problem of whether or not solar energy is suitable for marae, the problem itself must first be defined. The suitability of a solar powered system will depend on the specified needs of the marae, so that need must be investigated prior to the analysis of possible solutions.

From a purely energy focused perspective, the average energy demand profile is the need to be fulfilled, i.e., how much and what type of energy is used at what times. The energy demand curves for common building types (i.e., residential, school, industrial) and the average amounts of energy used are well documented in literature, making designing energy systems for them based on approximations relatively straightforward even in the absence of detailed site data. However, none of the typical examples of building energy use patterns like those described above are especially representative of a marae's energy demand.

Marae host a variety of events throughout the year, ranging from (for example) three or more-day tangihanga to weekend-long wānanga or hui that last only a few hours and many others. Each event will have a unique demand profile, different even from other events of the same type, and even "typical" demands can vary across different marae. Identifying a characteristic demand profile that can be used to represent the needs of marae is thus extremely challenging, but doing so could benefit many marae by providing useful data for electricians and consultants to perform estimates from, helping reduce the number of issues arising from under- or over-sized systems based on inapplicable or mistaken data.

The aim of this chapter is thus to establish an appropriate energy demand profile for a marae which can then be used in the following system design chapter. The first step in this is to identify what the main energy sources are, then obtaining usage data for each type as accurately as possible. The data can then be processed and analysed to find patterns, and a total energy demand curve developed from the constituent results. As marae are intrinsically connected to their communities, the energy demand curve of potential nearby buildings was also found for comparison and use in analyses of P2P energy trading opportunities.

3.2 DATA

Electricity usage data was provided by three different marae, designated as “Marae A”, “Marae B” and “Marae C” for anonymity. These three marae used Mercury as an electricity provider and were able to obtain historic demand data from Mercury’s website. The data was formatted in half-hourly increments, showing the electricity usage in kWh and charge in dollars (excluding fixed) at every half hour for an entire year.

Marae C and Marae B provided data for the year starting January 2023, while Marae A’s data started in August 2023. Because of this, and the fact that due to assumed power outages there were some gaps in the data, the raw data required some preprocessing before analysis. The average half-hourly demand for the year was found for each marae and used to fill in any blanks. For Marae A, the data was originally rearranged to match the dates given for Marae B and Marae C as much as possible, however after performing a seasonal decomposition of the energy demand in initial studies it was found that the demand was solely dependent on the size of the event rather than the season, with non-event days staying constant despite the weather, and with similarly varied high and low event demands being seen throughout the year. Since this indicated that the date was somewhat irrelevant to the demand, Marae A’s half-hourly demands were left as is and the dates assumed to match Marae B and Marae C.

With the demand data thus arranged, it was ready for analysis, the steps of which will be discussed in the next section.

3.3 MARAE ELECTRICITY DEMAND PROFILING METHODOLOGY

The demand data was analysed in three stages: first, by identifying some of the daily usage patterns using k-means clustering, then categorising and filtering daily usage pattern types, and finally synthesising a demand curve for each day type then distributing to synthesise a year’s worth of expected “average” marae usage data.

3.3.1 Stage 1: Identifying Demand Patterns

K-means clustering was initially used to identify marae daily demand patterns, as it is a simple, straightforward algorithm commonly used to find patterns in data by randomly selecting a specified number of cluster “centres” (expected patterns for the data to match), then grouping the data based on which of the centres a day’s demand pattern most closely resembles (Ikotun et al., 2023). The process is repeated until a minimum deviation of patterns from the generated centres is found, and the centres then used to represent the different demand day types.

The demand data was initially split into 24-hour periods (48 datapoints in each) then grouped into 16 clusters as an initial guess at the number of distinct demand patterns there may be. However, it became immediately apparent that marae usage patterns were extremely irregular, varying greatly in both demand magnitude and time of use. This meant the method struggled to provide accurate groupings, often singling out specific days and doubling up on groups that were visually similar in pattern but differed in scale (Figure 5).

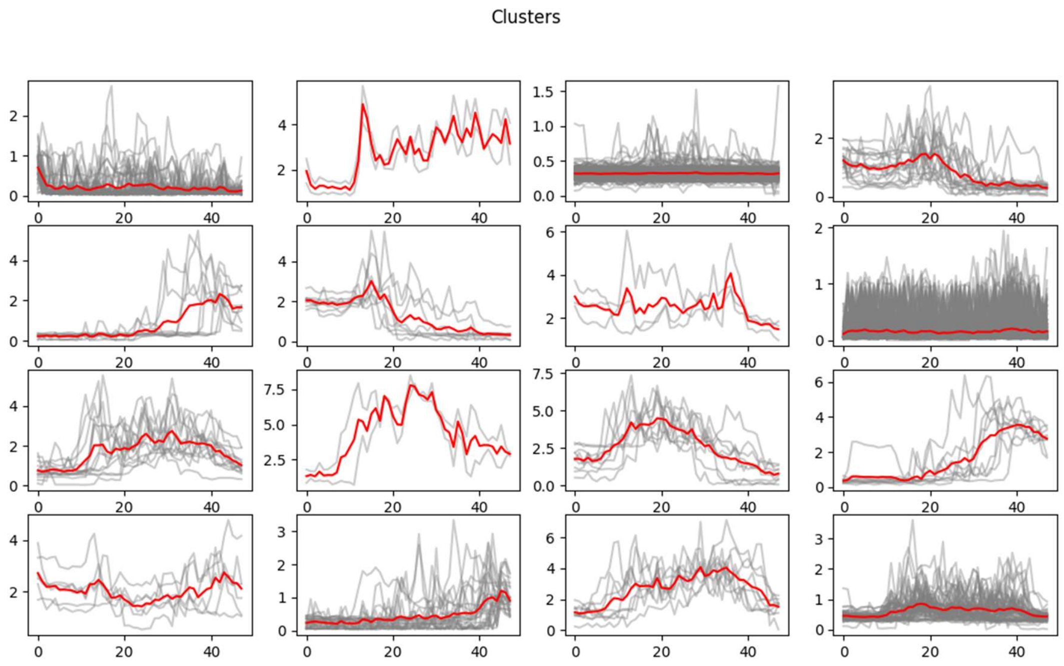

Figure 5: Marae Demand Data Grouped With K-means Clustering

Normalising the data helped group days with similar time of use patterns but magnified the issue of irregular oscillations which made distinguishing between some groups difficult, particularly when reducing the number of clusters to reflect the number of similar patterns identified (Figure 6).

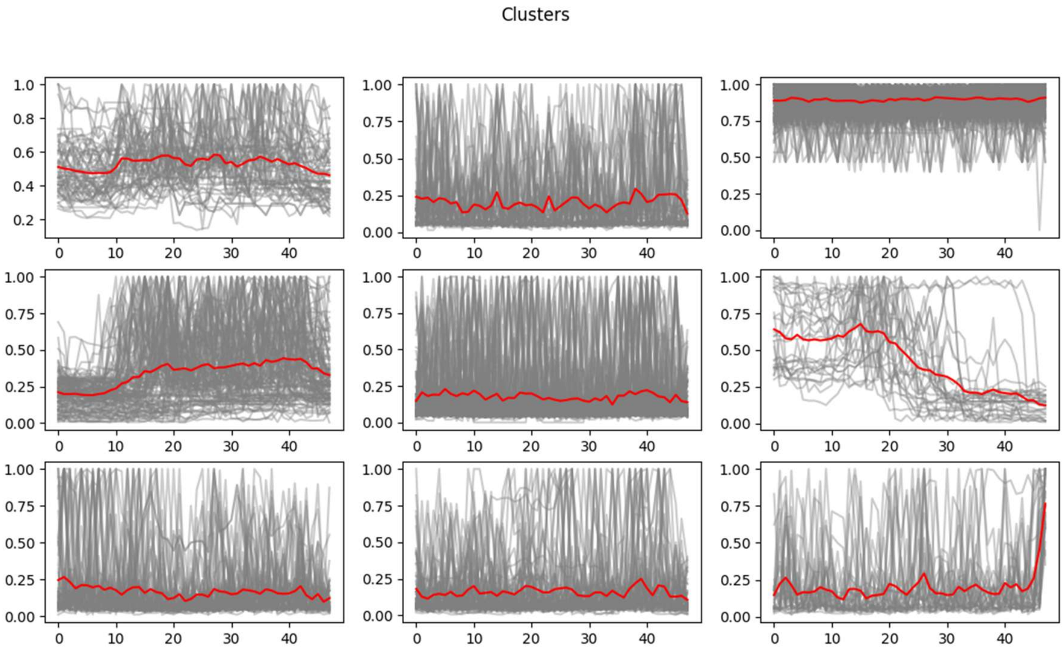

Figure 6: Normalised Marae Demand Data With K-means Clustering

Clustering the data nevertheless made apparent a few types of days, that is, most days typically had a low and flat profile, though oscillated frequently with a small margin around a median point, while some days started at a low, flat profile then quickly ramped up, or did the reverse by starting high and ramping down to a low, flat profile. Others started at a mid-point then ramped up, oscillated drastically while remaining mostly high, then ramped back down to a mid-point, and still others had completely irregular patterns that were difficult to place into a category with others. In the end, personal experience with marae events was used to specify groups, and the data filtered in Excel to match, which gave relatively similar profiles to those identified by the clustering method but contained a greater number of data points and so was expected to be more accurately representative of actual demand profiles. The methodology for this is outlined below.

3.3.2 Stage 2: Categorising and Synthesising Daily Demand Types

Marae host numerous types of events which will all have different electricity demand profiles depending on their needs. A broad classification was applied for this study, with events labelled as either “Single” or “Multiple” day events. Multi-day events were further split into constituent parts, with “Start”, “Middle” and “End” days. “Non-Event” days were defined as those whose daily demand sum fell below the median daily demand, since the majority of the daily demands were for non-event days.

The marae demand data was given in half-hourly increments over an entire year, with the date and time beside it in separate columns. To distinguish between the different day types, the sum of each day was found, and if the sum was higher than the specified limit that day would be classes as an "Event" day, if not it would be classed as "Non-Event". If the day prior to and after the "Event" day were "Non-Event" days, the day would be further specified as a "1-Day" event. If only the day prior to an event was classed as a "Non-Event" day, the day would be classed as a "Start" day. If only the day following an event day was classed as a "Non-Event" day, the day would be classed as an "End" day. All other days were assumed to be "Middle" days. This decision tree is shown in Figure 7 below.

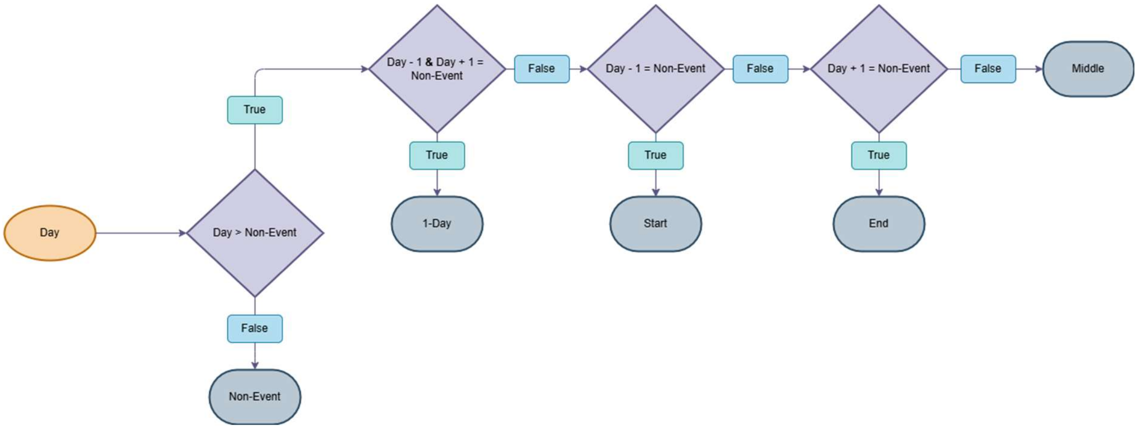

Figure 7: Day Type Classification Decision Tree

Once each day in the year had been classified, the data was separated so that each day was grouped with other days of the same type. The number of days, average usage per half hour, average daily usage and total annual usage for each group was found and used to analyse how energy use is distributed between day types. The average of the demand at each half-hour in a group was also found and used to represent a characteristic demand profile for each day type. This process was repeated for all three marae, and the resultant data averaged for each day type to get overall approximate data and demand profiles.

3.3.3 Stage 3: Normalising the Demand Curves

Since the data was so variable, a method was required to approximate a general characteristic demand profile. The average demand profiles found in the previous step are useful in identifying the shape of the demand curve, but the wide range of event sizes and lengths necessitated an additional analysis to ensure the magnitude of the demand curve is more accurately representative of the true demand. To this end, the demand curve for each day type was first normalised, then an expected "maximum event" demand curve was generated using the average demand curve and the highest hour of usage in the year to create an adjusted event profile that would encapsulate almost every possible event size including ones higher than those found in the years' worth of data. This was done by following the procedure below:

For each day type, each hour of the averaged daily demand was normalised based on the highest and lowest usage hour of that day via the equation below.

$$D_{norm,i} = \frac{D_i - D_{min,d}}{D_{max,d} - D_{min,d}} \qquad \textit{(Equation 1)}$$

Where:

- D_i = the demand at hour "i" (kWh)
- $D_{min,d}$ = the lowest hour of demand in the day (kWh)
- $D_{max,d}$ = the highest hour of demand in the day (kWh)
- $D_{norm,i}$ = The normalised demand at hour "x" (unitless)

The maximum event demand was then obtained for each hour of the day by the following equation:

$$D_{adj,i} = D_{norm,i} \times \left(D_{max,y} - D_b\right) + D_b \qquad \textit{(Equation 2)}$$

Where:

- $D_{max,y}$ = the highest hour of demand in the year (kWh)
- D_b = the baseload, assumed to be the average hourly demand for non-event days (kWh)
- $D_{adj,i}$ = the adjusted demand at hour "i" of the expected maximum event (kWh)

This process was repeated for the averaged event start day, middle day and end day to get an overall maximum event profile. The profile developed assumes that the highest hour in the year is the absolute maximum demand possible for the marae, and that the characteristic demand profiles found are accurately representative of the true demand profile. It can be used to compare with solar irradiation data and see how different sized solar PV and battery systems handle the scenario. The average and normalised demand curves developed here can still be used separately to the maximum event profile by pairing with analysis on the event frequency and magnitude to create an artificial annual demand profile. This process will be explained in more detail in the next section.

3.3.4 Stage 4: Understanding Event Frequency and Magnitude Distribution

An analysis was carried out on the frequency of events and their magnitudes, as there was a great amount of variation found in the data given. To find the frequency of events, the number of days in each day type group was counted for each marae, and the results averaged. The total annual energy usage of each day type was also summed for each marae and averaged for comparison. The average length of events was found by counting the number of consecutive days where the energy demand was above the baseload, and the median and standard deviation derived from the overall results. To find the range of magnitudes, the average, highest and lowest half-hourly and daily demand was found from the grouped data for each day type at each marae. Using Microsoft Excel's quartile function, the 25th and 75th quartiles of the daily usage were found for each day type and demand, then used to find the interquartile range by subtracting the 25th quartile's value from the 75th quartile. The overall range was found by subtracting the maximum from the minimum value, and a peak-to-average ratio obtained by dividing the maximum by the average.

Using these event frequencies and magnitudes with the demand curves obtained in the previous section, an annual demand profile was generated by distributing events across an example year. There was no obvious pattern to the frequency of events, and though some events could be predicted far in advance, i.e., the poukai of marae aligned with the Kīngitanga falling on set days or events booked months prior, others such as tangihanga are harder to predict. The whakatauki (proverb) "Ko Aituā, kāore āna maramataka" (Death has no calendars) reflects this sentiment.

To preserve the unpredictable nature of events, approximately 33 events (based on event frequency, see results) were distributed randomly throughout the year by using Excel's RANDBETWEEN function to generate a number between 1 and 365 for each day, and if the number associated with a date was less than 33 it was assumed to be the start of an event. A second column was made to find the event length, where the CHOOSE function was used with RANDBETWEEN to randomly select a length between 1 and 5 days while favouring 3-day events most heavily, followed by 1-, 2- and 4-day events. The equation used can be seen below.

$$Event\ Length = \ CHOOSE(RANDBETWEEN(1,10),1,1,2,2,3,3,3,4,4,5) \qquad \textit{(Equation 3)}$$

Days between the start and end (start date + event length) of an event were marked as "Event" days, while all other days in the year were counted as "Non-Event" days. Event days with a non-event day on either side were counted as 1-Day events, those with a non-event day prior to it but an event day following were counted as Event Start days, the reverse with a non-event day following and event day prior to it were Event End days and those with event days on either side counted as Event Middle days.

The associated average demand profiles were then applied to each day, with a random factor multiplied at each hour based on a triangular distribution (TDF) between the minimum, maximum, 25th, 50th and 75th percentiles of hourly demand from the day type. The TDF was used to reintroduce some of the variability seen in the raw data while favouring values within the interquartile range more than the outliers and was calculated as seen in the equation below.

$$TDF = (1 + (Q2 + (Q3 - Q1) \times (2 \times RAND() - 1)) + (Max - Min) \times (2 \times RAND() - 1))$$
(Equation 4)

The result was a year's worth of hourly demand for an average marae, including event loads. This will be used in a later section when estimating the ability of a given system to supply a marae's needs.

3.4 COMMUNITY DEMAND PROFILES

To understand how a marae-based solar PV and battery system could interact with the wider community, a representative community energy demand profile was developed for comparative analysis. For this study, the example community was assumed to include 10 residential houses (representing a nearby papakainga) and a kura (school). This was based on research done by Apperley & Toki (2023) as well as Curd (2017), who both modelled a community including 10 exemplar residential households and a marae (or three, in Curd's case), and comments from marae representatives who were interested in donating excess power to a kura as a way to support the community.

The electricity demand profile used for the 10 residential houses originated from the Household Energy End-Use Project (HEEP) conducted by BRANZ (Isaacs & HEEP Team, 2002). The average, winter and summer daily demand profiles were obtained for a single house in New Zealand, then multiplied by 10 to adjust for the number of houses in the papakāinga. The kura demand profile used was based on Remuera Intermediate in Auckland, which similarly provided a winter and summer average daily demand (Jian et al., 2011).

A years' worth of demand data was generated for both the papakāinga and kura by adding weekends and holidays with a baseload demand for the kura and applying a monthly adjustment factor to the average demand to account for seasonal changes in the demand. The adjustment factor (SF) was found by averaging 12 years of residential consumption trends for households in New Zealand (EMI, 2025), then dividing each month's average by the overall average daily demand for the year as seen in $SF=\frac{D_m}{D_A}$ (Equation 5 and Figure 8 below.

$$SF = \frac{D_m}{D_A}$$ *(Equation 5)*

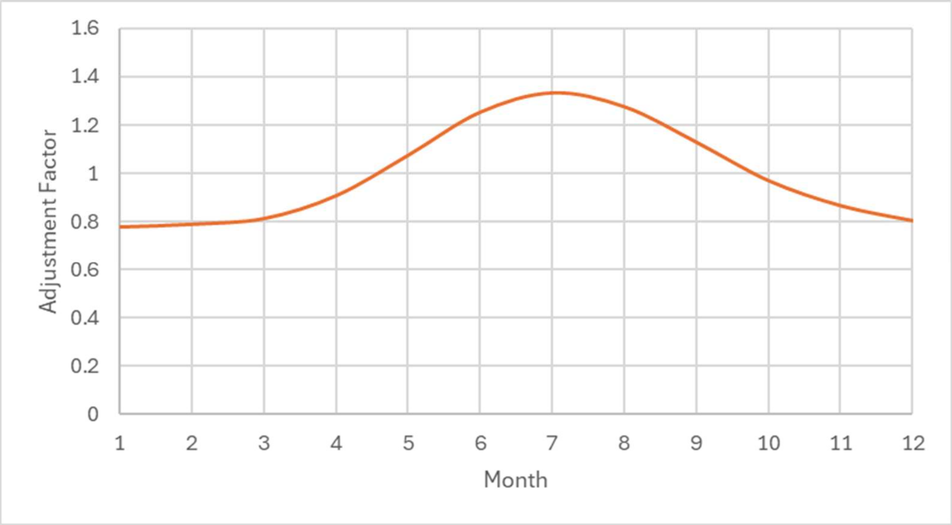

Figure 8: Seasonal Adjustment Factor for Each Month

3.5 RESULTS & DISCUSSION

From the analysis done, it can be seen that the annual energy demand for a marae is close to the annual energy demand for a household at ~8500 kWh/y (household demand in NZ is typically quoted at ~7000 kWh (Isaacs & HEEP Team, 2002)). If this is the only data point known, it could be assumed that the daily demand profile would also be similar to a household, and a system sized accordingly. However, deeper analysis shows that this is definitely not the case, with the marae having a mostly flat baseload when not in use which ramps up drastically during use.

The daily electricity demands each day of the year are overlaid for the three marae in Figure 9. The non-event or baseload demand varies between each marae (from 7 kWh/d at Marae C to 16 kWh/d at Marae B), but remains significantly lower than the event demands which can spike above 200 kWh/d. Of the three marae, Marae A appears to have the highest event demands, Marae B the lowest with the most frequency, and Marae C also has high demand but with the lowest frequency.

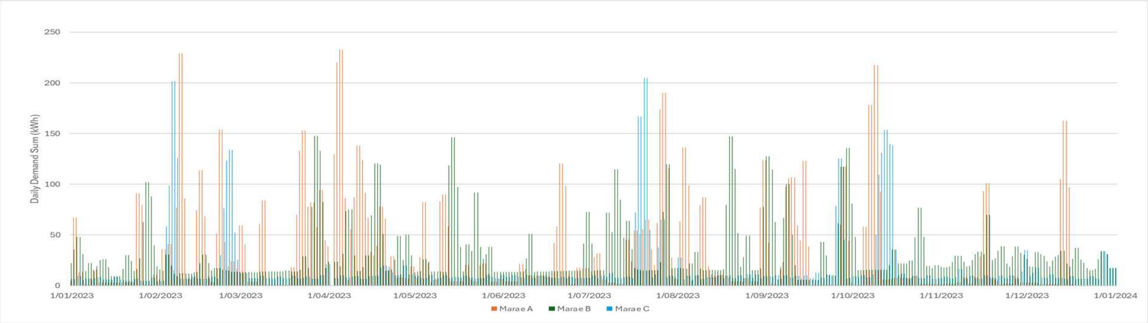

Figure 9: Sum of Electricity Demand for Each Day of the Year

From the analysis of the daily demand profile, it can be seen that there are five basic day types with completely different profiles.

The five demand profiles obtained broadly resemble those found using k-means clustering but with no duplicates and outliers, indicating that the filtering methodology used was appropriate for the dataset and successfully identified the common demand patterns.

First, the "Non-Event Day" or baseload (Figure 10), which is generally low and flat without much deviation.

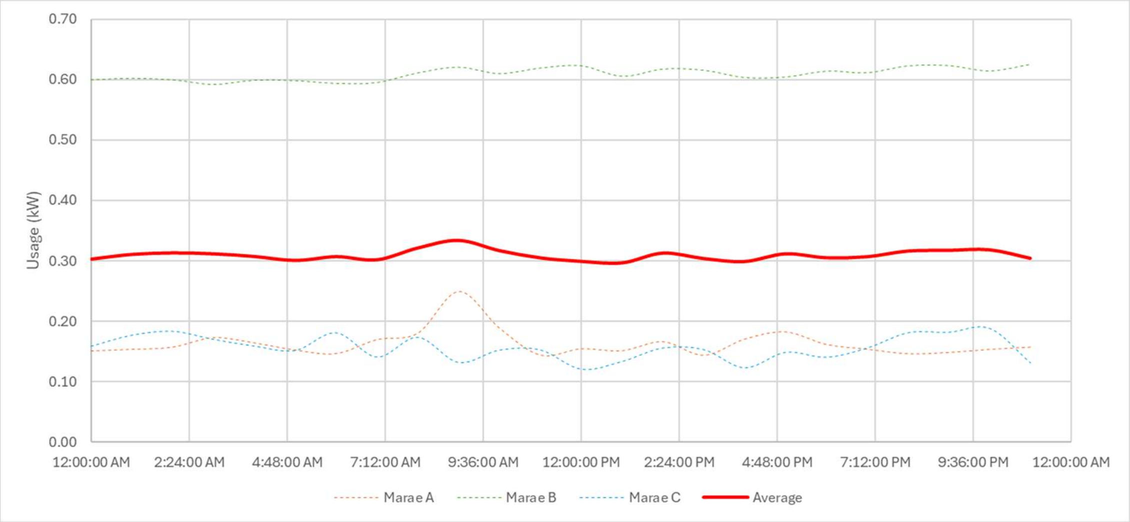

Figure 10: Non-Event Day Demand Profile

For two of the three marae analysed, this baseload sat at around 0.16 kW, however Marae B had a higher baseload of 0.6 kW. This difference would largely depend on the appliances left running when the marae is not in use and would vary from marae to marae, e.g., security lights, refrigerators, etc. Ultimately, it is almost low enough to be negligible, making up only 30% of the annual energy usage despite accounting for around 70% of the days in a year (Table 1). The majority of the usage comes from large, multi-day events comprised of a Start Day, zero or more Middle Days and an End Day. These day types had the greatest amount of variation, with the average appearing as a smooth curve but reality showing jagged peaks at alternating times. Take, for example, the grouped first days of Marae A (Figure 11). The general trend shows a low, flat beginning before it starts to ramp up around 7:00 AM. This is then followed by a series of peaks and troughs at inconsistent intervals, unique to each day and the presumed events occurring.

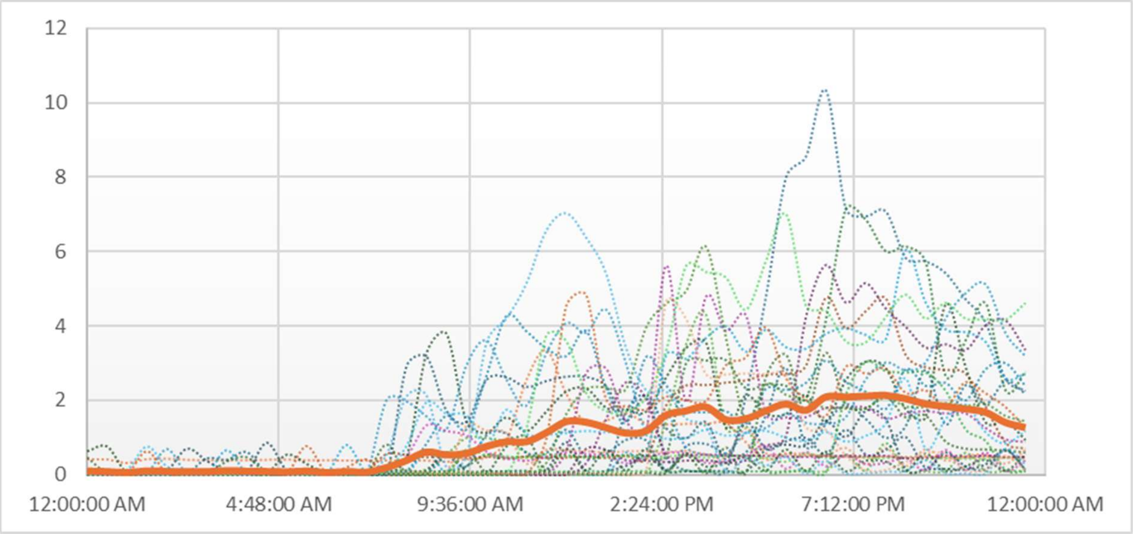

Figure 11: Marae A Event Start Days, Grouped Data vs Average

An explanation for this trend could be that in general marae workers start preparing for the day ahead at a regular time, turning on fridges and other equipment, but the trend that follows will be dependent on what happens after that, i.e., ope (entering groups of guests) arriving throughout the day to a tangi, a noho (overnight stay) having scheduled breaks, when and what is for lunch, etc. The variations caused by these spikes is smoothed out in the averages, and the overall trend can be seen to be similar across all three marae within a margin of error (Figure 12).

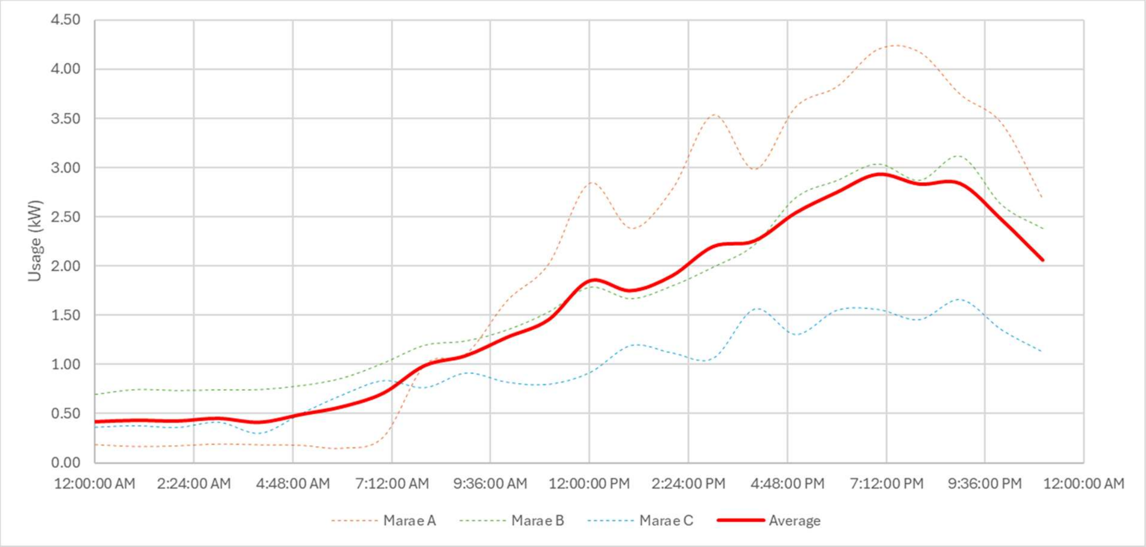

Figure 12: Average Marae Event Start Day Demand Profile

The same degree of variability is seen in the middle and end days, and the complete set of Grouped Data figures found in Appendix 1. The averages derived from them can be seen in Figure 13 and Figure 14 below.

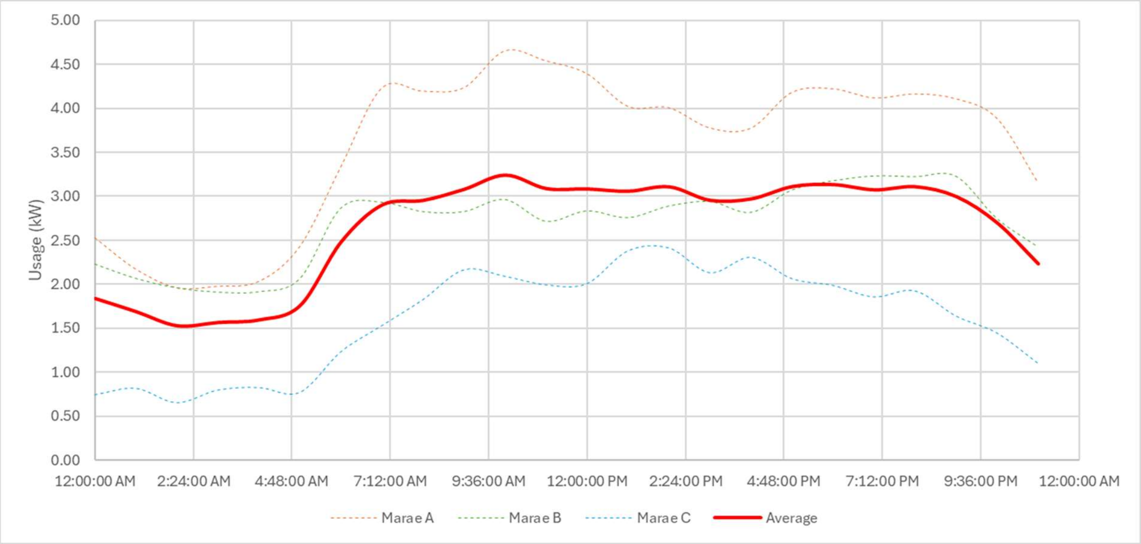

Figure 13: Average Marae Event Middle Day Demand Profile

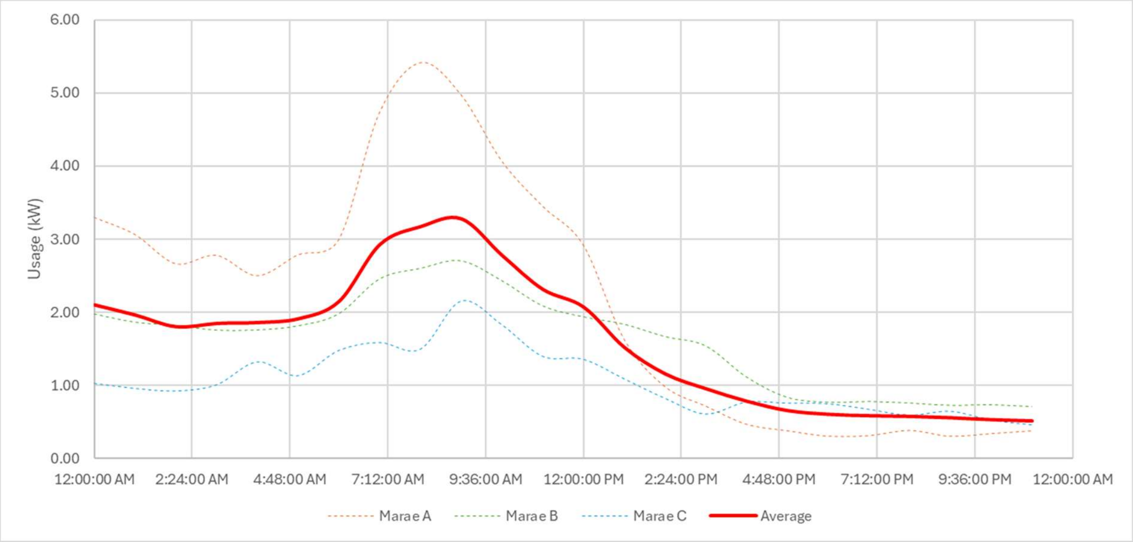

Figure 14: Average Marae Event End Day Demand Profile

Combining the start, middle and end day profiles, an average “Event Demand Profile” can be obtained for a 3-day event as seen in Figure 15.

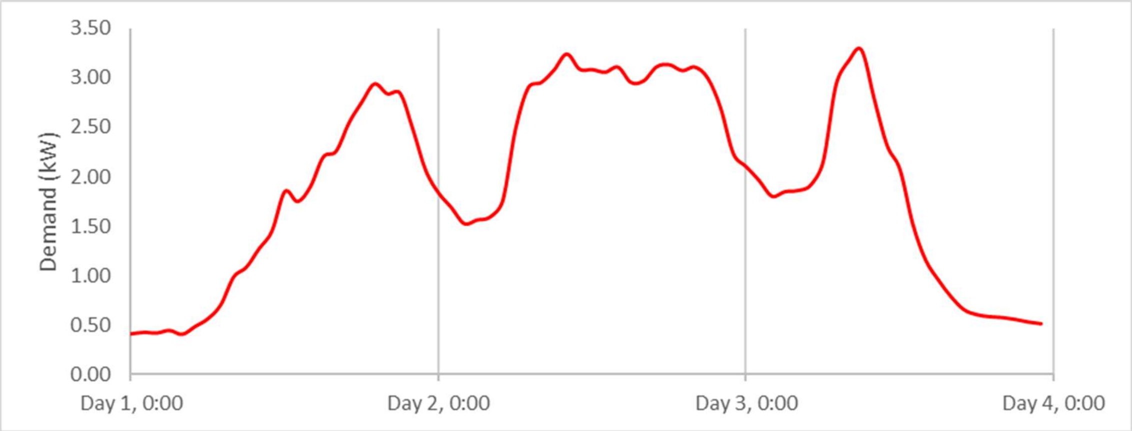

Figure 15: Average Marae Event Demand Profile

As seen in Figure 11 and the other grouped days in Appendix 1, the averages presented here are lower than some of the events held at the marae. To create an expected maximum event that encapsulates all of the events shown, the demand profile shown in Figure 15 was normalised then adjusted for the maximum hour in the year by the process explained in section 3.3.3 (Stage 3: Normalising the Demand Curves). The resultant demand curve can be seen in the following graph (Figure 16).

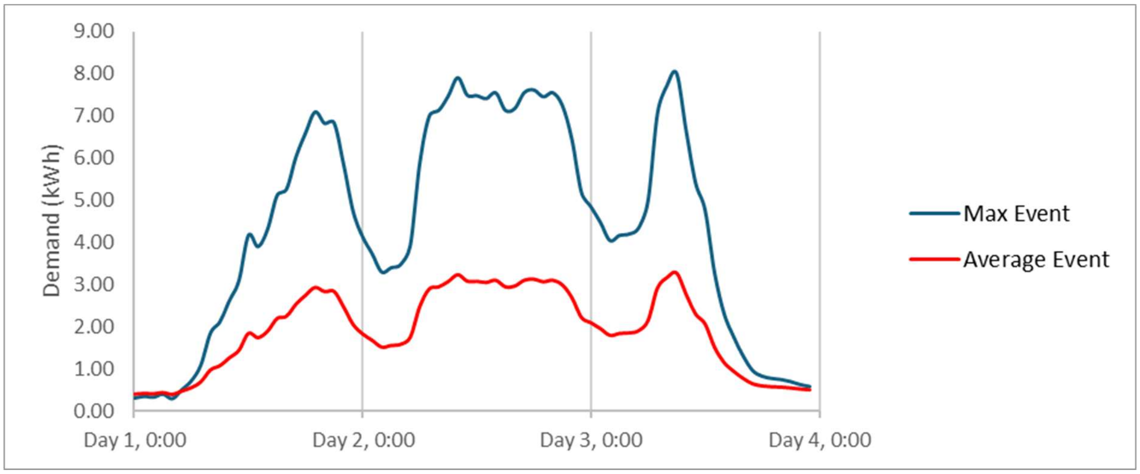

Figure 16: Maximum vs Average Marae Event Demand Curve

The final day type to be discussed is the one-day event, which had an average demand curve as shown in Figure 17.

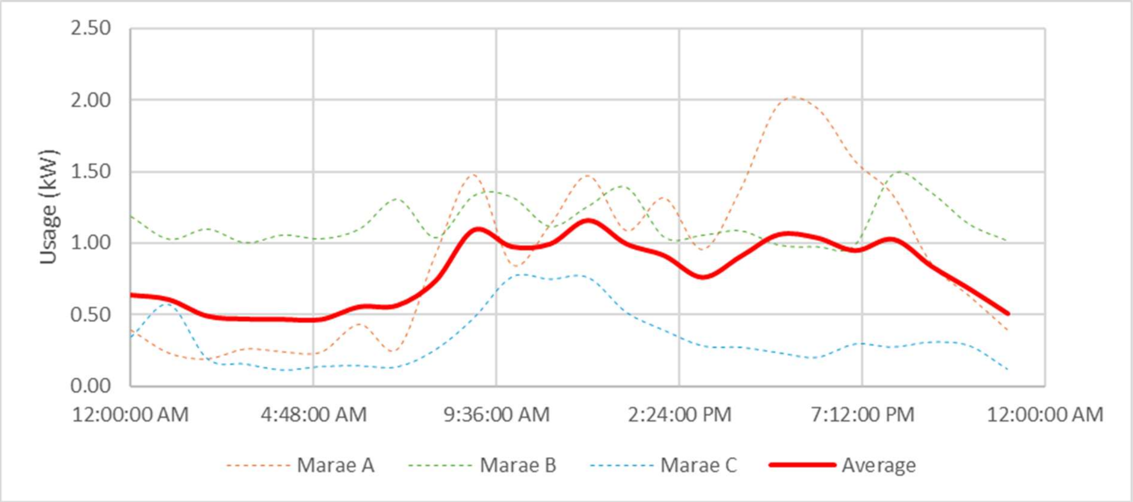

Figure 17: Average Marae One-Day Event Demand Curve

Unlike the previous days' demand curves, the overall usage pattern between the three marae and the average is not distinctly clear here. Looking deeper into the source data, it becomes clear that these averages are not appropriate measures of the one-day demand, as most one-day events last only a few hours but can occur at varying times (Figure 18). Thus the "daily" average approach that has been taken for the previous demand curves is not as applicable here, and a more appropriate method would be to find the average number of hours and related hourly demand of these events and apply it to the most common event time.

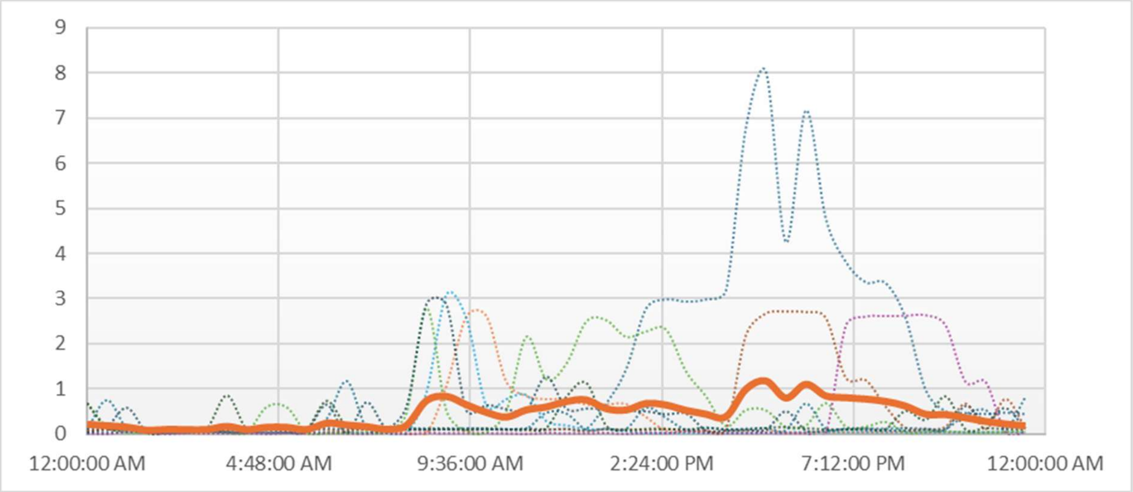

Figure 18: Marae A One-Day Events, Grouped Data vs Average

For Marae A, this would most likely appear as a 2-hour event with 3 kWh of hourly usage occurring around either 9:00 AM or 5:00 PM, but the overall average will vary when adding in the averages of the other marae. In this research, the demand profiles were left as-is because in terms of both frequency and magnitude they only made up a small proportion of the total events (see Table 1) and so it was assumed that this inaccuracy would not make a big difference in the overall results. Future work could be done to correct this and ensure more accurate results.

The demand profiles obtained above were used with an analysis of the magnitude and frequency of events to create an overall annual demand profile for a marae. The frequency of event days can be seen in Table 1, where the number of days per year of each day type is shown. For the magnitude analysis, the averaged range of demand for each day type is presented in the figures below (Figure 19 for the half-hourly demand and Figure 20 and for the daily demand).

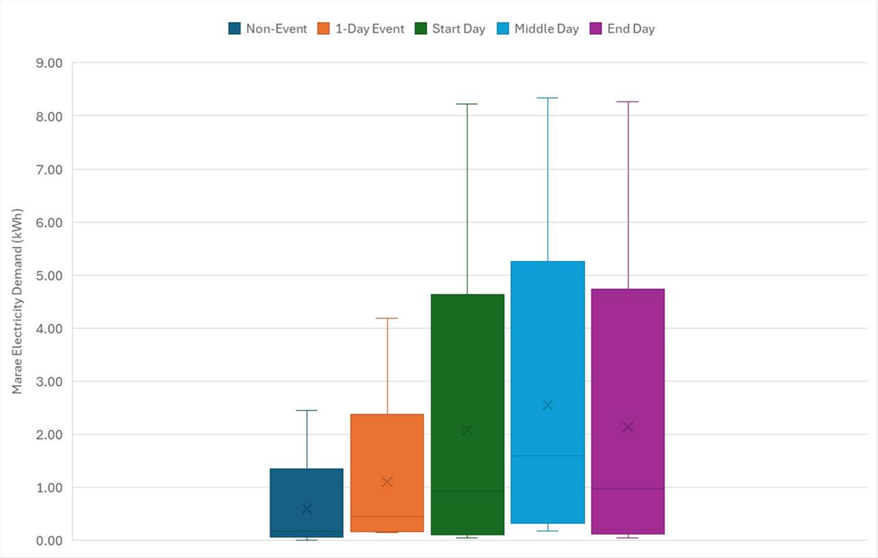

Figure 19: Range of Half-hourly Marae Electricity Demand

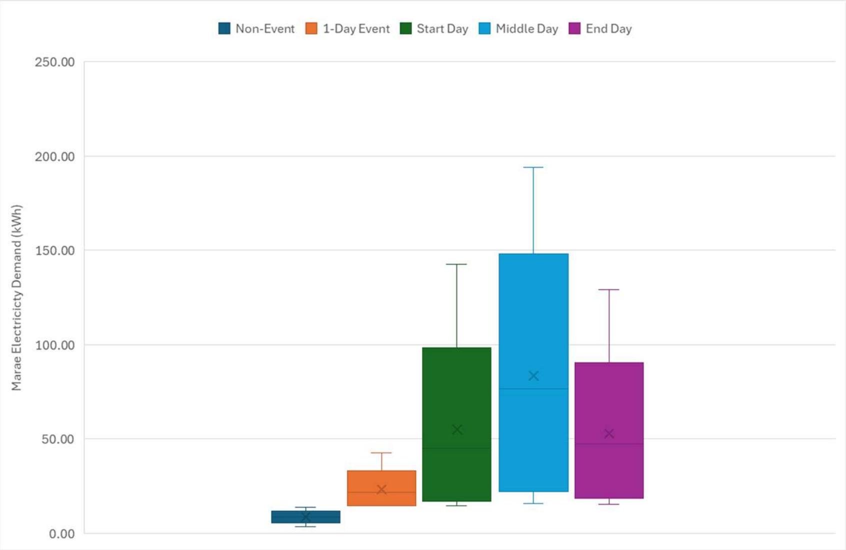

Figure 20: Range of Daily Marae Electricity Demand

Table 1: Overview of Demand Analysis

	Non-Event				1-Day Event				Event Start Day				Event Middle Day				Event End Day				Total			
	Average Usage	**Average Daily Usage**	**Annual Usage**	**No. Days**	**Average Usage**	**Average Daily Usage**	**Annual Usage**	**No. Days**	**Average Usage**	**Average Daily Usage**	**Annual Usage**	**No. Days**	**Average Usage**	**Average Daily Usage**	**Annual Usage**	**No. Days**	**Average Usage**	**Average Daily Usage**	**Annual Usage**	**No. Days**	**Event Days**	**No. Events**	**Total Usage**	**Event Usage**
	kWh/2	*kWh/d*	*kWh/y*	*per year*	*kWh/2*	*kWh/d*	*kWh/y*	*per year*	*kWh/2*	*kWh/d*	*kWh/y*	*per year*	*kWh/2*	*kWh/d*	*kWh/y*	*per year*	*kWh/2*	*kWh/d*	*kWh/y*	*per year*	*per year*	*per year*	*kWh/y*	*kWh/y*
Marae A	0.08	3.92	839.19	216	0.45	21.53	215.30	10	0.99	47.48	1281.85	27	1.79	86.11	6027.45	70	1.08	51.81	1398.83	27	134	37	9762.62	8923.43
Marae B	0.31	14.48	3325.50	227	0.57	27.32	136.60	5	0.85	40.72	1506.69	37	1.35	64.64	3813.47	59	0.81	38.71	1432.39	37	138	42	10214.65	6889.15
Marae C	0.16	7.57	2346.76	311	0.33	15.61	124.89	8	0.96	46.32	555.83	12	1.63	78.41	1725.08	22	1.06	50.79	609.46	12	54	20	5362.02	3015.26
Average	*0.18*	*8.66*	*2170.48*	*251*	*0.45*	*21.49*	*158.93*	*8*	*0.93*	*44.84*	*1114.79*	*25*	*1.59*	*76.38*	*3855.33*	*50*	*0.98*	*47.10*	*1146.89*	*25*	*109*	*33*	*8446.43*	*6275.95*

From the graphs above it can be seen that non-event days have the lowest demand and variability, with 1-day events having an only slightly higher demand, with just over 75% of the half-hourly demands sitting within the same bracket as the non-event range. This overlap caused some difficulties in separating one-day events from non-event days. The event start and end days have similar ranges, and the middle has the widest range. The range of values above the median is much wider than the range below the median, indicating a low number of very high demands that skew the results slightly upwards. The average (denoted by "X" on the graphs) is higher than the median in most cases because of this. Interestingly, the maximum half-hourly demand for the event start, middle and end days are all roughly aligned at 8 kWh, which is assumed to be the absolute maximum for the average marae. This value was used in generating the maximum event demand, with the maximum value of 8 kW for half an hour multiplied by two to 16 kW for an hour. The wide range of event magnitudes seen poses an issue for sizing energy supply systems to meet these demands, as a very large system will likely be needed to meet the upper end of this range, however for the majority of the time the demand will be much lower than this. A trade-off will be required between system size and cost vs supply reliability, as 100% supply for this case is likely to be costly, whereas 50% or even 80% supply will be significantly cheaper. A more in-depth analysis of this problem will be presented in the following chapter (Solar Electricity Supply Modelling). To help in this analysis, an annual demand curve was generated as seen in Figure 21 below.

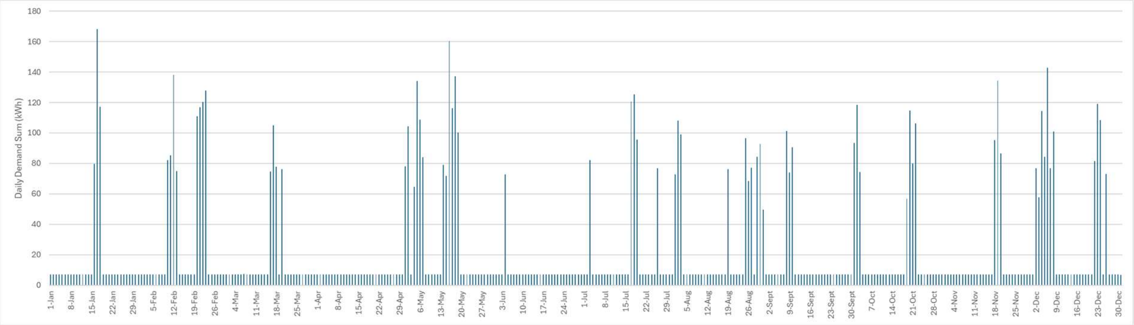

Figure 21: Simulated Marae Demand with Randomly Generated Events

The generated characteristic demand curve is broadly reminiscent of the demands seen in Figure 9: Sum of Electricity Demand for Each Day of the Year for the three marae, with a constant baseload and events of varying magnitudes and lengths distributed randomly throughout the year. The annual sum of the demand is also in line with expectations, at 8608.19 kWh/y compared to the 8446.43 kWh/y average in Table 1. 6239.78 kWh/y was used during events compared to 6275.95 kWh/y in the table, and 113 event days counted per year compared to 109. The close correlation between the expected average results, the original data's appearance and the simulated results indicates that the generated data is a valid representation of an average marae and so could be used to design a solar and battery powered system. The methodology is also useful in that the randomisation factors used to generate the annual demand profile can be reset as often as necessary, so creating a brand-new demand profile if desired or even a multitude of representative usage scenarios. Having such a wide array of data generated could be useful in future research utilising methods such as Monte Carlo optimisation, or to ensure the final results are rigorously tested.

3.6 CONCLUSION

The demand profiles seen in the results are artificial models generated from the data of three marae. Due to the generalisation done to produce them, they can be used as exemplars for a wide range of marae, rather than just the three marae individually. Of particular importance is the five characteristic day types identified by the study and their constituent demand profiles, which can be used in energy modelling analyses to understand how a proposed system will behave under the possible demand scenarios for a marae. One such example will be provided in the next chapter, where the developed demand profiles will be used to design a solar power system sized for marae.

4 SOLAR ELECTRICITY SUPPLY MODELLING

4.1 INTRODUCTION

Māui and his brothers planned to capture the sun using a net made with flax ropes, however this study will utilise the more modern solar PV panels and batteries to model an attempt to do the same. The time taken by Māui to identify barriers that would prevent him from completing his task and designing solutions to overcome them, for example building barricades to protect himself and his brothers from the heat of the sun, ultimately helped him succeed in his capture. This chapter utilises energy balance modelling to identify issues that may arise from different solar and battery supply configurations and identify which solutions will be most viable in achieving the goals of the marae.

Marae are supplied by a mix of energy sources: namely, grid-connected electricity, LPG bottles and even biomass in some cases. Adding solar generated electricity to the mix could displace some if not all of the current sources (with upgrades to the gas and biomass fed equipment) but whether this is a worthwhile endeavour remains to be seen. A techno-economic analysis must be conducted in order to determine whether a proposed system meets the needs of the marae, is affordable, and delivers what is promised for these unique use cases. However, depending on the specific requirements of the marae, the best solution could vary greatly. For example, some marae may focus on lowering their bills in the cheapest way and be happy with a small system to offset their costs, while others may want full control over their energy resources and thus would require a much larger system. This section attempts to derive a range of solutions that can meet the needs of most marae, from which a marae may select an approximate system size that suits them best for deeper analysis.

4.2 DATA

The key data sources required for this analysis were the electricity demand profile of a marae and the solar irradiation of the site. The electricity demand profile was obtained by research carried out in the previous chapter and was given in kW per hour for a year. Solar irradiation data was obtained from the NIWA SolarView tool for Waingaro, an area sitting in the average range of solar irradiation for the Waikato region, indicated by the red icon on the map below.

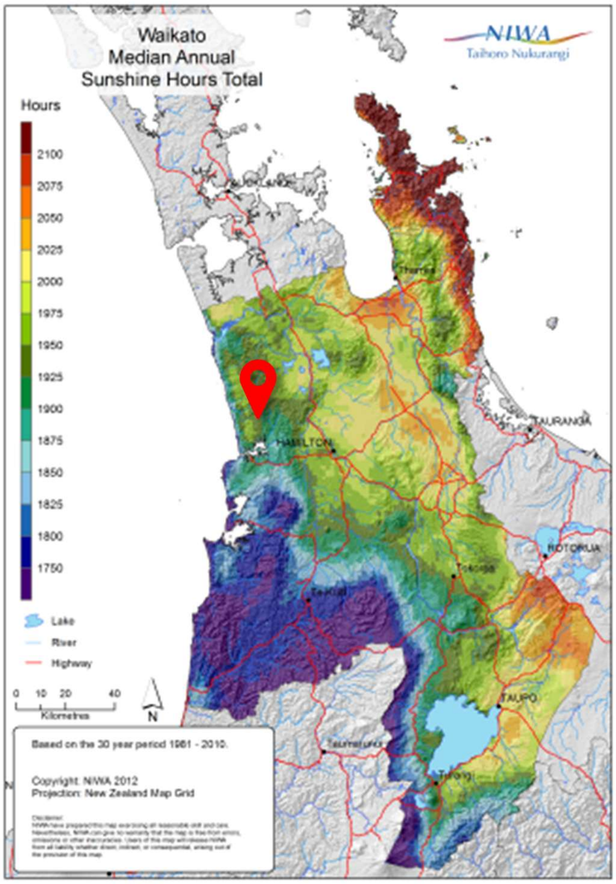

Figure 22: Waikato Median Annual Sunlight Hours (NIWA, 2012)

The data was given in W/m^2 on an hourly basis for a year and represented the average irradiation values over a ten-year period. To be consistent with the demand data set in an energy balance the values needed to be in kWh, so a simple conversion was carried out using the equipment specifications for solar panels detailed in Section 4.2.1.1. Specifically, the effective area of the panel in m^2 and the module efficiency of the panels, in the equation shown below:

$$S = \frac{I}{1000} \times A_e \times \eta_P \qquad \textit{(Equation 6)}$$

Where:

- S = Solar Electricity Supplied (kWh)
- I = Solar Irradiance (Wh/m^2)
- A_e = Effective Area of Solar Panel (m^2)
- η_P = Efficiency of Solar Panel (unitless)

4.2.1 Equipment Specifications

As shown above, specific equipment details were required in the analysis to give reasonable results. Specification sheets for solar panels and batteries were obtained from micromall.co.nz, which supplies a wide range of panels, inverters and batteries to a New Zealand audience. Inverter specifications were not used in the analysis due to costings including them with the batteries and efficiency losses assumed to be minimal, but in future analysis these could be included in more depth.

4.2.1.1 Solar Panels

The type of solar panels used in the analysis were LONGi Hi-MO X6 LR5-54HTB Mono 440W Solar Panel Black Frame Half-Cell (Micromall, n.d.-b). The full specification sheet will be provided in Appendix 2, but an overview of the key details used henceforth will be provided in the table below (Table 2: Solar Panel Key Specifications).

Table 2: Solar Panel Key Specifications

Specifications		
Name	LONGi Hi-MO X6 LR5-54HTB Mono 440W Solar Panel Black Frame Half-Cell	Link
Capacity	440	W
Max Panel Efficiency (η_P)	22.5%	
Unit Cost	$269.00	
Power Degradation		
Year 1 (D_1)	1.50%	
Year 2-25 (D_{2-25})	0.40%	
Lifespan (L)	25	years
Area		
Effective Panel Area (A_e)	1.85	m^2
Total Panel Area (A_P)	1.95	m^2

The total panel area was obtained from the dimensions noted in the specification sheet, while the effective panel area was found by removing the outer frame of the panel and leaving only the dimensions covered by the PV cells (see Appendix 2 for illustration). Power degradation refers to the reduction in efficiency faced by the panels as they age over a number of years, and in the analysis was subtracted from the max panel efficiency at the beginning of the noted year. The capacity was used to calculate the number of panels required to reach a given desired capacity, which was then multiplied by the unit cost to give the total solar array value for depreciation calculations.

The total capital expenditure (CAPEX) was obtained using a costing curve from "Commercial-scale solar in New Zealand" (Miller & Gretton, 2021), which was adjusted from 2021 NZD to 2024 NZD using the General CPI (Reserve Bank of New Zealand, 2025) as seen in Table 3 and Figure 23 below.

Table 3: Solar Array CAPEX

CAPEX (NZD $/Wp)			
Size (kWP)	***Lower***	***Base***	***Upper***
10	2.506516854	3.133146067	3.759775281
100	2.217303371	2.771629213	3.325955056
500	1.735280899	2.169101124	2.602921348
1000	1.638876404	2.048595506	2.458314607

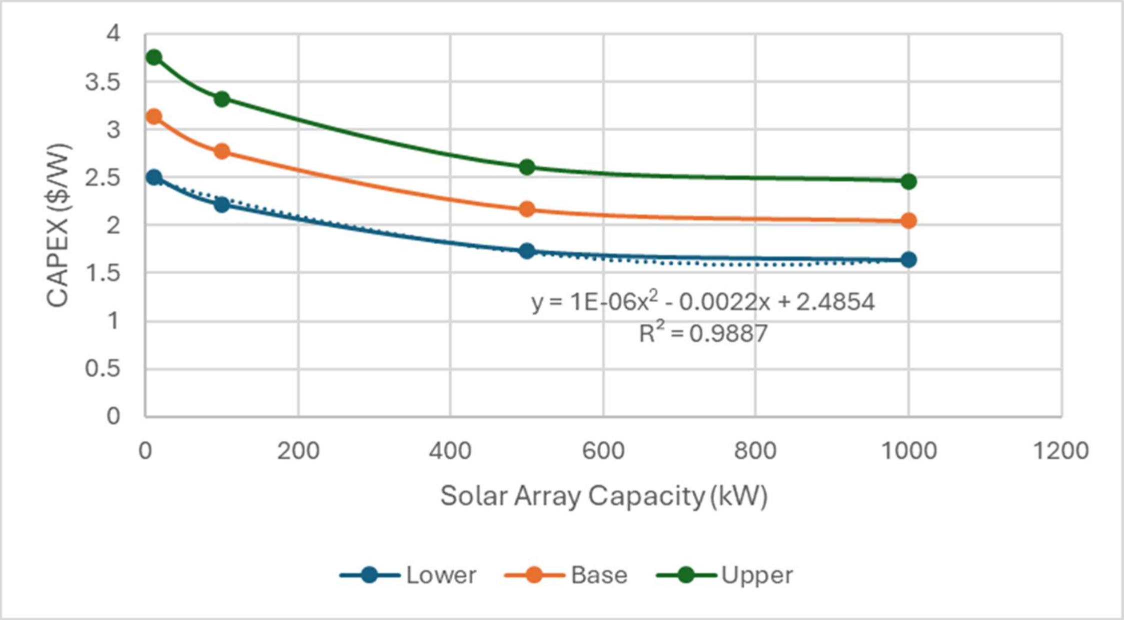

Figure 23: Solar Array Costing Curve

The equation for the Lower costing curve estimates were used in this analysis to reflect the drop in solar panel prices since 2021 in accordance with Miller & Gretton's (2021) recommendations, roughly aligning also with current quoted estimates for residential and commercial solar installations in New Zealand (My Solar Quotes, 2024; My Solar Quotes, 2025).

The operational expenditure (OPEX) of a solar array was obtained from NREL for three orders of magnitude: residential, commercial and utility scale arrays (NREL, 2024f, 2024d, 2024b). Solar arrays are typically low maintenance, requiring little or no additional work during operation, however costs for occasional cleaning and repair/replacements of parts has been included in these estimates.

The values provided by NREL were for 2024 but with the base year set to 2022 USD. This was converted to 2022 NZD then again to 2024 NZD using the General CPI (Reserve Bank of New Zealand, 2025). The Base costs in Table 4 below were used in this analysis, with an "IFS" statement in Microsoft Excel, with systems 10 kW or below using the residential base cost, systems 100 kW or below using the mid base cost (extrapolated from between residential and commercial scale estimates using a straight-line approximation due to the large jump in price between systems of these sizes), systems 200 kW or below using the commercial base cost and systems greater than that using the utility base cost.

Table 4: Solar Array OPEX

OPEX (NZD $/Y)			
Size (kW)	***Lower***	***Base***	***Upper***
7.9 (Residential)	53.9766123	55.25002157	57.0605
200 (Commercial)	33.6096549	34.31373063	35.41444
100000 (Utility)	39.0923366	39.83057234	40.76997
100 (Mid)	43.7931336	44.7818761	46.23747

4.2.1.2 Batteries

The type of batteries used in this analysis were Battery Revolution Deep Cycle (Micromall, n.d.-a). As with the solar panels, the full specification sheet is provided in Appendix 2, and the key details are specified below in Table 5.

Table 5: Battery Key Specifications

Specifications		
Name	Battery Revolution Deep Cycle	Link
Type	Lead-C	
Capacity	1.56	kWh
Unit Cost	$418.99	
Amperage	130	Ah
Voltage	12	V
Max. DOD	60%	
Cyclic Life		
30% DOD	7000	
60% DOD	2400	
80% DOD		
Lifespan	20	years

The capacity of a battery bank was assumed to be the capacity of a single battery (see above) multiplied by the number of batteries needed to get the input capacity. The configuration of the batteries in the bank and the complexities of the discharge at each second/minute was not investigated due to the high-level nature of the analysis and hourly dataset, and the battery bank referred to simply as a "Battery" henceforth. The maximum depth of discharge (DOD) multiplied by the capacity was assumed to be the total amount of electricity that could be discharged at any one time, as seen in the equation below.

$$B_{Capacity}(Max) = DOD(Max) \times b_{capacity} \times n_B \qquad \textit{(Equation 7)}$$

Where:

- $B_{Capacity}(Max)$ = maximum capacity of the battery bank available to discharge (kWh)
- DOD(Max) = maximum depth of discharge (%), see Table 5
- $b_{capacity}$ = rated capacity of single battery (kWh), see Table 5
- n_B = number of batteries in bank

The capital costs for different sized batteries were obtained from Transpower's report on battery storage in New Zealand (Transpower New Zealand Limited, 2017). These values were in 2017 NZD and so were converted to 2024 NZD using the General CPI as seen in Table 6 below.

Table 6: Battery CAPEX

CAPEX (2024 NZD $/kWh)	
Size (kWh)	***Base***
<10kW/20kWh	1608.75
<1MW/2MWh	1930.5
>4MW/8MWh	1544.4

The above battery costings are in line with current quoted values for batteries in New Zealand so were assumed accurate. To properly reflect the cost increases and decreases associated with increasing battery capacity, a polynomial curve was fitted for the three given data points and the resulting equation used to find the CAPEX of different battery sizes as seen in Figure 24 below.

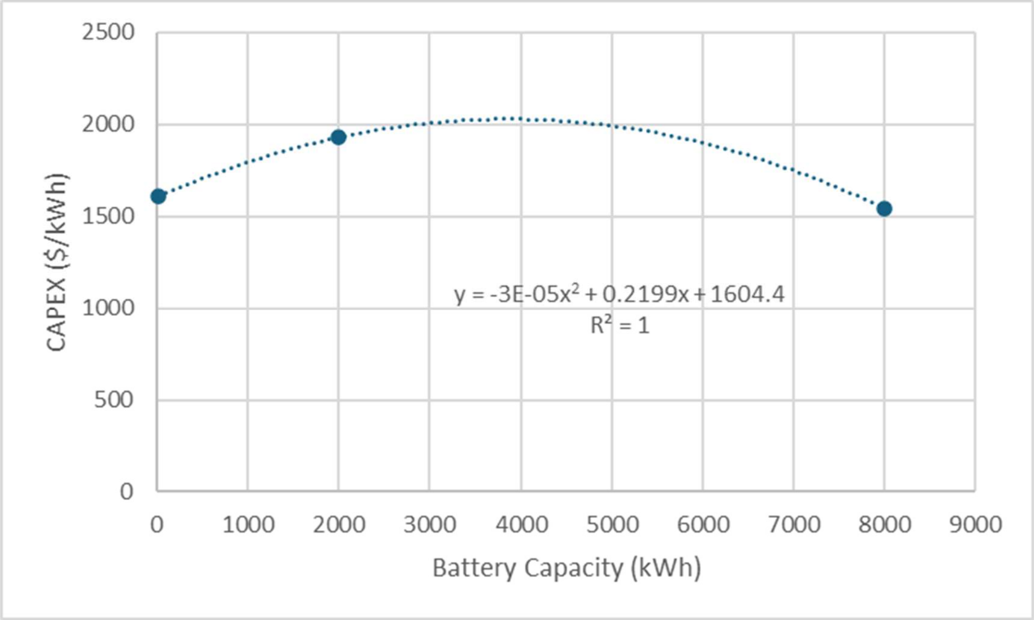

Figure 24: Battery CAPEX Costing Curve

The OPEX values for batteries were obtained similarly to the solar array OPEX seen above from NREL (NREL, 2024c, 2024a, 2024e). Systems with capacities lower than 12.5 kWh used the base costs in the first row, those with capacities less than 20 kWh used the base values in the next row, less than 100 kWh used the base values extrapolated between the 5-20 kWh versus 100-2000 kWh base values (assuming straight line extrapolation), and systems greater than 100 kWh used the second to last row's base values. These values were converted from 2022 USD to 2024 NZD.

Table 7: Battery OPEX

OPEX (NZ $)			
Size (kWh)	***Lower***	***Base***	***Upper***
5-12.5	116.255051	153.6253448	178.8205
5-20	144.355538	188.2091948	222.0441
100-2000(4hr)	82.910015	87.26361158	106.861
20-100	113.632777	137.7364032	164.4525

Batteries do not typically require much maintenance, so operational costs should thus be low, conflicting with the relatively high costs seen in the table above. However, these OPEX costs also include the cost of replacing the battery at end-of-life, as well as any other auxiliary parts that may need replacement like the inverter for example.

4.3 BASE MODEL SET-UP

Adding solar generation and battery storage to the marae's energy supply mix can help displace some or all of the grid-provided electricity, and with upgrades to equipment could eventually displace biomass and gas as well. The sizing of the solar array and battery is important when determining how much of the current energy supply is being displaced and how much it will cost. To determine the optimum size for a marae, a range of scenarios will be run with different optimisation conditions to understand how a solar and battery energy system might interact with a marae's demand. Before modelling the results of any of the specified scenarios, a base model is needed to calculate results, where the inputs can be varied to match the scenarios. A techno-economic model was developed in this research to calculate the energy balance, costs and benefits of an input solar and battery system for a given demand and solar irradiance. The process followed for the technical energy balance and economic aspects of the model will be described separately in the following sections.

4.3.1 Energy Balance Methodology

To begin the set-up of the base model, assumed dummy values were input for the solar and battery capacities of the system in kW and kWh respectively. The number of batteries and panels in the system was then back-calculated from these values, and the resultant solar and battery supply calculated using $S=\frac{I}{1000} \times A_e \times \eta_P$ (Equation 6 and $B_{Capacity}\ (Max) = DOD(Max) \times b_{capacity} \times n_B$ (Equation 7. The marae demand data generated previously was used with the irradiation data and specification sheets found in section 4.2 to calculate the energy balance of the marae and proposed system, which can then be changed by varying the input capacities. The energy balance was done at each hour of the year to identify which of the available energy sources was being used in each time interval [(t – 1), t]. The balance model assumes that if solar supply (*S*) is greater than demand (*D*) at any time (*t*), the demand will be fully supplied by solar, and the excess will be used first to charge the battery then any remaining oversupply sold to the grid at a specified price. If the solar supply is less than the demand, the state of charge and capacity of the battery (*B*) will be checked to see if it can supply the remaining demand, and if that too fails to supply the demand the energy balance at that hour will end in a deficit of the remaining demand which is assumed to be fulfilled by the grid at a cost. This procedure can be seen in the equations below.

$Balance(t) = -D(t) + S(t) + B(t) - C(t)$ *(Equation 8)*

```
$if\ S(t) > D(t)\ \{$
        $B(t) = 0$
```

$$C(t) = Min[S(t) - D(t);\ \ B_{Capacity}(Max) - SoC(t) \times B_{Capacity}(t)]\ \}$$

$$else\ if\ S(t) < D(t)\ \{$$

$$B(t) = Min[D(t) - S(t);\ \ SoC(t) \times B_{Capacity}(t) - DoD(Max) \times B_{Capacity}(Max)]$$

$$C(t) = 0\ \}$$

Where:

- Balance(t) = the energy balance at time “t” (kWh)
- D(t) = the demand at time “t” (kWh), see Data and Figure 21
- S(t) = the solar supply at time “t” (kWh), see $S = \frac{I}{1000} \times A_e \times \eta_P$ (Equation 6
- B(t) = the battery supply at time “t” (kWh)
- C(t) = the charge supplied to the battery at time “t” (kWh)
- $B_{Capacity}$(Max) = the maximum capacity of the battery (kWh), see $B_{Capacity}\,(Max) = DOD(Max) \times b_{capacity} \times n_B$ (Equation 7
- $B_{Capacity}$(t) = battery capacity at time “t” (kWh), equal to $B_{Capacity}(t-1) + C(t-1) - B(t-1)$
- DoD(Max) = maximum depth of discharge of the battery (%), see Table 5
- SoC(t) = battery state of charge (%) at time “t”, equal to $(B_{Capacity}(t-1) + C(t-1))/B_{Capacity}(Max)$ and assumed to be 50% at the beginning of the first year

After repeating this process for every hour of the year, the total demand, total solar energy supply, energy deficit and excess were summed up for the year, and the number of hours where the power from the system is insufficient to meet the demand is counted for the year. The percentage of the demand supplied by the specified system is also found by dividing the annual demand less the deficit by the demand. These and other factors were used in analysing the economics of the system, which will be described in the next section.

4.3.2 Economics Methodology

There are a number of available texts on the different types of economic analyses for solar and other renewable energy technologies. A comprehensive example is “A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies”, which was developed by NREL (Short et al., 1995). Another example is the report produced by EECA on “Commercial-scale Solar in New Zealand”, which produced results more relevant to the New Zealand scenario. From the techniques and assumptions described in both of these reports, a range of economic measures were analysed to compare results, namely the system capital and operational expenditure (CAPEX and OPEX), the levelised cost of energy (LCOE), total life-cycle costs (TLCC) and net present value (NPV). The CAPEX, OPEX and TLCC provide a measure of affordability, so marae can see at a glance whether a system of the proposed size is within their budget or if additional funding will need to be sourced before proceeding. The NPV and LCOE are useful when comparing solar with other energy supply options over the long term. The economic analysis for one year as well as over a 25-year period will be described in the sections below.

4.3.2.1 Annual Cashflow

Before calculating the different measures listed above, an average annual cashflow was required between income from selling excess energy and payment for energy from the grid when the system fails to supply the demand. The buying price of electricity is highly variable, and for marae, businesses and residential buildings depends greatly on the electricity provider and plan selected. For larger energy users such as industrial sites, the electricity price would usually depend on either the spot market price or on a hedge contract price negotiated with the distribution network. The selling price of electricity is similarly varied, though to a lesser extent. Some electricity providers offer a solar buy-back rate for their customers, where the electricity will be bought by the provider at a specified price and paid as a "credit" on the customer's future electricity bills. This system works well for smaller residential systems aiming for savings and bill reductions, but for fully off-grid systems does not offer many benefits. Furthermore, some providers specify limits to the size of the systems they are willing to work with (with maximum sizes ranging between 10-50 kW), adding further complications for large systems.

Peer-to-peer energy trading platforms are becoming a popular alternative to these options, where excess power is sold at an agreed upon rate to specified users via a brokerage platform. This allows for greater flexibility in the selected selling and buying rate, as prices below standard electricity buying rates but above current buy-back rates could be selected as a bargain for both the buyer and seller. Alternatively, the power could be sold at a rate of $0 to selected buildings in the community such as a school or set of kaumatua flats to benefit the wider community in savings rather than gain economic benefits for just the marae. This scenario will be explored further in a later chapter. For the purposes of the base model, the selling price and buying price were assumed to be constant throughout the year, at an averaged rate of $0.25/kWh for buying grid electricity and $0.15/kWh for selling excess energy. These values are based on current average rates for electricity in New Zealand obtained from Power Compare (2025), which varied between $0.20/kWh and $0.30/kWh for the Waikato Region. The selected values were varied when performing a sensitivity analysis to understand their impact on the overall system economics.

To obtain the average annual cashflow of a marae in regard to energy, the total annual energy deficit and excess were multiplied by the selected electricity buying and selling rate respectively. The net cashflow became the income from the sold electricity (*Income(y)*) plus the savings from the usual electricity bill (*Savings(y)*) minus the operational expenditure (*OPEX(y)*) of the system and tax (*Tax(y)*) in each year "y". This is shown in the equation below. In Year 0, this equation also includes capital expenditure (*CAPEX*) but in subsequent years CAPEX is assumed to be zero. The discount factor (*df(y)*) is used to revert the value of the cashflow to the base year (Year 0).

$$F(y) = (Income(y) + Savings(y) - CAPEX - OPEX(y) - Tax(y)) \times df(y) \qquad \textit{(Equation 9)}$$

$$Income(y) = p_s \times \eta_P(y) \times Balance_{Sur}(y)$$

$$Savings(y) = p_b \times \eta_P(y) \times (D(y) - Balance_{Def}(y))$$

$$Tax(y) = 0.28 \times (Income(y) - Depreciation(y))$$

$$Depreciation(y) = 0.07 \times (n_P \times uc_P + n_B \times uc_B)$$

Where:

- $F(y)$ = net cash flow in year "y" (\$/y)
- $df(y)$ = discount factor in year "y", decreased annually using a discount rate of 2% and equation $df = \frac{1}{(1+2\%)^y}$
- p_s = selling price of electricity, \$0.15/kWh in base case
- $Balance_{Sur}(y)$ = total electricity surplus from the system in year "y" (kWh)
- p_b = buying price of electricity, \$0.30/kWh in base case
- $Balance_{Def}(y)$ = total electricity deficit from system in year "y" (kWh)
- n_P = number of solar panels in array
- n_B = number of batteries in bank
- uc_P = unit cost of solar panels (\$/panel)
- uc_B = unit cost of batteries (\$/battery)
- $\eta_P(y)$ = efficiency of solar panels in year "y", decreased annually as seen in Table 2

Since the efficiency of the panels is expected to decrease annually, the surplus power available was decreased correspondingly in each year following. Taxes and depreciation were included in this analysis, however many marae could be classified as non-profit organisations and thus be tax-exempt. Removing this cost could improve the economic benefits in the analysis results, however as it is unclear how many marae are currently registered as non-profit and whether income from solar could be declared as non-taxable income (with answers differing on a possibly case-to-case basis), it was needed to cover all cases. An analysis period of 25 years was selected as this is the recommended warranty period of most solar panels. The panels are likely to have a longer lifespan than this, but efficiency will continue to decrease so more panels will be required to get the intended supply.

4.3.2.2 CAPEX and OPEX

The capital and operational costs of the system were found using the tables seen in section 4.2.1 (Table 3-Table 7). These tables presented CAPEX and OPEX costs by capacity, i.e., $/kW of solar capacity and $/kWh of battery capacity, so to use them the costs were simply multiplied by the capacity to get approximate estimated costings for the battery and solar specified. The total CAPEX was the sum of the solar and battery CAPEX, and the total OPEX similarly the sum of the solar and battery OPEX. These equations can be seen below.

$$CAPEX = CAPEX_P \times n_P \times c_P + CAPEX_B \times n_B \times c_B \qquad \textit{(Equation 10)}$$

Where:

- CAPEX = total capital expenditure for the system ($)
- $CAPEX_P$ = CAPEX for solar panels by capacity ($/kW), see Table 3
- n_P = number of solar panels in system
- c_P = capacity of individual solar panel (kW), see Table 2
- $CAPEX_B$ = CAPEX for solar panels by capacity ($/kWh), see Table 6
- n_B = number of batteries in system
- c_B = capacity of individual battery (kWh), see Table 5

OPEX for the year was derived similarly, by:

$$OPEX = OPEX_P \times n_P \times c_P + OPEX_B \times n_B \times c_B \qquad \textit{(Equation 11)}$$

Where:

- OPEX = total capital expenditure for the system ($/y)
- $OPEX_P$ = OPEX for solar panels by capacity ($/kW), see Table 4
- $OPEX_B$ = OPEX for batteries by capacity ($/kWh), see Table 7

The OPEX and CAPEX are useful measures for affordability, highlighting the expected up-front and ongoing costs of installing a solar and battery system. They are also useful as a base in further economic calculations such as for TLCC and LCOE as seen in the following section.

4.3.2.3 TLCC and LCOE

The total life-cycle cost of the system is the CAPEX plus the OPEX for each year of its lifespan, which, based on the warranty period of solar panels, is 25 years in this case. This is shown in the equation below:

$$TLLC = CAPEX + \sum_{y=1}^{25} OPEX(y) \qquad \textit{(Equation 12)}$$

The levelized cost of electricity (LCOE) can be further derived from this, by dividing the TLCC by the total amount of electricity produced by the system over its lifetime, shown in the equation below:

$$LCOE = \frac{TLCC}{\sum_{y=1}^{25} S(y) \times \eta_P(y)} \qquad \textit{(Equation 13)}$$

Where:

- S(y) = the total solar generation for year "y" (kWh/y)
- η_P(y) = the efficiency of the panels at year "y", which decreases linearly at a rate of 0.04% per year after the first year as seen in Table 2

The LCOE and TLCC are useful measures to compare with alternative options for the site, such as staying grid-connected or investigating wind or hydro powered systems. An LCOE lower than the current price of electricity can be a good indicator of whether a proposed system will be economically viable, and so will be used as a constraint in viability analysis

4.3.2.4 NPV

The net present value (NPV) of the solar and battery system at end-of-life is a useful measure of how financially viable an investment in a proposed system could be. A positive NPV indicates returns outweigh the costs over the lifetime of the system, so this can be added as a constraint in the analysis of whether a proposed system is suitable or not for a marae's needs. The calculation is carried out as follows, taking into account the system CAPEX as well as the sum of the net cashflow for each year in its lifetime (25 years).

$$NPV = -CAPEX + \sum_{y=1}^{25} F(y) \qquad \textit{(Equation 14)}$$

4.3.2.5 SPB

Simple Payback (SPB) is used to explain how long it will take for a system to pay itself off, ignoring effects such as inflation and depreciation. It is a quick and easy way to determine whether a proposed system is profitable, with short SPB indicating a system will pay itself off quickly and likely turn a greater profit than a system with a very high SPB. It is calculated as seen in the equation below with values obtained from Year 0:

$$SPB = \frac{CAPEX}{Income(y0) + Savings(y0) - OPEX(y0)} \qquad \textit{(Equation 15)}$$

4.4 SENSITIVITY ANALYSIS

A sensitivity analysis was performed on a number of key variables to understand their impact on the results, specifically the electricity buying and selling price along with the CAPEX for solar and battery separately. Two scenarios were run, one assuming a 100 kW solar array alone and the other including a 100 kWh battery, where each variable was changed plus or minus 20% and the percentage change in payback presented in a tornado chart.

4.5 DIFFERENT SYSTEM CONFIGURATION RESULTS OVERVIEW

The supply and economics calculations presented above were carried out for combinations of solar array and battery capacity inputs ranging between 0-500 kW/kWh respectively using a data table. The results of each capacity combination were plotted for the percentage of demand supplied, the LCOE and the NPV separately, then together on an area plot to see where systems meeting different criteria individually overlap. The criteria selected to determine whether a proposed system was suitable or not were systems having NPV greater than $0 (assumed to be economically viable), systems with LCOE lower than the average electricity price ($0.25) and systems with either 100% of the demand supplied (complete autonomy from grid) or greater than 80% of the demand supplied (suitable for emergency response). Graphing the areas where system sizes meet one or more of these criteria allows for marae with differing values and interests to see where they might look first. The CAPEX was also considered to be a limiting factor as the budgets and funding options of different marae may vary, so an additional graph was made simply mapping the CAPEX vs different system capacity configurations, and areas presented for different CAPEX ranges.

4.6 RESULTS

Using the energy balance model described above, the resulting percentage of electricity demand fulfilled by a range of solar array and battery capacity combinations was found and plotted in Figure 25 below.

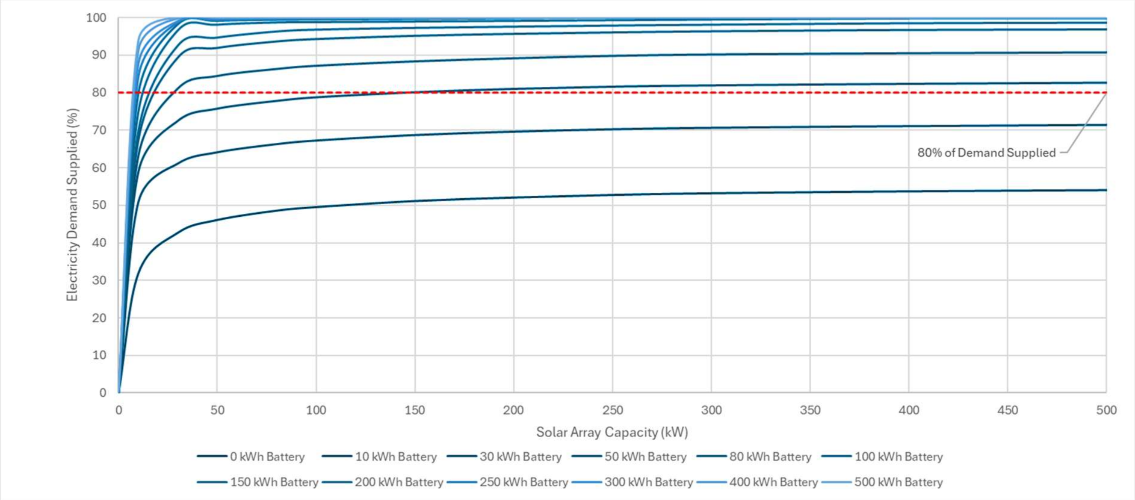

Figure 25: Percentage Electricity Demand Supplied by Different Configurations of Solar and Battery Capacities

Achieving 100% supply solely using a solar and battery powered system requires a large battery but not always a proportionally large solar array, as can be seen in the figure above (Figure 25). This is likely due to the infrequent nature of events, with large events being carried out almost entirely on battery power but smaller events and non-event days being powered directly by the solar array. Having such a large battery capacity but low event frequency means that the majority of the time the battery will be underutilised, except for the few days a year when it will be near empty.

The lifetime of a battery is dependent on its cyclic usage pattern, so having a low typical DOD could mean the battery lasts longer than estimated and thus save money on replacements, but whether these savings and the added energy security are worth the higher investment costs will depend on the needs of the marae. It may appear as more appealing an option for marae with typically low energy security than those situated closer to major urban centres. A cheaper option for marae still wanting some energy security but willing to remain grid-connected could be to invest in systems that can supply the majority but not all of the demand (i.e., 80% or more), unlocking battery capacities down to 50-30 kWh, significantly less than the 150 kWh minimum required for 100% supply.

The cost increases seen with larger solar array and battery capacities can be prohibitive depending on the budget of the marae. Understanding the economic benefits a specified system can provide will help marae to decide if solar is a worthwhile investment, and whether it will truly provide the desired savings. The LCOE of a range of system sizes are provided in Figure 26 below, with the current LCOE of the marae (assumed to be $0.25, the current average rate for electricity) included for reference.

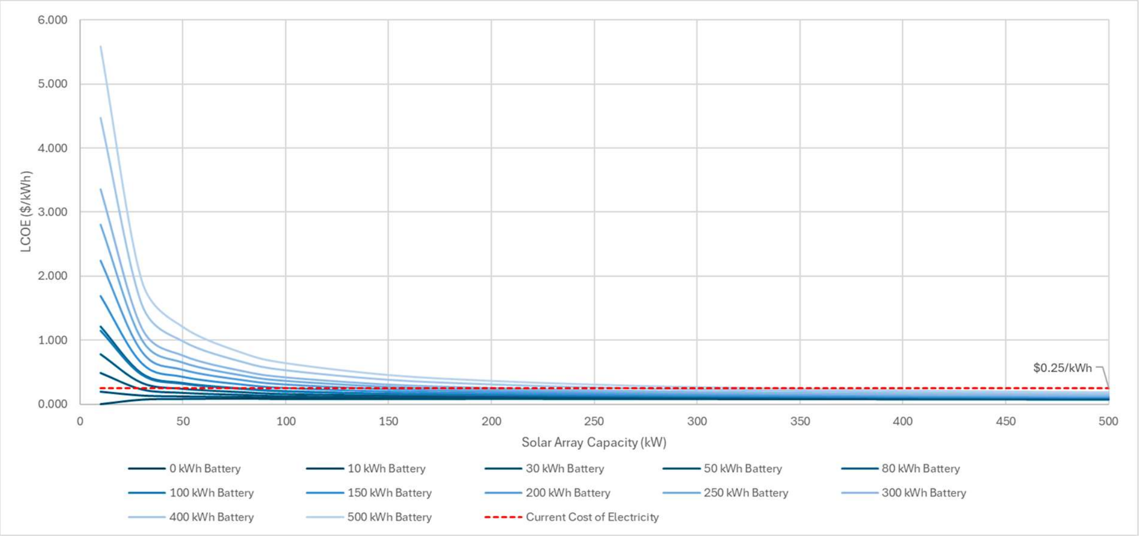

Figure 26: LCOE of Systems with Different Configurations of Solar and Battery Capacities

Configurations with LCOE lower than the reference are assumed to be improvements on the current marae situation, and it can be seen that all of the specified systems analysed here (with capacities ranging between 0-500 kW/kWh respectively) eventually end up below this point. Smaller systems with battery capacities between 0-10 kWh have LCOE lower than the reference with any capacity solar array added, indicating a small system will cost less over its lifetime than the current arangement, but systems with larger battery capacities require similarly large solar arrays to give the same LCOE's. The increase in capital costs associated with larger batteries being included means economies of scale in terms of the solar power generated are needed to balance them out.

The LCOE is a useful measure to compare the total amount of electricity generated by a system and its costs with alternatives like the current state, however larger solar arrays will generate more power than the marae needs, especially during non-event days. Since the buy-back rate of solar-generated electricity is lower than the cost of buying electricity, the savings purported by the LCOE may not be realised in reality. To better understand the economic status of a specified system at the end of its lifetime, the NPV was also found for a range of system capacities as seen in Figure 27.

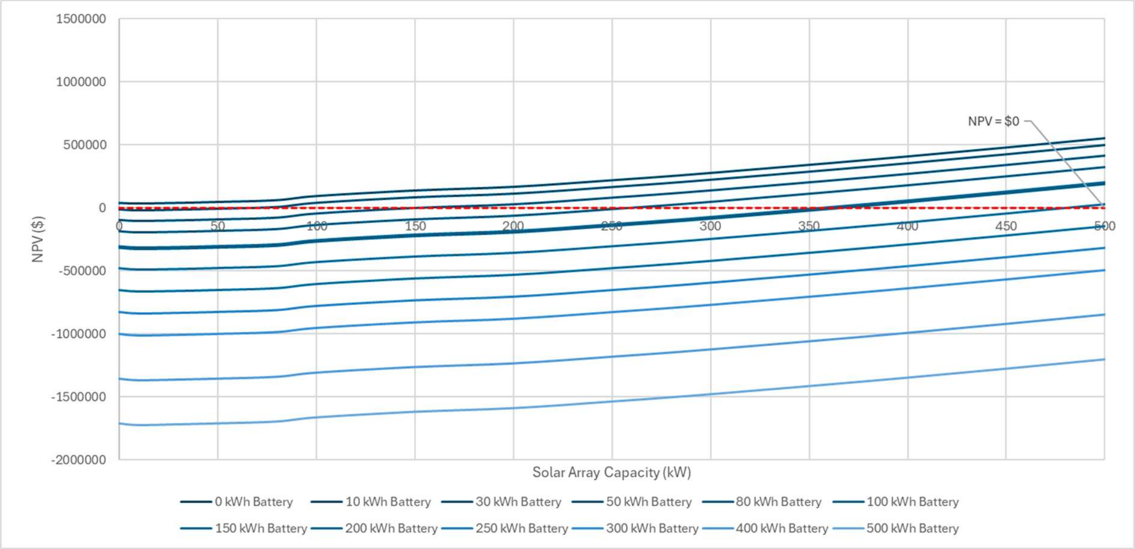

Figure 27: NPV of Systems with Different Configurations of Solar and Battery Capacities

The NPV calculated here includes savings from the purchase of electricity from the grid as an income stream, so when NPV equals zero it means the savings and income from selling electricity are equivalent to the cost for buying the system and any operational costs. Configurations with NPV of zero or above are needed to ensure the system can at the very least pay itself off, however if profit is not of great importance (i.e., a marae may focus on energy security more than income), a system with an NPV lower than zero may be chosen. The graph above shows that systems with smaller battery capacities and larger solar array capacities have the greatest NPV's, with large batteries requiring large solar arrays to become economically viable. Compared to the LCOE graph, there are fewer configurations that can provide benefits over the status quo if they are required to pay themselves off, likely due to the divide between the price for buying versus selling electricity at the household level being too wide and the consistent energy usage (and thus savings) being too low to justify. Larger systems are easier to pay off due to economies of scale, and could likely negotiate higher prices for selling electricity to further increase the NPV and returns on investment. NPV could also be increased by using alternative electricity selling methods such as P2P energy trading and potentially securing a higher selling price and income stream, an option that will be explored in further detail in the next chapter.

Lines of SPB were generated by extrapolating results between calculated system configurations. It can be seen that systems with very large solar arrays but comparatively small batteries have the smallest SPB, echoing the results found in the NPV analysis. Systems with large batteries are thus difficult to justify investing in with a purely economic lens.

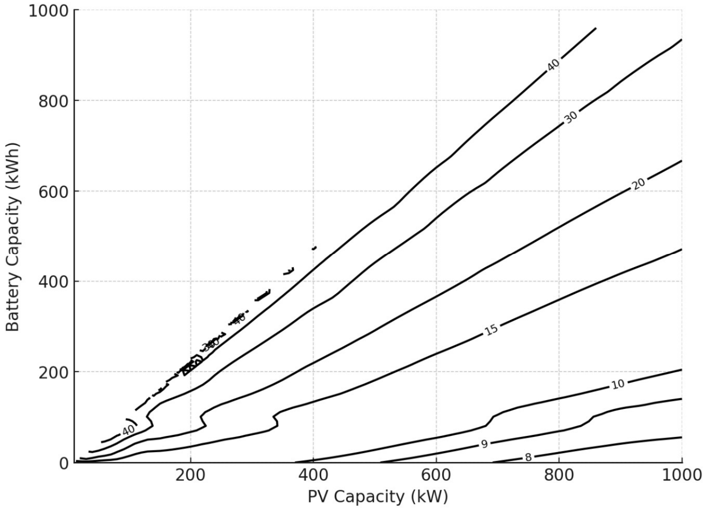

Figure 28: SPB of Systems with Different Configurations of Solar and Battery Capacities. Contour lines are of constant simple payback.

The SPB analysis was repeated with different electricity selling and buying price inputs to understand how these prices impact the results. From the graph below, it seems that having a higher selling price gives much lower SPB even with an increase in buying price, likely due to the large amounts of excess energy available to sell when the marae is not in use.

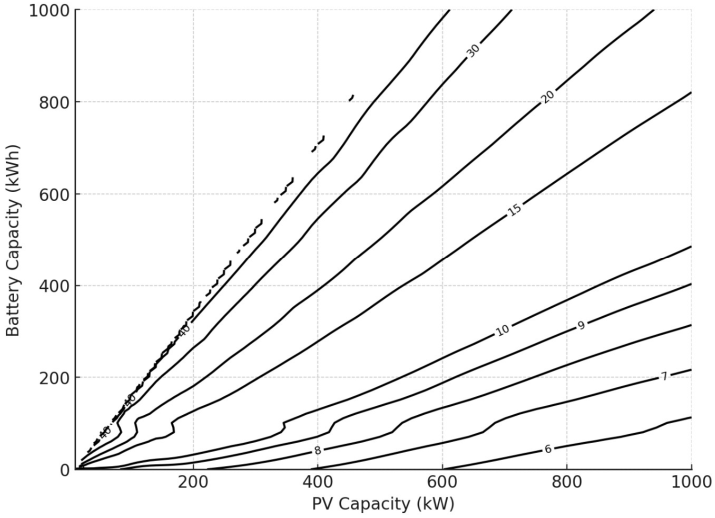

Figure 29: SPB with $0.35/kWh Electricity Buying Price and $0.20/kWh Selling Price. Contour lines are of constant simple payback.

Each of the previous graphs (Figure 25, Figure 26 and Figure 27) presents a range of possible solar array and battery configurations and some criteria that could be used to determine whether a specified system meets the needs of a marae. They are helpful when selecting a system with only one characteristic of interest (i.e., 100% of the demand supplied), however in most cases other factors will also influence the final decision on system size.

The ranges of systems that can fulfil each criteria individually (i.e., systems where 100% or more than 80% of the electricity demand is supplied, where NPV is greater than $0, and where LCOE is lower than the status quo) were overlaid into Figure 30, providing a summary of possible systems that can meet one or more of the selected criteria.

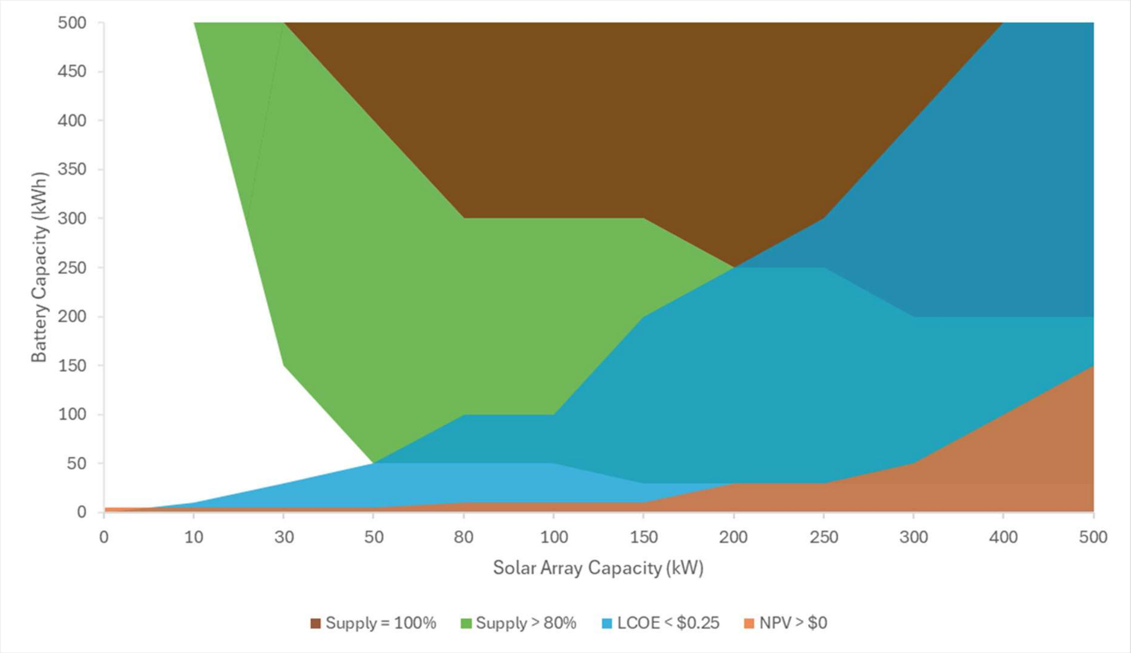

Figure 30: Overview of Solar and Battery Capacity Configurations Meeting Different Criteria

On this graph, different regions of solar array and battery capacities appear that fulfil each criterion individually and overlap where more than one criterion is fulfilled. Marae can then decide based on their own principles and needs what criteria apply to them and focus their attention on systems within those bounds.

For example, a marae interested in 100% supply with a low LCOE may select a system with a solar array capacity of 300 kW and battery capacity of 300 kWh, while a marae who wants a cheap system that will pay itself off and provide savings without needing all of its energy demands supplied might look into an 80 kW solar array with 10 kWh battery.

To complement Figure 30, an overview of the expected CAPEX ranges for different combinations of solar array and battery capacities is presented below, showing at a glance which regions might be affordable based on the budget of a particular marae.

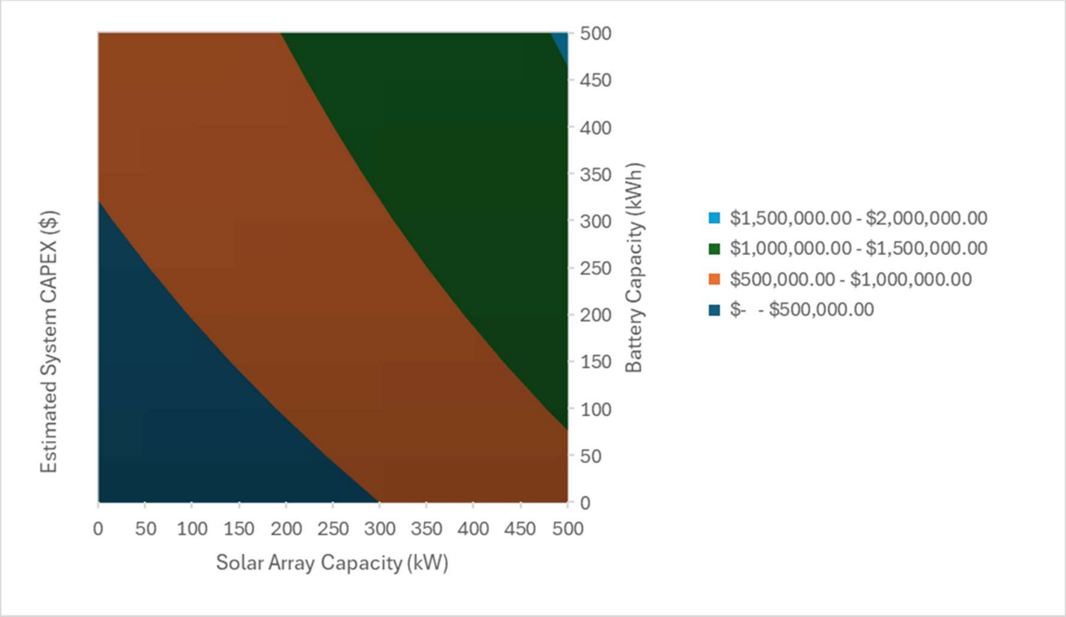

Figure 31: CAPEX Ranges for Different Configurations of Solar and Battery Capacities

The tornado chart below (Figure 32) presents a sensitivity analysis of simple payback periods for two system configurations: a 100 kW solar PV-only system and a 100 kW PV system with 100 kWh battery storage. The chart shows how varying key input parameters by ±20% affects the payback period, expressed as percentage change from the base case. This format helps identify which factors most influence financial returns and where attention should be focused when assessing system feasibility or optimising design.

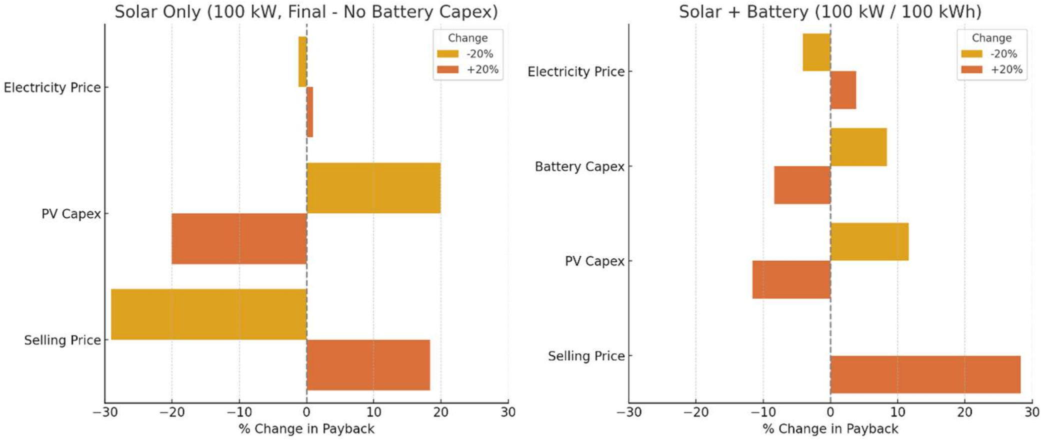

Figure 32: Sensitivity Analysis Tornado Chart. Note negative values indicate longer payback periods.

One of the most immediate observations is the dominant influence of the electricity selling price (buyback rate) on payback performance. For the solar-only system, reducing the selling price by 20% leads to a nearly 30% increase in the payback period, while increasing the selling price shortens payback by over 18%. This highlights how crucial export compensation is to system economics—especially for commercial systems that often produce surplus power during the day. In the PV + battery scenario, the impact is even more pronounced: a 20% increase in the selling price reduces the payback period by over 28%. A 20% decrease in selling price resulted in no payback of the system. This heightened sensitivity reflects the battery's ability to store and release energy at strategically valuable times, effectively maximising the return on exported energy.

Importantly, the analysis also underscores the potential advantages of market access and aggregation strategies. Small-scale solar and battery systems often face low or fixed feed-in tariffs, limiting their ability to monetise excess energy. However, through aggregation into Virtual Power Plants (VPPs) or participation in spot markets, system owners can unlock better pricing by acting collectively. Aggregators can shift export timing based on market signals or trade power on behalf of multiple assets, effectively increasing the achievable selling price for distributed generation. In markets where this is possible, aggregated systems can participate in demand response, frequency control, or real-time trading, commanding higher revenues than static buyback arrangements. For battery-equipped systems in particular, this opens up stacked value streams, where revenue is earned not only from arbitrage but also from grid services, enhancing the economic case and reducing payback times. Although outside of the scope of this work, the concept of multiple marae aggregating surplus electricity and participating in the electricity market as a VPP is an interesting area and should be area for future exploration.

Overall, this highlights that improving the selling price—whether through favourable policy, market design, or advanced trading mechanisms—is among the most powerful levers for improving solar and battery project economics. It suggests that system owners, developers, and policymakers alike should explore ways to facilitate access to flexible, dynamic, and fair export compensation mechanisms, especially as the grid continues to decentralise.

In contrast, electricity price (import tariff) has a surprisingly minor effect on payback. For the solar-only system, a ±20% change in electricity price shifts payback by only around ±1%, and slightly more for the battery-integrated system (up to ±4%). This relatively small sensitivity can be attributed to the fundamental role of solar in offsetting electricity consumption. Once a system is sized to meet a substantial portion of on-site demand, further changes in electricity price have diminishing impact, especially when self-consumption is already high. For prospective system owners, this suggests that solar investments are less exposed to grid price volatility—particularly beneficial in uncertain or deregulated electricity markets.

PV Capex plays a major role in shaping payback outcomes, particularly for the PV-only system. Here, a ±20% change in Capex causes nearly ±20% change in the payback period, indicating a direct linear relationship. This reflects the high share of up-front capital in solar projects and reinforces the importance of equipment pricing, financing structures, and installation costs. When batteries are added, the relative influence of PV Capex is diluted slightly. This is because the total system cost increases with battery inclusion, so a ±20% change in just the PV portion translates to a moderate impact on overall payback.

As expected, battery Capex has no influence on the PV-only system, as it contains no battery. In the PV + battery configuration, battery Capex does affect payback, though the impact is smaller than that of PV Capex or selling price. A 20% increase or decrease in battery Capex alters the payback period by about 8–9%. This suggests that while battery pricing is important, especially in capital-intensive projects, its influence is somewhat buffered by the value batteries provide (e.g., increased self-consumption, improved export timing). As battery prices continue to decline globally, we can expect this factor to become more favourable for system economics, especially in markets with low or variable feed-in tariffs.

From a broader perspective, this analysis highlights a few important trends. First, systems are more sensitive to revenue-side factors (like export value) than cost-side ones, particularly in the presence of batteries. Second, solar-only systems are more exposed to changes in capital cost, while storage-integrated systems diversify the drivers of financial performance. Finally, the fact that electricity price changes have such minimal effect suggests that solar PV systems are robust hedges against energy market uncertainty.

4.7 CONCLUSION

An analysis was performed on a range of solar array and battery capacity configurations resulting in graphs of LCOE, NPV and Percentage Demand Supplied versus capacity. Data points where the solar and battery capacity combination resulted in a positive NPV, an LCOE lower than the average electricity price and/or where greater than either 80% or 100% of the demand was supplied were overlaid on an area graph to help identify areas where more than one factor of interest overlap and the overall range of system configurations where adding solar could be beneficial for marae. A graph of CAPEX versus capacity was also created to further identify systems within different marae’s budgets.

The results obtained in the above analysis assume that the marae is the sole user of the generated electricity, and that any monetary benefits would be used by the marae alone. However, marae are tightly integrated with their surrounding communities, so benefits are likely to be shared outside the boundaries of the marae where possible. The following chapter explores some opportunities to gain greater benefits from the system by including the wider community in the system boundary.

5 COMMUNITY-CENTRED SOLUTIONS

5.1 INTRODUCTION

Māui's adventures usually end in great benefits for his community. After identifying an issue his people are facing, he then sets out to help solve it. In the story of Māui and the sun, the issue was people not having enough time in the day to work productively, thus he slowed down the sun and gave his community more time. This was a huge undertaking for a single person, and the danger and risk associated with it outweighed the benefits to an individual so thoroughly that no one else had ever though to try it. But Māui was a creative problem solver, and his main concern was always the wellbeing of the community, and so he dared to catch the sun. More than the benefits to the individual then, the benefits to the collective should be investigated in order to fully follow in Māui's footsteps and design a solution that truly benefits the marae and its surrounding community.

The base case created in the previous chapter assumes that the energy and income from excess energy is used solely by the marae. However, that assumption ignores the fact that marae are communal assets, collectively owned and maintained by their respective hapū. Any monetary benefits obtained by the marae would be used to benefit the community, mostly internally through equipment upgrades or maintenance for the marae, but they could also be shared externally by targeted grants or scholarships to hapū members for example. Another option for obtaining community benefits from a marae solar and battery powered system is by energy sharing, gifting the excess energy generated by the system to the community residents or to other important community buildings such as a school (kura) or kōhanga reo.

Transferring the energy generated directly to the community demand source would be difficult unless the demand is near the marae, e.g., neighbouring or on the same property, and even then, the marae may need to register as an energy provider if the power crosses a property boundary (Abaunza, 2020). Peer-to-peer (P2P) trading is an alternative method that allows the marae to "sell" their excess power to specified users at an agreed upon price via a broker, avoiding the legislative and technical complications of a more direct route and simplifying the experience for both the marae and wider community.

The base case created in the previous chapter assumes that the energy and income from excess energy are used solely by the marae. However, that assumption overlooks the fact that marae are communal assets, collectively owned and maintained by their respective hapū. Any monetary benefits obtained by the marae would ultimately be used to benefit the community, either internally through equipment upgrades or maintenance, or externally through targeted grants, scholarships for hapū members, or other initiatives that contribute to community well-being. Additionally, beyond financial redistribution, there are opportunities to maximise community benefits by integrating energy-sharing models that directly provide power to local households, schools (kura), or early childhood centres (kōhanga reo).

While sharing electricity with the community aligns with the principles of manaakitanga, the technical and regulatory challenges of such an approach must be considered. Transferring electricity directly to a neighbouring demand source, such as a papakāinga, would require either physical infrastructure to connect the properties or a formal energy-sharing agreement. If the energy is transferred across property boundaries (e.g. using a microgrid), the marae may need to register as an energy provider, which introduces further regulatory and administrative complexities. The current regulatory framework is not set up well to support to use of community energy systems and microgrids. An alternative to direct energy transfer is peer-to-peer (P2P) trading, where surplus electricity is "sold" to community members at a rate lower than standard retail electricity prices but higher than current buy-back rates from electricity retailers. This approach could increase the financial viability of solar adoption for marae while simultaneously benefiting the broader community, and is a scenario analysed in this chapter. Finally, the potential for solar energy to enhance energy resilience and disaster response capabilities is an increasingly relevant factor, especially in rural areas prone to power outages.

This chapter focuses these key topics, providing a broader discussion on how marae can navigate the financial, regulatory, and cultural landscape of solar energy adoption while optimizing community benefits.

5.2 COMMUNITY ENERGY RESILIENCE

For marae located in rural areas, energy resilience is a very real issue faced by their communities. Kawhia for example is reliant on a single 110 kV line from the Te Awamutu substation over 60 km away, so any faults along the line would take out electricity for the entire community and blackouts occur much more frequently than in areas with high energy resilience (Transpower New Zealand Limited, 2001). Installing a large energy source at the marae that feeds back to the grid would increase resilience by allowing electricity to flow to nearby houses and keeping the marae operational during a blackout. This can be a great advantage for marae as it allows them to provide manaakitanga to their guests no matter the condition of the lines. Increasing local electricity supplies can also help lower transmission infrastructure upgrade costs in the long run, with less total lines needing upgrades than if the same amount of generation was added further away from the demand source. Transmission upgrades and community security of energy supply were not considered in the above analysis, however including them could generate some interesting results for the community as a whole so it is recommended that future work include some consideration of this factor.

5.3 EMERGENCY RESPONSE HUBS

Marae are innately suited to become bases of their community during emergencies such as natural disasters, having large kitchens and dining areas capable of feeding hundreds of people, room to sleep them, plus all the necessary ablutions. With the addition of a solar and battery powered system the marae can keep operating even when power supply to the community is cut off, and having electricity freely available could provide some resilience over a typical diesel generator or gas-powered appliances if the supply of these fuels is also compromised. Any amount of electricity available during an emergency would be helpful, even if only to power a radio or computer to communicate with emergency responders, and it was assumed in this analysis that a system providing 80% of the marae electricity demand would be most useful during an emergency. However, the specific configuration of such a system would need more rigorous analysis to determine how well the marae could function with limited supply. Other factors such as whether the marae has its own water treatment system and location (e.g., on a hill in a flood or tsunami prone area) could also influence whether a marae is a suitable emergency response hub. The design of a marae emergency hub utilising solar energy could be a useful area to explore in future.

5.4 AGGREGATED MARAE ENERGY TRADING MODEL

Solar and battery systems sized to supply 100% of the marae's electricity demand can be too large to enter into a residential-scale energy payback contract but are also too small to sell energy at a utility-scale. They may be able to secure a contract at a commercial-scale, but depending on the size of the system may be too small for even that. One option to overcome this problem is to aggregate the energy supplied by a number of affiliated marae, sell the power together then distribute the profits. This could work well in cases where many marae are associated with a single entity such as an iwi group or incorporation like Waikato Tainui, who can negotiate a contract on behalf of the related marae. If the entity is a profitable business, they could even consider purchasing the solar and battery systems themselves for the individual marae, lowering the costs by purchasing in bulk, providing free energy to the marae and making their profits from selling the excess electricity when the marae is not in use, thus making it both a charitable and profitable venture. The specifics surrounding the configuration of such an arrangement could be an interesting future investigation.

5.5 EXAMPLE COMMUNITY-CENTRED SOLUTION: ENERGY SHARING

Energy sharing is a potential way to directly impact the wider community using the excess electricity generated by a solar powered system. The electricity could be gifted either directly (by installing a transmission system between the marae's solar powered system and the intended recipient) or indirectly (by using a P2P trading platform) to specified buildings in the community. These could be residential houses, other communal buildings such as schools or libraries, or any buildings specified to be valuable to the community. Using the gifted energy, their overall draw from the grid would be lessened and would result in lower electricity bills. The extra savings gained by the community can thus be added to the economics analysis of a proposed system to see if it is more economic to share the energy than sell it, which will be carried out below.

5.5.1 Electricity Supply and Demand Methodology

In this analysis, it is assumed that the buildings receiving the excess power are either sufficiently close to the marae or are participating in a P2P arrangement that allows the marae to freely gift the excess energy to them at no cost. Since the analysis is relatively high-level and not site-specific, this eliminates the need for complicated modelling of the electricity transmission network and P2P logistics, which is likely to vary on a case-by-case basis (i.e., accounting for energy losses due to transmission will vary depending on distance, with longer distance perhaps needing a larger system to offset the losses or receiving lesser benefits than a closer distance). Network constraints (real and/or perceived) are often raised as a barrier to large increased levels of behind the meter solar. For some projects, assessments of network capacity and additional modifications are required to manage operational impacts of increased solar generation. These additional network capacity issues have not been considered here, and it is assumed that network infrastructure is sufficient to deal with and P2P transmission. Alternatively, where the distance between the marae and other community buildings is not too far, a local microgrid could be established to facilitate the direct sharing of electricity. This is likely to not be financially viable unless large network upgrades are required as a result of the solar system.

The community demand profiles obtained in section 3.4 can be used with the marae demand profile and excess solar electricity supply to understand how a proposed system might interact with the wider community. The methodology used to do this was the same as in the previous chapter, using the base model to obtain the NPV and percentage demand supplied by different sized systems. Any excess electricity generated by the system after the marae demand had been met was supplied to the community for free until that demand was met then sold to the grid, and the savings obtained by the community added as another income stream to the annual cashflows and NPV calculations.

In the model this was implemented by replacing Balance(t) in Equation 9 with the Balance for Papakāinga and Kura respectively as seen below:

$Balance_{Papakainga}(t) = Balance(t) - D_{Papakainga}(t)$ *(Equation 16)*

$Balance_{Kura}(t) = Balance(t) - D_{Kura}(t)$ *(Equation 17)*

The “community” demand was assumed to be either the Papakāinga or Kura demand (see section 3.4) and results calculated separately for each of these options. The selection of system capacity configurations that have NPV greater than \$0 is graphically compared for each of these options (Marae Alone, Marae with Papakāinga or Marae with Kura) to see how the payoff changes with different electricity demands. The percentage reduction in bills seen by either the Papakāinga or Kura across different solar array and battery configurations was also found and graphed to see how much the community will benefit from the system separate to the marae.

5.6 RESULTS

The range of solar array and battery configurations that return an NPV greater than zero for a marae’s demand by itself or with a Papakāinga or Kura demand added are presented in Figure 33 below.

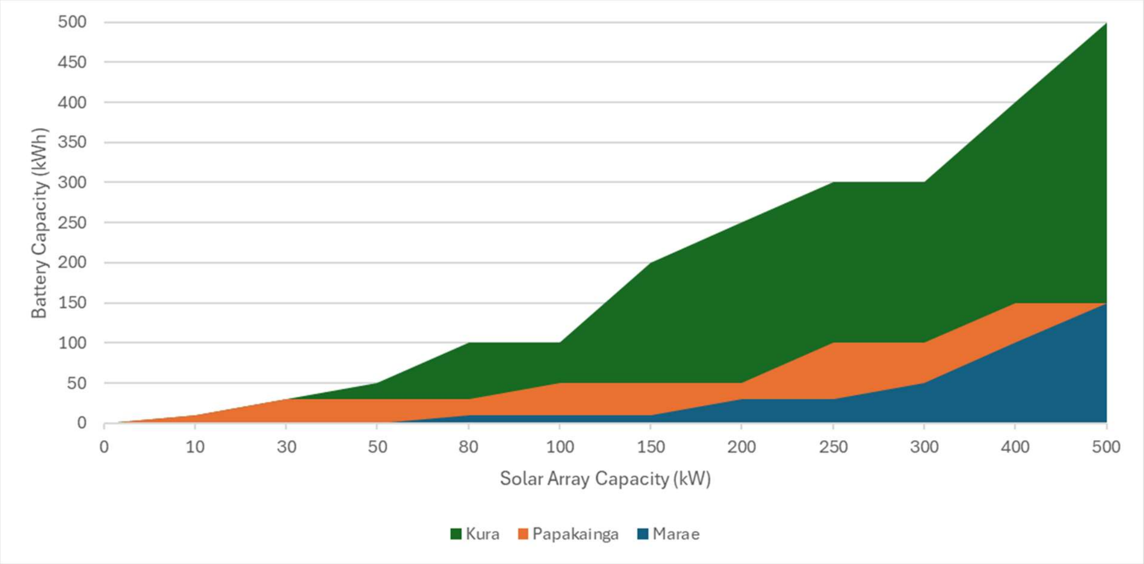

Figure 33: System Configurations with NPV > \$0 for Marae, Marae + Kura and Marae + Papakāinga

It is clear that the added demands considerably increase the range of economically viable system configurations. The difference between the buying and selling price of electricity means that the economics favour usage of the generated electricity over export, so the savings earned by a large, regular energy user such as a school greatly improve the economic outlook of a system over just a marae with typically low use. In a configuration like this, the solar array is used almost entirely by the school, while the battery is left as a backup to run the marae's events. Adding the Papakāinga demand only slightly improved the NPV ranges over a marae by itself, though this is likely limited by the number of houses included in the analysis. A larger community with more houses in the papakāinga will present a greater demand and thus more opportunities for savings.

On a more personal level, the reduction in electricity bought and thus bills paid for electricity by the houses in the Papakāinga or Kura is a useful metric for community benefits from the system, which can be seen in Figure 34 and Figure 35.

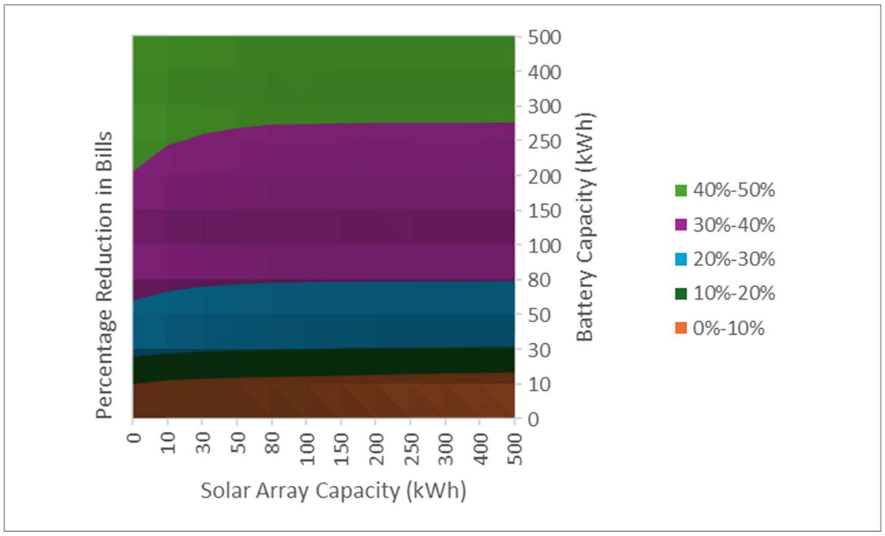

Figure 34: Reduction in Electricity Bills for Papakāinga

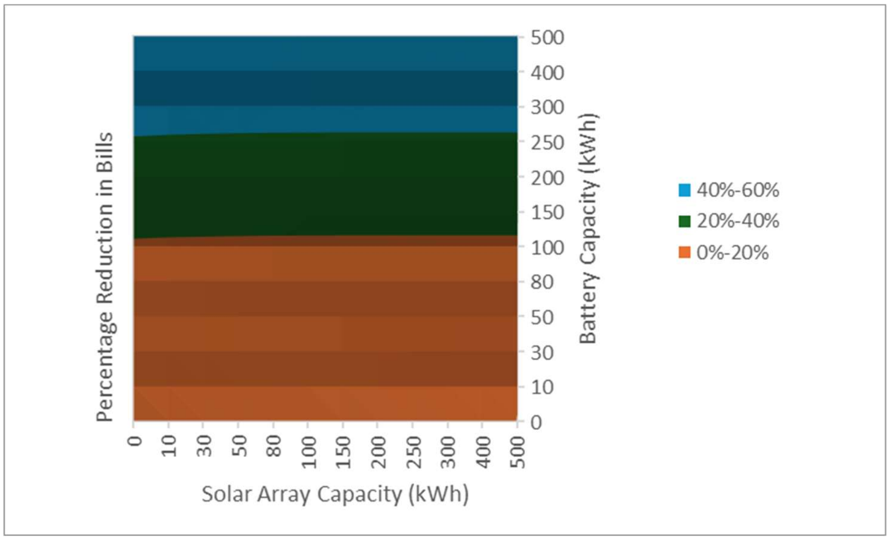

Figure 35: Reduction in Electricity Bills for Kura

The Papakāinga has a higher bill reduction at a lower battery capacity than the Kura due to its lower overall demand. However, it caps out at supplying around 50% of the demand while the Kura can reduce its bills by up to 60%. This is due to the electricity time of use or daily demand curves, which show schools using most of their energy during the day when solar supply is high while households tend to use more energy in the early morning and evening when solar supply is low. Since the battery is not used by either the Kura or Papakāinga, being kept as a backup to supply the Marae during events, 100% of the community demand cannot be supplied in this analysis. More analysis is required to understand whether a larger communal battery or individual household/school batteries might be beneficial.

5.7 CONCLUSION

Using a solar and battery powered system to supply a marae's electricity demand alone has limited economic opportunities due to its low typical usage (non-event) and the gap between electricity buying vs selling prices. Considering the marae as part of a wider community, other benefits could be obtained that may make the investment worthwhile even with low or negative returns, such as improved community energy resilience and the potential for a marae to become an emergency response hub. By sharing excess energy with the community, including a residential Papakāinga and nearby Kura, benefits can be quantified as returns for the community as a whole rather than the marae alone. Using P2P trading the excess electricity generated by the system can be supplied to other demands in the community, saving more money on bills and spreading the positive impacts of the system outside of the marae. The increased savings also improves the range of economically viable systems (system configurations with positive NPV), meaning a wider array of options are available for marae to choose from that could better overlap with other ranges of interest like 100% supply.

6 CONCLUSION AND RECOMMENDATIONS

Marae are the cultural centres of Māori communities and are used to host range of events, from tangihanga to wānanga. As the price of electricity increases marae are facing rising bills, and in a bid to combat these many have started to look at solar power as an alternative energy source. However, due to their unique demand profiles it is difficult to design an appropriate system to meet their needs. This thesis develops a characteristic electricity demand curve for marae that can be used to understand their needs then finds a range of solar and battery powered system sizes to meet them.

The demand curve is made up of five different characteristic day types: Non-Event days, which maintain a very low and flat baseload demand, 1-Day Event days, which typically have low to medium demand for only a few hours maximum, Event Start days, which start low but quickly increase to a high demand that drops slightly late at night, Event Middle days, which stay relatively high throughout the day, and Event End days, which start high before decreasing back to the baseload.

Most days in the year are Non-Event days, with the marae in use for only a third of the year or approximately 30 events. Events vary greatly in length, electricity demand magnitude and time-of-use, making it difficult to obtain a properly representative demand curve. By filtering the data of three marae into the five day-types described above then finding the average at each hour, the characteristics of each day type's demand can be found. These average demand curves can then be adjusted to find the maximum demand curves, which are used to design solar and battery systems capable of supplying 100% of the electricity demand.

The average demand curves can also be randomly applied with adjustments to a year's worth of time data to get an annual characteristic demand curve for an average marae, which can be used to understand how a specified solar and battery powered system will interact with a marae. Balancing the supply from the system with the marae demand, the energy deficit or surplus can be found at each hour of the year, then multiplied by an electricity price for either buying or selling electricity respectively to get an income and expenditures stream for a year. Adding CAPEX and OPEX for a specified system size, an economic analysis can be done to find the LCOE, NPV and SPB for the investment.

Repeating this analysis over a range of system capacity configurations, a selection of system sizes that give desirable results (i.e., LCOE lower than current buying price of electricity, NPV greater than zero or low SPB) can be found and plotted to find regions with overlapping desirable factors, thus presenting ranges of system sizes that can suit different marae's needs. For example, a marae focused on reducing their electricity costs at the lowest cost might invest in a 10 kW solar array and 10 kWh battery, which will only supply approximately 50% of their electricity demand, but the excess energy sold will pay for the rest of the electricity bought from the grid. Alternatively, a system with a 300 kW solar array and 50 kWh battery will supply over 80% of the demand at a much higher cost, but the income from the excess electricity will be much higher as well.

Larger systems that can supply 100% of the demand are much harder to justify economically for marae, as the low magnitude but high frequency non-event usage and very high magnitude but low frequency event usage means that it is difficult to increase savings without a large jump in system capacity and cost. This, however, does not mean it is impossible to do, as more creative configurations and wider community involvement can greatly improve the benefits obtained from a system. Supplying the excess electricity to a nearby school or papakāinga for example will generate much greater savings for the community as a whole than for the marae alone, and other opportunities such as aggregating marae energy and trading as a collective could also be explored in future analyses.

Economics are not always the sole focus of Māori energy initiatives, with factors such as energy resilience, environmental protection and community benefits often weighted higher due to culturally significant values such as manaakitanga, rangatiratanga and kaitiakitanga. Presenting the results as ranges fulfilling different needs (e.g., 100% of the demand supplied for marae wanting full control over their energy resources or a high NPV indicating high savings and returns that could be used to benefit the community) allows marae to select systems that are viable based on their own set of criteria, rather than standardised results optimised for economics.

Research around the different community benefits that could be obtained from the installation of a marae-based solar and battery powered system is an area with much to consider. Investigating alternative energy trading strategies to enhance the economics of the system could also be greatly beneficial for marae and their communities.

In terms of the analysis already done, improvements could be made to the supply sizing methodology, focusing on finding the optimum sizes based on the conditions provided. More rigorous analysis could also be done around the transmission of electricity between the system and the marae and community. The demand characterisation analysis could also be repeated with a larger dataset or higher number of marae to verify the results more accurately, and alternative demand analysis methods investigated to compare.

Overall, there are a number of benefits that could be gained by marae installing solar and battery systems that suit their needs, however the high capital costs required for an appropriately sized system could serve as a barrier to some. Using Māui as an inspiration, creative problem solving and working with the wider community can help make the system more affordable and reap greater benefits. Thus, for marae wanting to harness the sun’s energy, following in Māui’s footsteps by obtaining any necessary help, making an actionable plan, and being prepared to take on difficult challenges will help them succeed.

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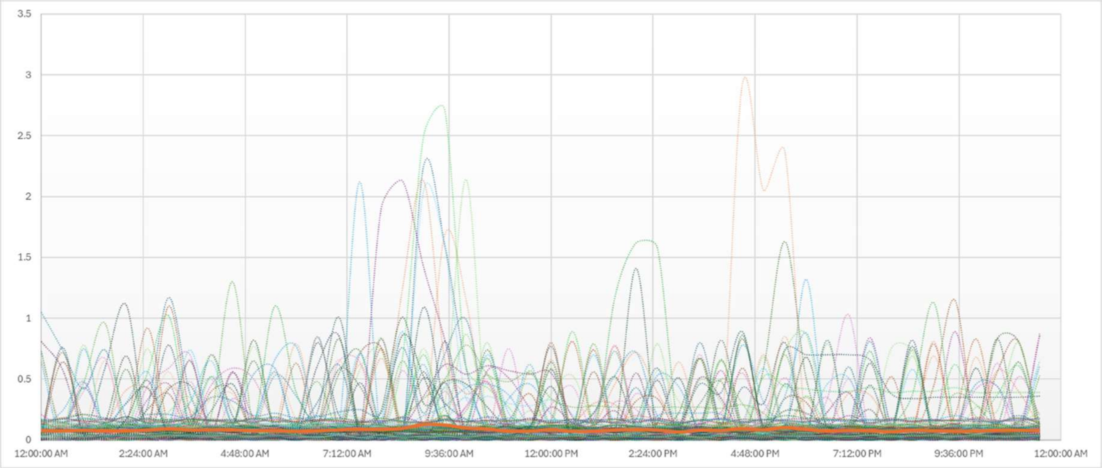
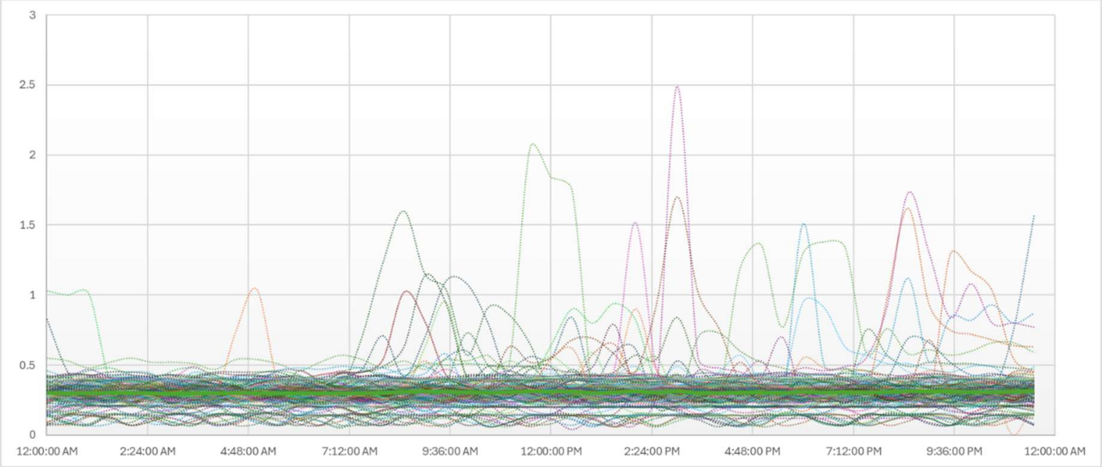
APPENDICES

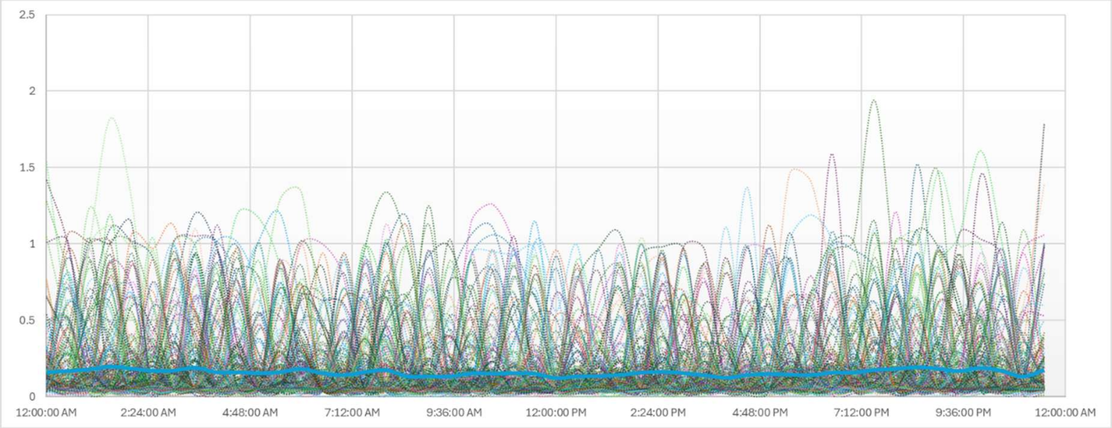
Appendix 1: Grouped Data for Marae

The clustered data for each day type and marae is presented below, with bold, coloured lines representing the average profile for each marae. The orange lines indicate Marae A, green being Marae B and blue for Marae C.

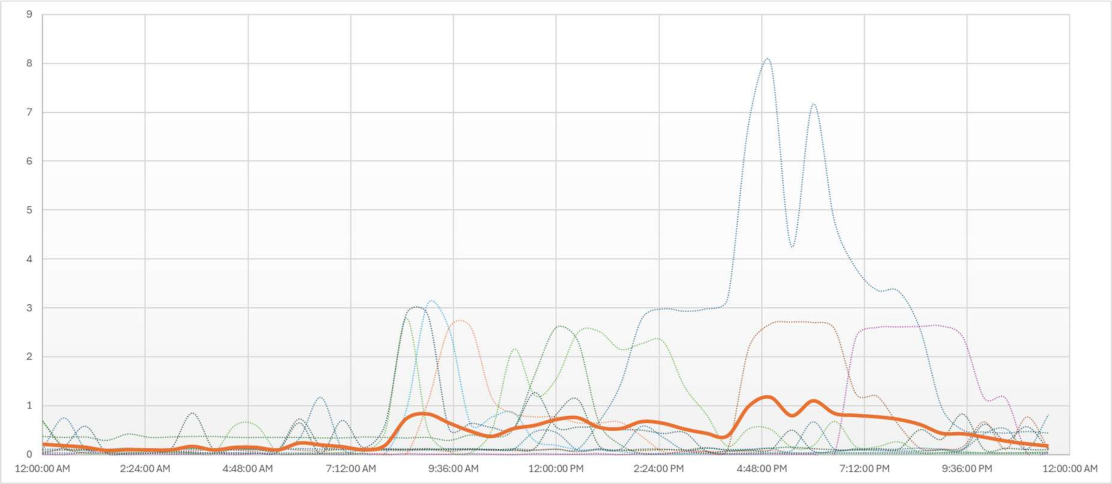
Non-Event Daily Demands

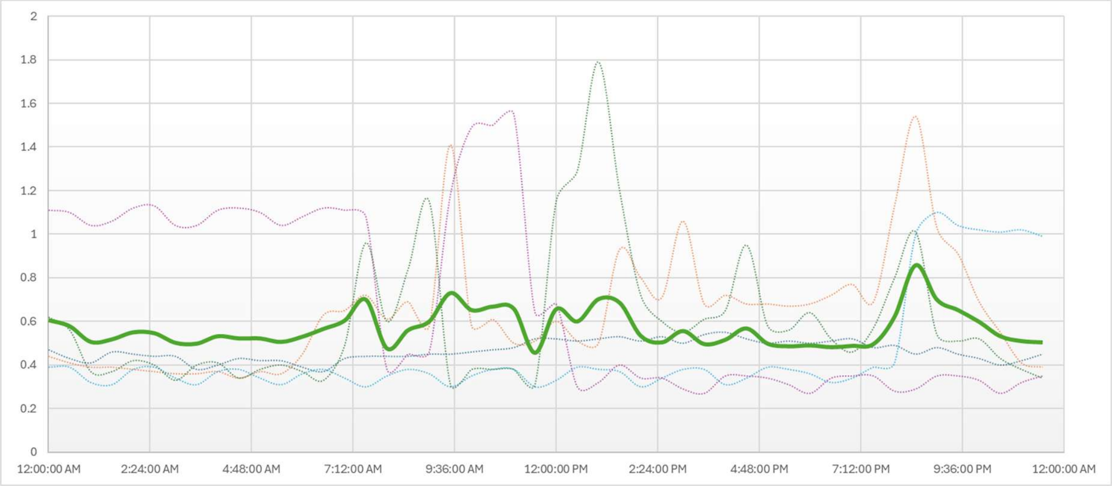


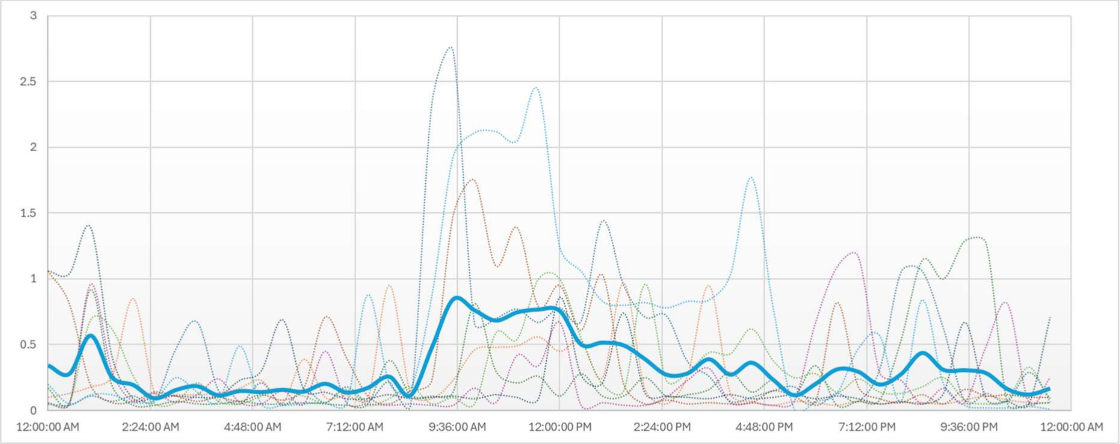




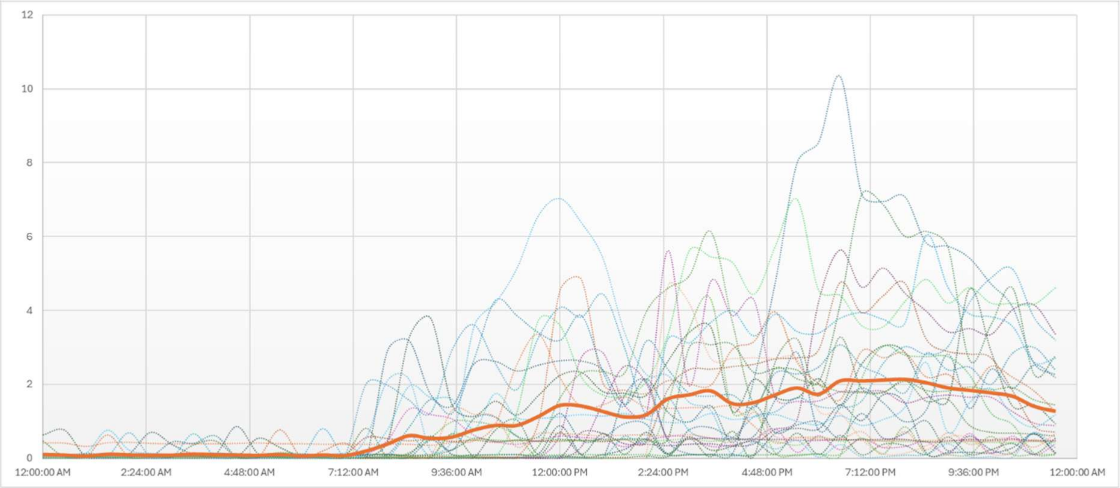
1-Day Event Daily Demands

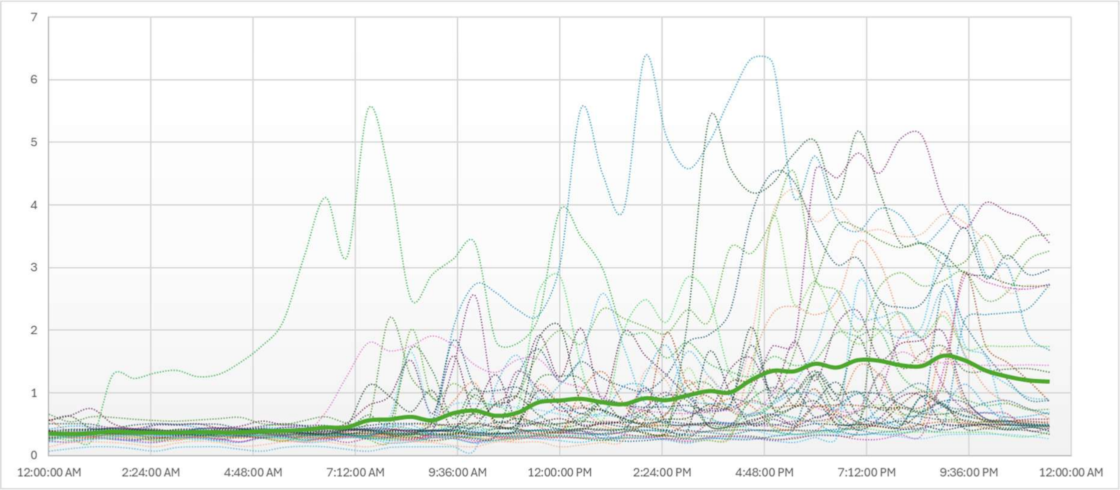


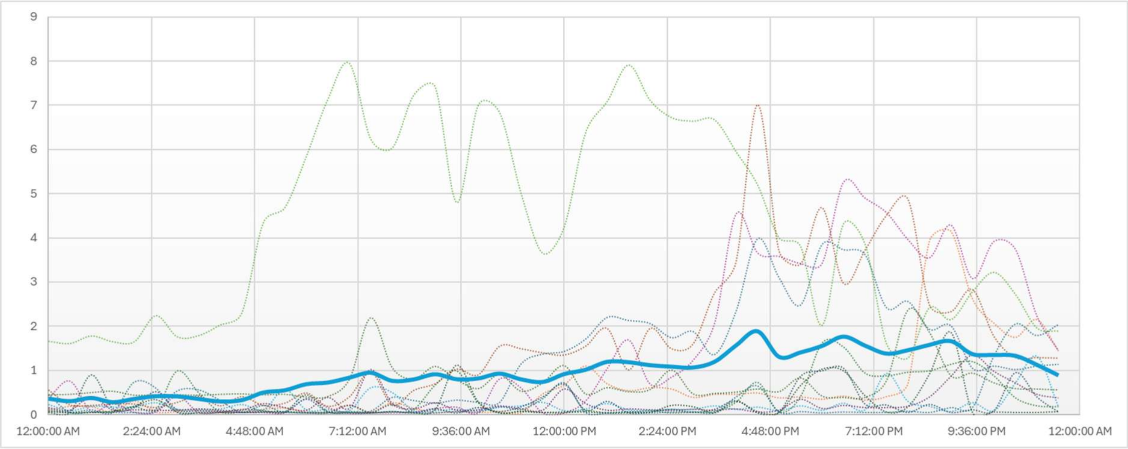




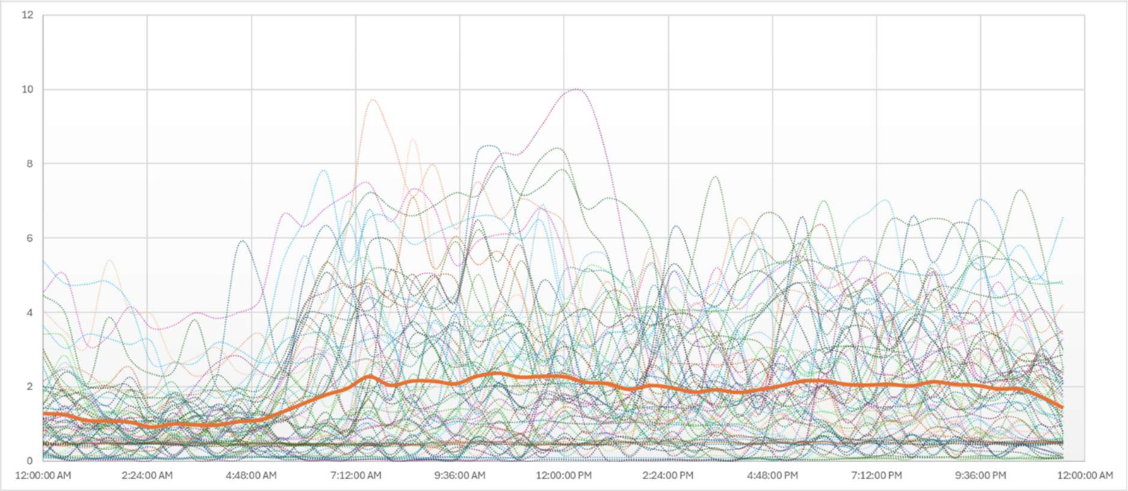
Multi-Day Event Start Daily Demands

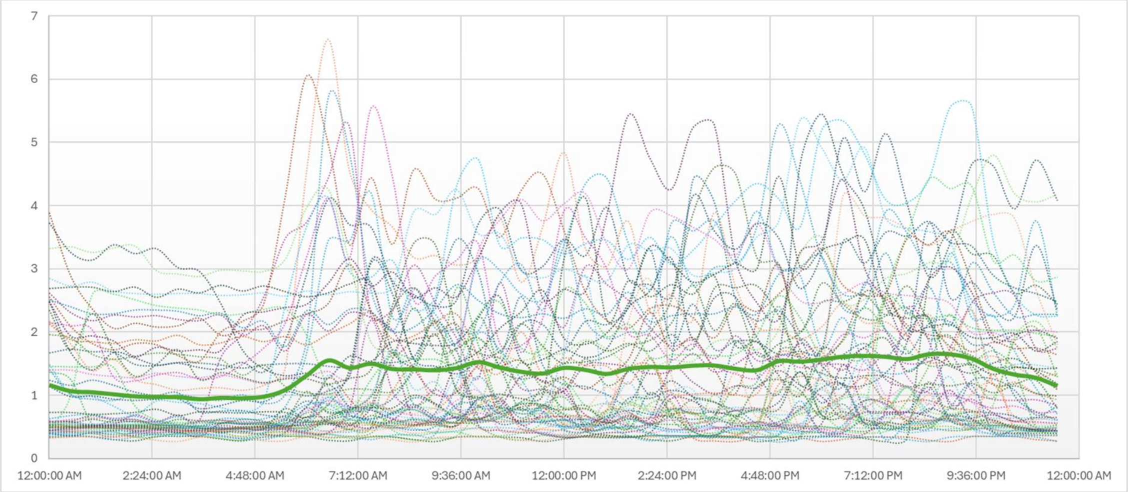


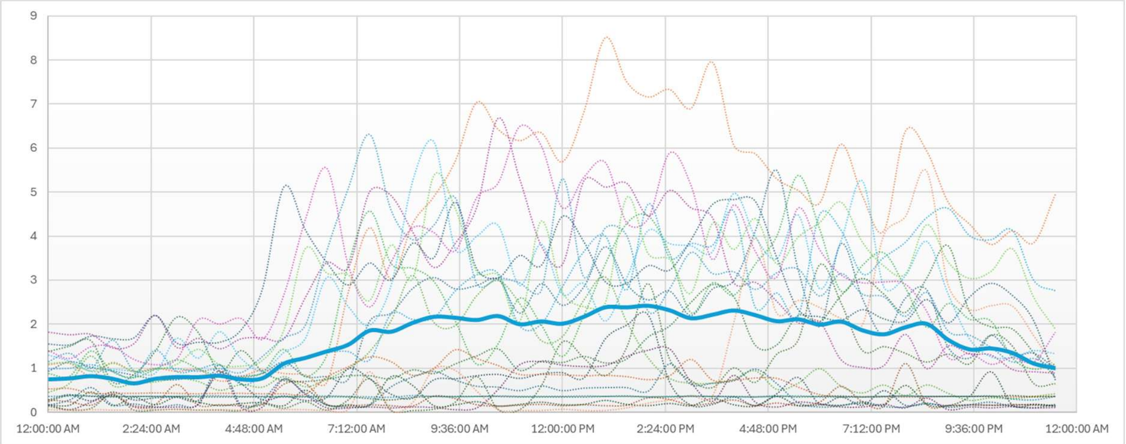




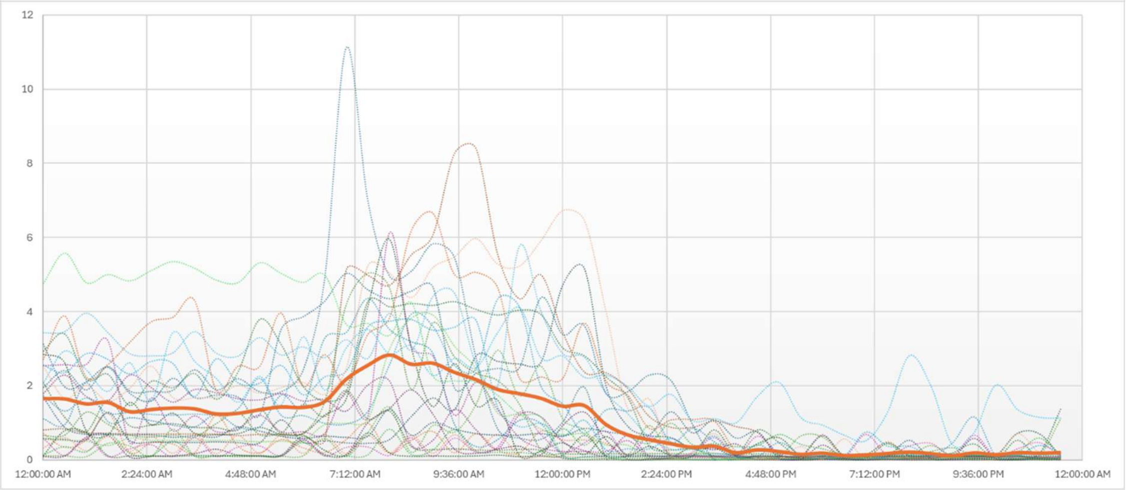
Multi-Day Event Middle Daily Demands







Multi-Day Event End Daily Demands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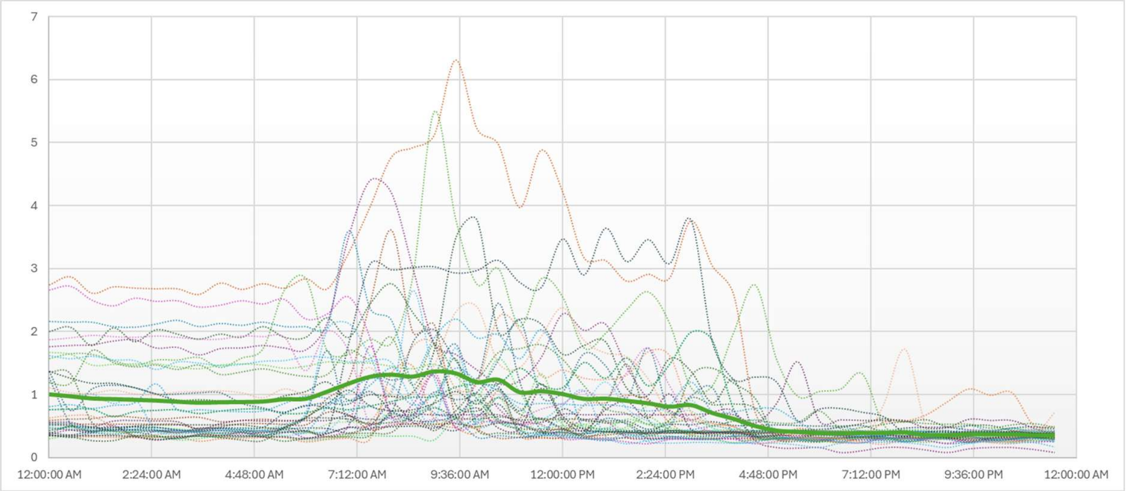
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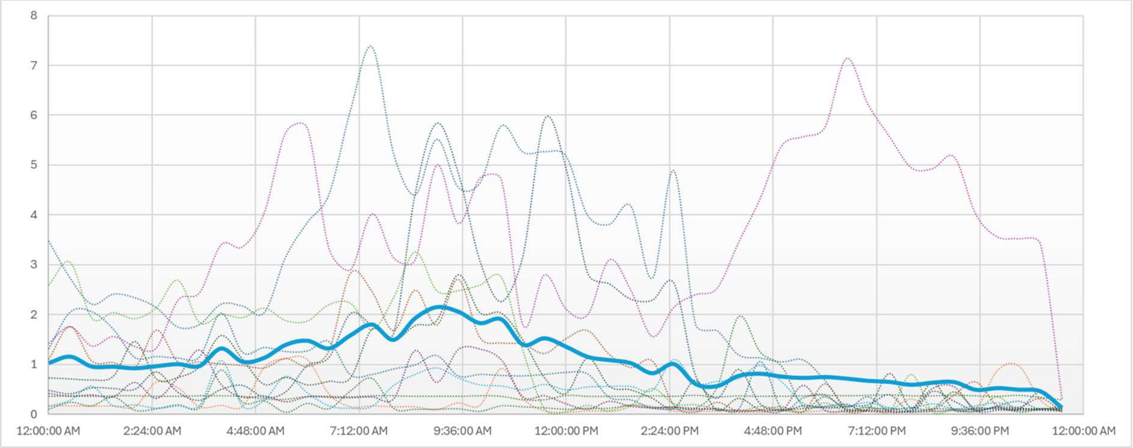
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Appendix 2: Specification Sheets for Solar Panels and Batteries

A full specification sheet was obtained from Micromall for the LONGi Hi-MO X6 LR5-54HTB Mono 440W Solar Panel (Micromall, n.d.-b), and is provided for reference below.

Hi-MO 6

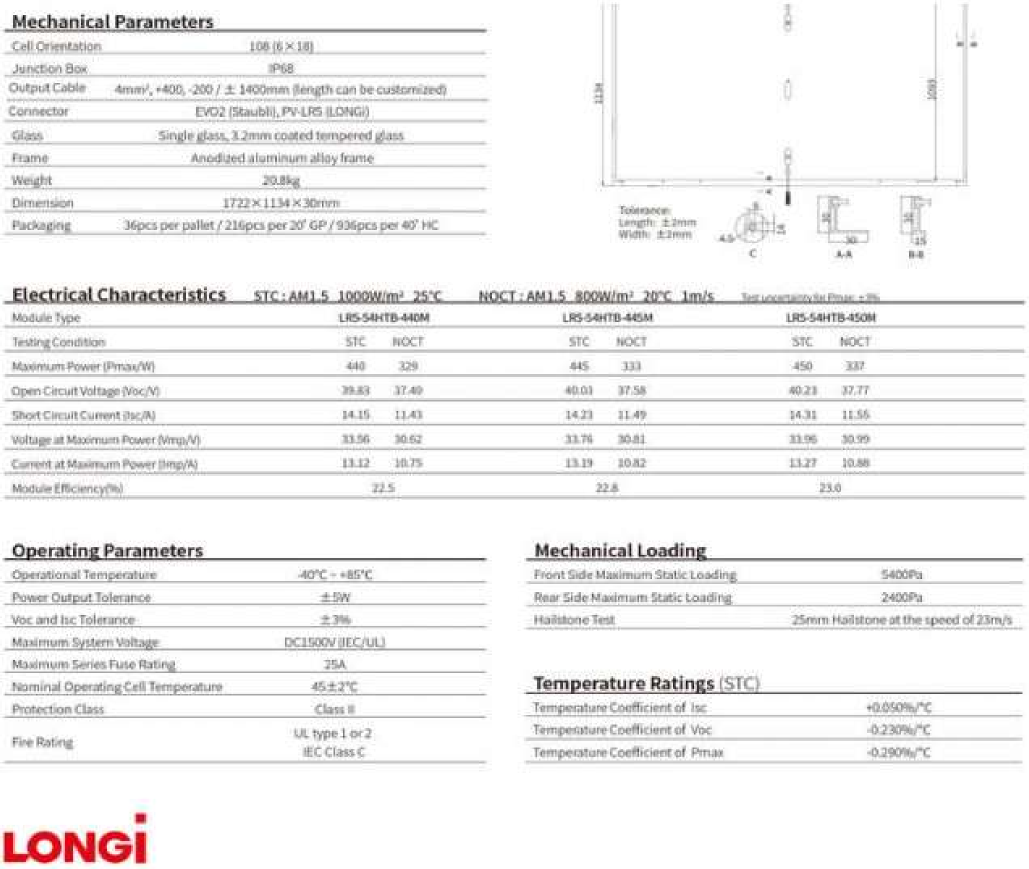
LR5-54HTB 440~450M

23.0%	±5W	<1.5%	0.40%
MAX MODULE EFFICIENCY	POWER TOLERANCE	FIRST YEAR POWER DEGRADATION	YEAR 2-25 POWER DEGRADATION

Additional Value

Mechanical Parameters

Cell Orientation	108 (6×18)
Junction Box	IP68
Output Cable	4mm², +400, -200 / ± 1400mm (length can be customized)
Connector	EVO2 (Staubli), PV-LR5 (LONGi)
Glass	Single glass, 3.2mm coated tempered glass
Frame	Anodized aluminum alloy frame
Weight	20.8kg
Dimension	1722×1134×30mm
Packaging	36pcs per pallet / 216pcs per 20' GP / 936pcs per 40' HC



Tolerance:
Length: ±2mm
Width: ±2mm

Mechanical Parameters

Cell Orientation	108 (6×18)
Junction Box	IP68
Output Cable	4mm², +400, -200 / ± 1400mm (length can be customized)
Connector	EVO2 (Staubli), PV-LR5 (LONGi)
Glass	Single glass, 3.2mm coated tempered glass
Frame	Anodized aluminum alloy frame
Weight	20.8kg
Dimension	1722×1134×30mm
Packaging	36pcs per pallet / 216pcs per 20' GP / 936pcs per 40' HC

Electrical Characteristics

STC : AM1.5 1000W/m² 25°C   NOCT : AM1.5 800W/m² 20°C 1m/s   Test uncertainty for Pmax: ±3%

Module Type	LR5-54HTB-440M		LR5-54HTB-445M		LR5-54HTB-450M	
Testing Condition	STC	NOCT	STC	NOCT	STC	NOCT
Maximum Power (Pmax/W)	440	329	445	333	450	337
Open Circuit Voltage (Voc/V)	39.83	37.40	40.03	37.58	40.23	37.77
Short Circuit Current (Isc/A)	14.15	11.43	14.23	11.49	14.31	11.55
Voltage at Maximum Power (Vmp/V)	33.56	30.62	33.76	30.81	33.96	30.99
Current at Maximum Power (Imp/A)	13.12	10.75	13.19	10.82	13.27	10.88
Module Efficiency(%)	22.5		22.8		23.0	

Operating Parameters

Operational Temperature	-40°C ~ +85°C
Power Output Tolerance	±5W
Voc and Isc Tolerance	±3%
Maximum System Voltage	DC1500V (IEC/UL)
Maximum Series Fuse Rating	25A
Nominal Operating Cell Temperature	45±2°C
Protection Class	Class II
Fire Rating	UL type 1 or 2 IEC Class C

Mechanical Loading

Front Side Maximum Static Loading	5400Pa
Rear Side Maximum Static Loading	2400Pa
Hailstone Test	25mm Hailstone at the speed of 23m/s

Temperature Ratings (STC)

Temperature Coefficient of Isc	+0.050%/°C
Temperature Coefficient of Voc	-0.230%/°C
Temperature Coefficient of Pmax	-0.290%/°C

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The specifications of the battery were similarly obtained from Micromall (Micromall, n.d.-a), and are listed below.

Battery Specifications:

Voltage: 12V

C10: 100Ah

C100: 130Ah

Dimensions (LxWxH): 400mm x 110mm x 286mm

Charge Voltage: 14.4V

Standby Voltage: 13.2V

Weight: 34.00kg

Includes one battery and a premium tester.

IP Rating of Enclosure: IP21