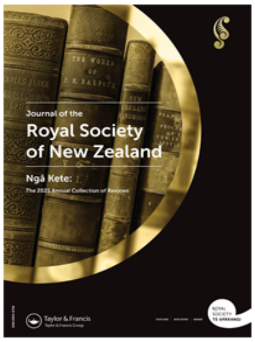

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The role of smart community microgrids in Aotearoa's energy future

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ABSTRACT

There is a pressing need to expand electricity production in Aotearoa New Zealand to meet sustainability goals and lower energy costs. This new generation needs to be based on renewable sources, chiefly wind and solar, for both sustainability and economic reasons. While there remains a role for the legacy grid, microgrids provide a means of co-locating generation with load, minimising transmission line investment and energy losses. This paper explores the advantages of smart community microgrids in this context, but also examines the challenges in terms of the existing legacy grid approach. Three case studies are given as examples, covering an isolated community with no grid connection, a more conventional residential community of 30 households, and a community with local commercial/industrial loads in addition to housing. These case studies show the benefits in terms of local consumption of locally generated electricity coupled with sharing or local trading within the community. Microgrids can support New Zealand's transition to a more electrified, equitable, economical and low-emissions energy system, but their development does require not just exploitation of new technologies, but also adjustment to the legacy grid model and a fresh approach to electricity infrastructure planning and management.

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Introduction

Electricity demand in Aotearoa New Zealand ('Aotearoa') is expected to almost double over the next 25 years, and all of that growth will need to be based on renewable sources in order to meet sustainability goals (MFE 2023; Transpower 2023). These new renewables, solar and wind in particular, lend themselves to distributed installation, breaking away from the legacy electricity grid concept of central generation and outward energy flow to points of consumption (Mehigan et al. 2018). Distributed generation

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enables local grouping of generation, storage and loads, both domestic and commercial, in what are described as microgrids (Marnay et al. 2015; Pelez-DeLaMora et al. 2021), which are in turn connected to the backbone grid itself, the high voltage distribution network, or National Grid. Such microgrids are often appropriately considered as having a community focus, and potentially can assist in alleviating energy poverty and hardship (Berka et al. 2020; Jones and Leibowicz 2021; Valencia et al. 2021; Trivedi et al. 2022; Barrett and Watt 2023).

This localised form of growth of generation capacity significantly moderates the need for the capacity of the backbone grid itself to be expanded in order to meet the expected demand increase, in terms of both generation and transmission/distribution (El-Khattam and Salama 2004; Jenkins et al. 2010), and consequently can minimise increased energy losses in the distribution network (Pesaran et al. 2017). Further issues with the Aotearoa legacy backbone arise from the distances between major generation sources and major loads, and the potential geophysical vulnerability of the landscapes through which large sections of the backbone grid run (Civil Defence 2023). Potentially, for these reasons, microgrids can contribute to a more economical and efficient overall grid, and enhance resilience and security of supply. Appropriately designed, in adverse events (weather, geophysical, etc.), they can be disconnected from the failing backbone grid, to become islanded and autonomous, continuing to provide electricity, albeit with possibly reduced capacity, to their communities (Marnay et al. 2015; Gundlach 2018; Bird et al. 2019).

However, the integration of distributed renewable sources, and the development of microgrids, does require significant re-thinking of the overall regulation, management, financing and control of the electricity system and backbone grid, in terms of electrical stability and security, in terms of matching supply and demand, and in terms of ownership, business models, responsibility and funding/costing (Vanadzina et al. 2019; da Costa and Bonatto 2023; Eklund et al. 2023). This paper reviews important facets of distributed community microgrids, their implementation, and the benefits from and challenges to their adoption, with a particular focus on the current and future environment of Aotearoa, including governance, legal, economic, financial and *mātauranga* Māori issues, in addition to the potential energy and environmental contributions of such microgrids. Specific representative example communities are included as case studies, highlighting these aspects.

Smart grid evolution: distributed renewable energy and microgrids

The owner/operator of the Aotearoa Electricity grid, Transpower, in a 2016 report (Transpower 2016), identified urbanisation, growth in population, electrification of transport, heat and industrial processes, coupled with evolving carbon emission mitigation including carbon pricing, as leading to significant expected increases in electricity demand over the period leading to 2050. They also identified that much of this increased demand, which would need to be provided by renewable resources, was likely to be supplied by wind and solar generation, which lend themselves to distributed location, but are also non-dispatchable (Apperley 2017; Electricity Authority 2023), in that their ability to produce electricity is dependent on local wind or sun, so that they cannot always be simply powered up on demand. This implies both a requirement for energy storage, and new smart means of controlling and managing energy consumption profiles to match consumption with generation. In a later report (Transpower 2023), it was estimated this likely growth in demand by 2050 would be around 68% from current (2023) levels, but that the required growth in generation capacity to meet this would be around 137%, because of the non-dispatchable nature of the majority of the new generation (Electricity Authority 2023). Clearly, by any account, the country is looking at very significant growth in required electricity generation over the next 25 years.

The legacy-grid centralised-radial topology model for electricity supply and distribution, which has dominated world-wide for the past 100 years, requires that power generation and demand are balanced in real time (Transpower 2016). This requirement has resulted in the majority of the complexities, the risks, and the costs, of present-day power systems. Achieving this real-time balance, in the context of significant time-of-day and seasonal variation in demand, has typically involved ensuring adequate reserves of energy resources are held – fossil fuels in the case of oil, gas and coal systems, and water in the case of hydro systems. Overall, the design, construction, and operation of these legacy systems essentially involves top-down planning of power generation, driven by economic considerations, load anticipation, resource availability and the need for grid-wide security of supply. Significant expansion of the legacy grid involves major and costly increases in all of its three defining aspects, generation capacity, backbone grid capacity, and local network distribution capacity, rendering this model effectively no longer fit for purpose (Aguero et al. 2017).

However, driven by both environmental and economic concerns, and enabled by rapidly advancing technology, we are seeing the confluence and evolution of lower-cost renewables and the smart grid (Babayomi et al. 2023), with the latter characterised by bidirectional power flow, distributed generation and storage, and integrated sensing, measurement, and communication. The smart grid model is best described from two perspectives (Apperley 2017). First, the new renewable generation sources lend themselves to a significant degree of distribution, which challenges the hierarchical radial transmission model of the legacy grid. Second, evolving distributed smart sensing and control technology, coupled with local generation and storage, enables smart load control, load matching, and energy flow management, at the local level. Concerns with long-distance hierarchical/radial energy transfer and real-time load following from centralised generating systems, are growing less and less salient and dominant as smart microgrids, with their highly distributed generation, storage, and load management, become more prevalent (Tomin et al. 2022).

Consequently, in terms of the anticipated significant increase in demand for electricity, microgrids have the potential to lead to a substantially fresh approach to energy infrastructure planning and management, involving a bottom-up technique based on localised energy balance, i.e. maximising the balance between local generation and local load, and minimising the dependence and impact on the remote resources of the grid. The dominant effect of such an installation on the legacy grid is not so much one of increased non-dispatchable generation capacity, but one of reduced load (Apperley et al. 2015). Coupled with this approach are a new set of imperatives for consumers, in terms of modified behaviour, and changed demands, time-shifted loads, and altered incentives and expectations, as they become more aware of the need for behavioural change and the local impact of their actions.

However, the adoption of the microgrid model represents a significant transition from the existing legacy grid, from technical, operational, and ownership/business perspectives, requiring a nationally developed plan and investment strategy for successful implementation.

Microgrids can follow a wide variety of designs, as can be seen in the examples of the next section. They may for instance be entirely residentially based, covering a group of houses forming a community, which could be public housing, *papakāinga* housing, a chosen community, or any other co-located community of interest (McCabe et al. 2018). Alternatively, they may simply cover an industrial or commercial site, or they can comprise both housing and industrial/commercial loads. From a microgrid perspective, other consumers such as schools, retail stores, EV charging stations, street lighting, and other community facilities such as *marae*, halls, swimming pools, or even water treatment plants, potentially contribute a wider variety of load patterns within the microgrid. Enhancing its ability to effectively manage energy flow and generation/load balance.

A further aspect of microgrids is the potential for them to be arranged in fractal structures (Apperley 2019; Mindra 2023), essentially hierarchically. For example, an individual house may form its own microgrid, but then multiple household level grids could be connected together (at a higher level) as a community grid. That community might then be connected (say) with an industrial site, together forming a local area microgrid. Load, generation, and control can then be shared across all levels of such a fractal microgrid, and it would present a single connection point to the backbone electricity grid.

Overall, the key advantages that can be associated with microgrid development include:

(a) The capacity for an increase in delivered energy without the need for costly backbone grid expansion, both in terms of centralised generation and line capacity;
(b) More effective integration of new renewables (wind and solar) into the electricity system;
(c) Reduction in backbone grid transmission line losses normally associated with increased energy delivery (Hung et al. 2014; Pesaran et al. 2017; Oliva et al. 2022) through local consumption of locally generated electricity;
(d) Increased overall resilience, since at times of backbone grid failure, local supply can potentially be maintained;
(e) The potential for greater community engagement in the ownership, management and utilisation of these energy resources, contributing to a healthy environment, both for the individual and the planet (Fraker 2013).

Microgrid examples

To demonstrate how smart microgrids can be configured and operated, three Aotearoa based examples are described here. The first of these is an islanded community microgrid (that is a microgrid not connected to the backbone electricity grid). This has been included as a base design without any dependency or impact on the electricity grid itself. This is followed by a more conventional community microgrid, still based solely on residential housing, and a third example is a community-based industrial site which incorporates houses, urban commerce, and a factory.

An islanded community microgrid

This example is based on a design developed for a Māori community in Aotearoa, at Motairehe on Aotea/Great Barrier Island (Apperley and Toki 2023). There is no existing electricity grid on the island. The design was developed to cover 10 households plus a small *marae*, but in such a way that it could be expanded (fractally) to cover the entire local community (approximately 40 households) in the future.

Annual load profiles were established for 10 individual households. As there is currently no grid supply to the community, it was necessary to create these profiles to represent anticipated post-microgrid electricity use by adapting those from 10 real households with similar occupancy and appliance utilisation characteristics, located at a similar latitude on the mainland. The target houses do not currently have electric hot-water systems, do not use electricity as their primary form of heating, and have a range of occupant numbers, both adults and children. The resulting base load profiles created for these houses varied considerably, in terms of average daily use, hourly use over the day, and seasonal variation, and included basic demands such as lighting, heating and cooking. The data used were hourly data over a whole year – 8760 data points for each of the 10 houses.

A load profile for the *marae* was also established using similar techniques, based on its occupancy level. One of the household profiles with two adults was used as the starting point, but the data were doubled to represent four adults (estimated long-term *marae* occupancy). To this base-load profile was then added a randomly generated load of 14 *hui* (extended meetings) over the year, with their start dates randomly generated, and with randomly allocated durations of one to three days, leading to a total of 27 days of *hui* over the year. This was based on discussions with the community regarding typical *hui* frequency, size and duration. An estimated supplementary load profile was created for these *hui*, which included additional cooking, lighting, refrigeration and heating during the event, plus overnight accommodation for the participants.

An initial analysis (Phase 1) was carried out with each house and the *marae* operating independently (no microgrid), but with identical installations of solar panels and batteries, based on the average load profile, and a rule-of-thumb starting point for stand-alone solar installations in Aotearoa:

- solar panel capacity ~ average daily load/4
- battery capacity ~ average daily base load × 3

For this Phase 1 analysis, each site (each of the 10 houses and the *marae*) was assumed to be provided with (i) solar panels of 4 kW capacity, allowing for an estimated average daily full load of 16 kWh, plus (ii) a battery of 22.5 kWh capacity, corresponding to an average daily base load of 7.5 kWh. This sizing was based on the averages across all 11 sites. Annual solar data for Aotea was used to calculate the solar panel output for each hour of the year (Suppers and Apperley 2015). A discretionary or divertible load was also added in for this Phase 1 analysis, representing potential future growth in electricity consumption. This might, for example, represent hot-water heating or EV charging, i.e. electricity usage carried out when there is a surplus, over and above the base load. This discretionary load was set to a daily maximum (per site) of 5 kWh, and was invoked only when the site battery was at 95% charge level or more, and there was surplus solar generation. This produced an overall total average discretionary load across the community of 30.4 kWh per day, and there were just nine days over a year in which no discretionary load was possible at all.

Under simulation testing of this Phase 1 autonomous mode of operation and with this configuration, for four of the households there were no base load supply failures (shortfalls) at all over the entire year. For the other six households, there were times when their systems were unable to meet the basic household needs, with one house showing the most extreme case of 317 h (3.6% of the 8760 h of the year) of inadequate base load supply. The *marae*, because of its very high peak demands during *hui*, showed 2184 h (25%) in which the system was unable to meet its demands, and averaged over the whole year, the shortfall amounted to nearly 9 kWh per day. Of these shortfall hours, 574 (26%) occurred during *hui*. Of course the shortfall occurrences for the individual houses do not all occur together, although after a day of low sunshine, it is more likely that such events may coincide. All of the shortfall hours for the 10 households, 673 in total, were spread across 355 h of the year.

By contrast, all sites, including the *marae*, showed a significant number of hours in which there was an unused surplus of solar energy. The total wasted energy across all 11 sites for the whole year (energy being produced that could not be used because of inadequate load or battery capacity) was 18.8 MWh, spread over, on average, 1550 h per site, per year (18%), and representing 26% of the total solar generation. It should be noted that the sizing of panels and batteries used in this analysis is based on rule-of-thumb guidelines, and that optimisation of sizing in relation to cost, and to the incidence and circumstances of inadequate supply or unused surplus energy can be further explored.

Clearly with demands and surpluses varying between households, and the occasional peak demand from the *marae* during *hui*, community sharing has the potential to achieve a greater degree of local balance between generation, storage and demand, with interconnection leading to more effective utilisation of the distributed energy sources (Mair et al. 2021). The microgrid design as represented in Figure 1 provides one sharing solution, and is now considered. In this Phase 2 configuration, each node primarily manages its own load, generation and storage, but when it has a surplus, it presents it to the microgrid as additional generation, and when it has a shortfall, presents it to the microgrid as an additional load. Discretionary loads can be prioritised, for example if the microgrid overall has a shortfall, then a node may disable a low-priority load. Also shown in the *marae* set-up is the notion of community services – in this case, street lighting and EV charging. In fact, such services could be simply connected to the microgrid itself (rather than be part of the *marae* node), as could, for example, additional community solar panels. The community may choose to prioritise some services, such as street lighting over others such as EV charging.

For the Phase 2 microgrid analysis, initially the discretionary loads were ignored, but the same total solar generation and the same total battery storage were modelled as for the earlier Phase 1 non-networked analysis. It was assumed that all houses had the same sized system of solar panels and batteries, but the *marae* could have a different configuration. The design process attempted to achieve a distribution which minimised the overall energy transfer between the *marae* and the houses, in either direction. It was

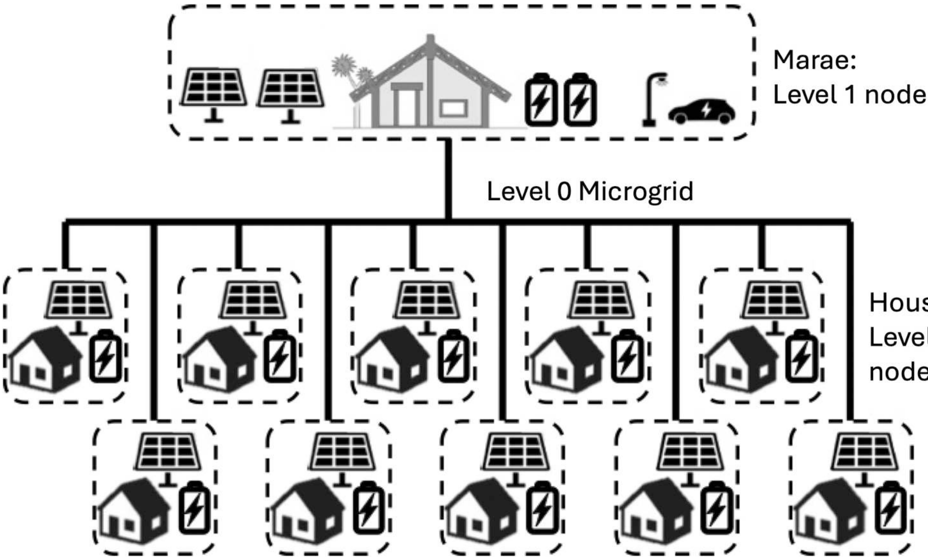

Figure 1. The proposed Motairehe microgrid comprising 10 houses and the *marae*.

anticipated that the Phase 2 microgrid would achieve an overall better utilisation of the generated electricity than the Phase 1 non-networked approach, reducing over the entire site both the wasted excess production and shortfalls in supply.

The initial stage of the Phase 2 analysis consisted of considering the total generation capacity, the total load and the total storage, across the whole community and *marae*, and carrying out an hourly energy balance analysis for the whole year (Apperley 2017). However, a second stage of the Phase 2 analysis considered also the distribution of generation and storage between the houses and the *marae*, to explore and minimise the overall grid flow, since a higher grid flow would require a more substantial interconnecting cable, and/or imply greater energy transmission losses. Because there is no existing grid, the power cables connecting the houses and the *marae* as an electricity network are a part of the capital cost of the microgrid implementation, as would be any new household wiring, and potentially plumbing for electric hot-water cylinders, for example.

The results for this initial Phase 2 analysis are shown in the energy balance plot of Figure 2. In this plot, points below the diagonal represent hours when load (demand) is not fully met (i.e. there is a shortfall, with delivery (vertical position of the point) exceeded by demand (horizontal position of the point)). The impact of *hui*, which overall present a significant load, can be readily seen, as the hours which correspond to *hui* at the *marae* are highlighted in this plot as orange dots. What is remarkable is that by considering the total generation, the total load and the total battery capacity, in this Phase 2 microgrid analysis, allowing for sharing of load among houses and with the *marae*, the overall number of shortfall hours over the year for the whole community is reduced by 97% to 64 (< 1% of the total year), markedly less than the 2184 h of shortfall experienced by the *marae*, and the 355 h of shortfall experienced by all of the houses together with the Phase 1 non-networked analysis. Of particular note is that only 16 of the shortfall hours actually coincide with *hui*.

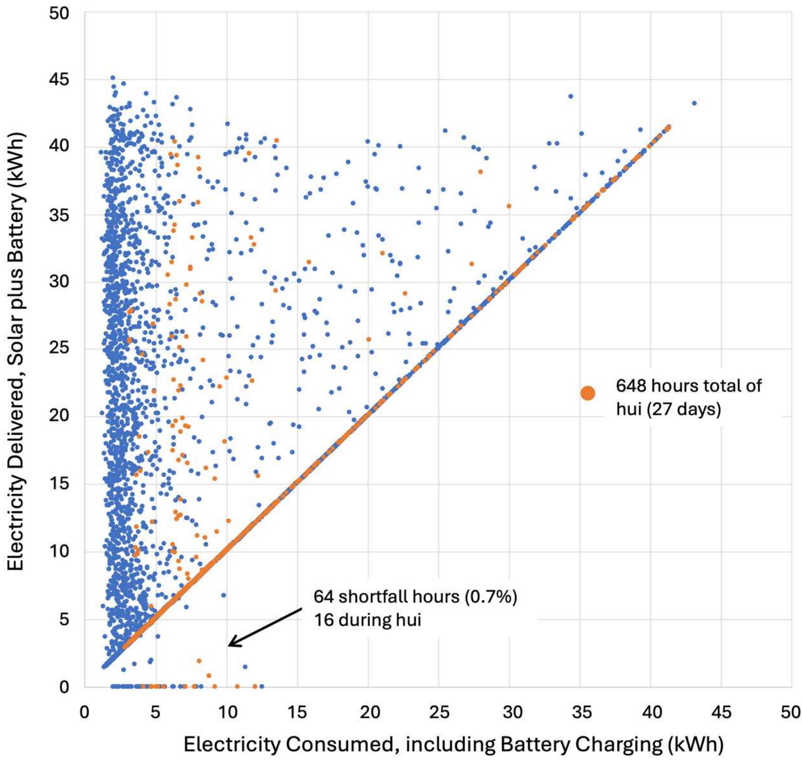

Figure 2. The overall hourly energy balance over a full year for the Phase 2 microgrid model. (Orange dots represent hours when *hui* are taking place, other hours are blue dots.)

The plot of Figure 2 represents just the base load, and any discretionary load would need to be taken during the hours of surplus, represented by those points above the diagonal. There are 3309 h in this surplus category for the network (38%), representing a total of 33.2 MWh over the year, but within the microgrid it is anticipated much of this energy would be used for discretionary loads, which have not been included in this analysis. It should also be noted that each node (household or *marae*) requires 'smart' control to prioritise demand in the following sequence:

(i) Local (for the node) base load;
(ii) Local battery charging;
(iii) Microgrid (full community, including *marae*) needs;
(iv) Local discretionary load.

To determine (iii) and (iv) does require more sophisticated software at each site, and communication between sites, than is conventionally seen in isolated off-grid solar systems, which do not usually concern themselves with (iii).

It is clear from this analysis of the community microgrid model (Phase 2), that overall a much better utilisation of the generated electricity has been achieved, reducing across the entire site both the excess production and the shortfall in supply. This has utilised the same overall total number of solar panels, and the same overall total battery storage, as with the initial Phase 1 non-microgrid configuration.

Residential community microgrid

A second example is based on a residential group of 30 houses with a single connection to the electricity grid. Actual annual hourly electricity consumption profiles for 30 separate houses have been utilised here. Clearly the design aim is to ensure that as much as possible, the locally produced electricity (roof-top solar panels on each of the houses) is locally consumed, and at the same time, the electricity taken from the grid is reduced, although not necessarily to zero, as was the case for the islanded system of the previous example. A design trade-off here is that the cost of providing appropriate battery storage needs to be weighed up against the cost of drawing electricity from the grid (Apperley et al. 2015; Donkoh et al. 2020), which includes the potential cost of backbone grid expansion.

From the 30 household full-year hourly load profiles used in this model (8760 data points per house), across the community the average total daily consumption is 546 kWh, or 18.2 kWh on average per house per day, and the average total community *hourly* consumption is 22.7 kWh, or 0.76 kWh on average per house per hour, across the whole year. The profiles used here reflect typical household loads, as shown in Figure 3, with morning and evening peaks, and low consumption during the early morning hours.

The microgrid simulation for this community is based on a 2.5 kW solar array and 12 kWh of battery storage for each of the 30 houses. These values are less than those used in the previous example, because this community is connected to the grid, and can take

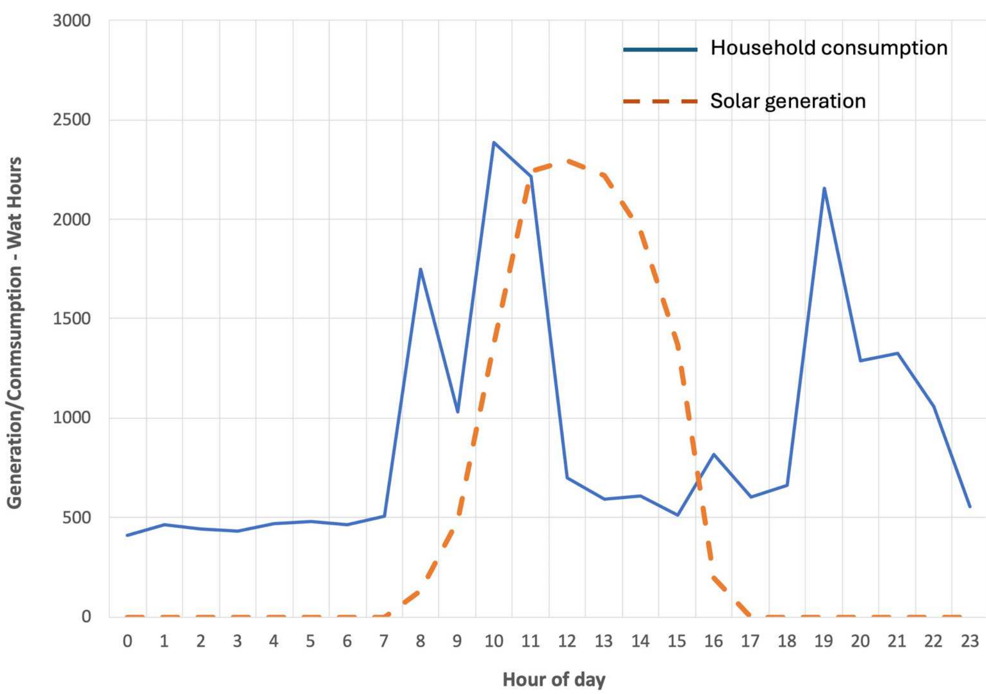

Figure 3. An example hourly load profile for one of the houses in the group, reflecting a typical household consumption pattern. Also shown, for comparison, is a typical generation profile for a 2.5 kW solar array, on a cloudless day.

advantage of its legacy infrastructure for peak events. Aspects of this simulation are shown in Figure 4, where it can be noted:

(i) There are many hours (4599, more than 50%) where local demand is fully met by local generation. These are the points on the diagonal of the energy balance plot.
(ii) All of the locally generated electricity is locally consumed, since there are no points above the diagonal which would represent a surplus.

The simulation also shows that with this configuration of solar panels and batteries, the average daily grid consumption is more than halved, down 59% from 546 to 224 kWh. The peak daily grid consumption is also reduced, by 33%, from 953 to 638 kWh, as is the annual hourly peak consumption, down 21% from 92 to 73 kWh, relieving pressure on the backbone grid. It can also be noted that if the solar panel array size is increased, then this does further reduce the average daily grid consumption.

A comparison of the load profiles for the community without the microgrid and with the microgrid, for a one-week period, is shown in Figure 5. From this it can be seen that the solar generation tends to take over the supply at sunrise, with the grid demand reduced to zero for much of the day, and with any surplus being stored in the batteries, this enables supply to continue on until midnight on a typical day.

This example has shown the benefits of a microgrid over individual household solar systems, in that there is effectively trading between houses which ensures that as much

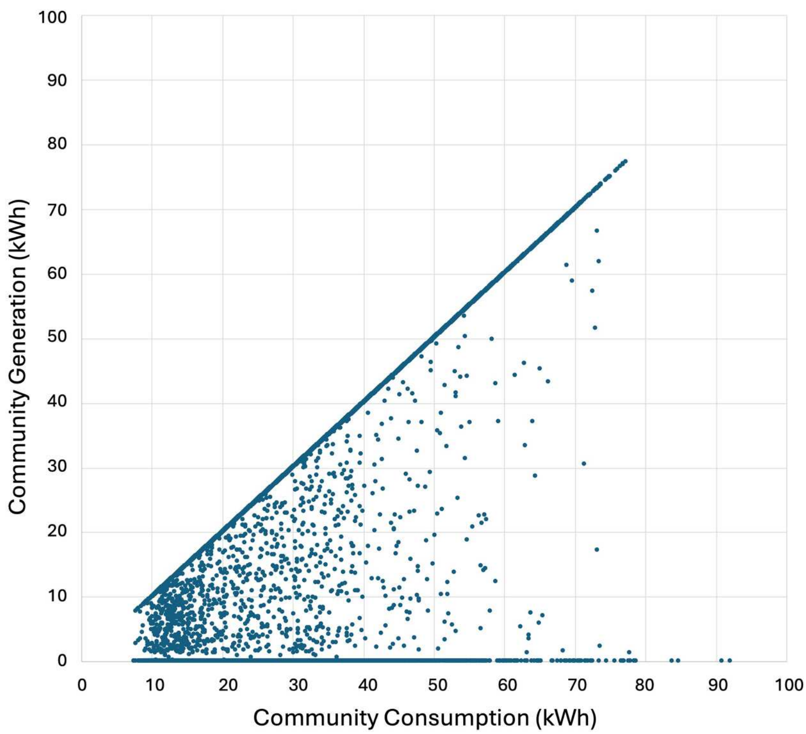

Figure 4. Hourly energy balance for the simulated community over a whole year. Points on the diagonal represent balance of local generation and load; points below the diagonal are hours in which local generation does not meet demand.

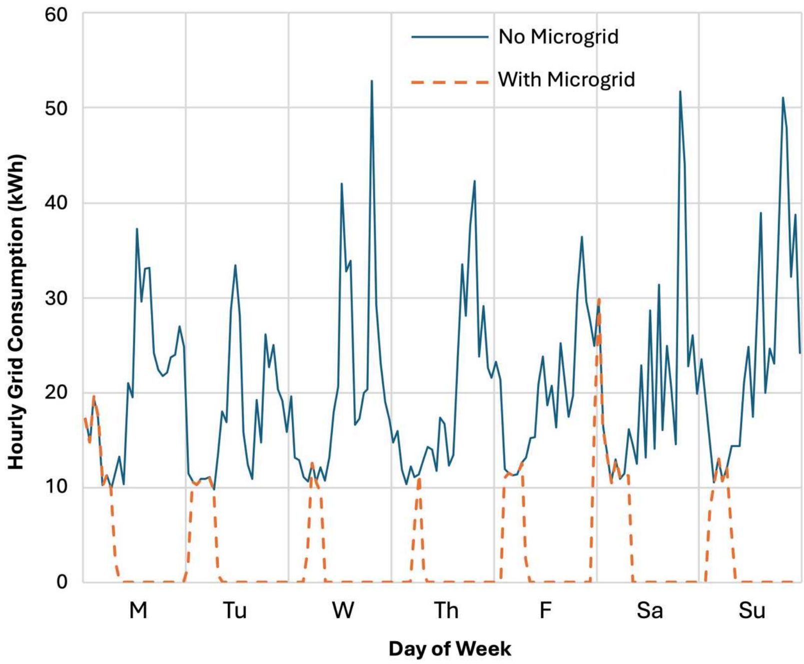

Figure 5. Hourly grid consumption for a one week period, showing the overall community consumption, and the substantially reduced grid consumption with the microgrid described.

as possible, all of the locally produced electricity is consumed locally, because of the varying demands between houses. While the analysis is based on existing household load profiles, it is suggested that increased household consumption, for example through reduction of gas heating, and/or adoption of electric vehicles, could be accommodated through microgrid implementation, avoiding the need for backbone grid expansion. Also, with a community system such as this, there is no reason why community services, such as street lighting, schools and other public resources, should not be included in the microgrid. In fact, adding in such non-residential usage will produce greater diversity in the loads, potentially providing greater opportunity for balancing load and generation.

If should also be noted that this microgrid has effectively added 322 kWh per day, on average over the year, to the overall grid generation, or in other words, relieved the grid of this load. However, although the overall grid electricity consumption is reduced by 59%, and the annual peak daily consumption by 33%, the annual peak hourly consumption is reduced by only 21%. It is this short-term peak which the grid connection must be sized for, and since the reduction is less than the other metrics, this implies that operational costs for the grid will need to be apportioned over a smaller volume of electricity, possibly resulting in an increased charge per kWh or per grid connection.

Factory-centred energy community

This example explores a factory-centred energy community comprising a grid connected microgrid working cooperatively to balance local renewable solar generation with factory, residential, commercial and EV transport electricity demands. The scenario incorporates a meat processing factory and a town of similar energy consumption, as shown in Figure 6. The factory processes over two million animals per year, and includes separate lamb and beef slaughter and boning facilities, a casings plant, a rendering plant and a fellmongery. The wide range of processes and products produced leads to dynamic utility usage, and heat storage potential. In this example, the adjacent town is assumed to comprise about 6000 houses, include 3000 electric vehicles and a range of public and commercial buildings. The main electrifiable transport needs of the community include private commuter vehicles, light commercial vehicles and some trucks.

The model is based on an existing meat processing factory located in Aotearoa that is working to transition from coal and LPG boilers to renewable electricity for process heat supply. The annual energy demand for the factory, after switching fully to renewable electricity, has been estimated to be 20% lower at 71.1 GWh because of improved efficiency, made up of 9.7 GWh for powering pumps, conveyor machinery, chillers and freezers, and 61.4 GWh for producing hot water from high temperature heat pumps and steam from electro-boilers.

Hourly electricity and heat flow data for the factory have been collected for a full year, and used to determine the hourly electrical demand profile. The plant runs in a semi-continuous manner with weekend shut-downs, and also closes in the middle of the year for maintenance and repairs, and over the Christmas-New Year break. From an annual perspective, electrical and thermal energy demand are both highly variable, but factory load variability at the daily level appears much less significant, except for weekends.

The residential load for 6000 houses was compiled from 24 available household load profiles. Seasonal effects on demand are evident in these data, with high electricity use in

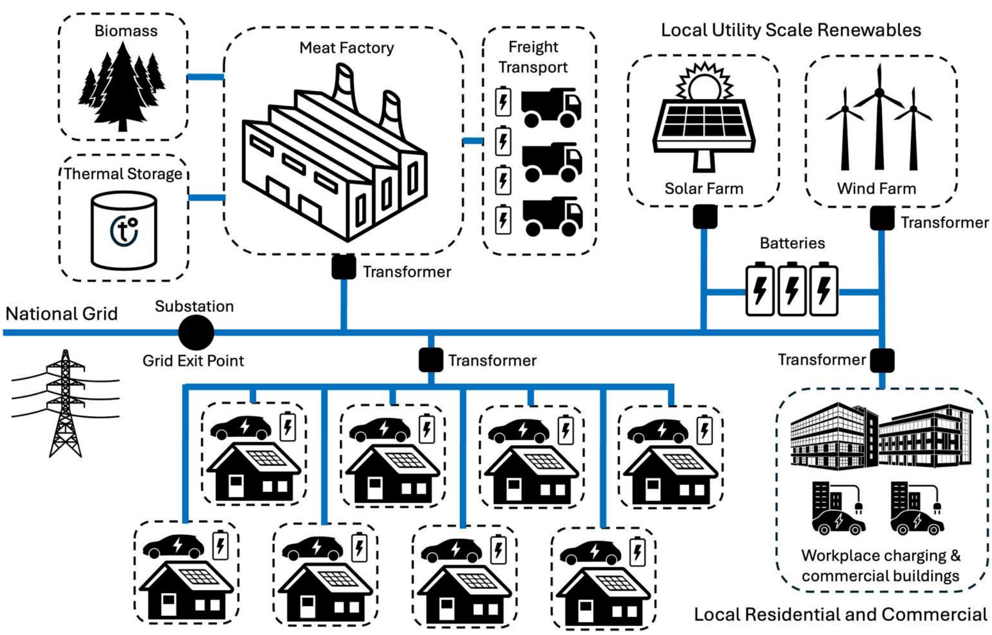

Figure 6. Microgrid based on a factory-centred energy community with local renewable generation and energy storage.

winter compared to summer. At a weekly level there is a clear trend of regular peaks in the morning and evening as was shown in the house of Figure 3, one of the houses also used in this example. The residential load for the 6000 houses totals 41.9 GWh/year, with a winter peak of 12.3 MW.

The commercial load for the town was estimated using open-source data for a similar climate zone (Ong and Clark 2014), and includes a warehouse, industrial services, a fire station, a primary school, a motel, a regional high school, two offices, a medical centre and a wastewater treatment plant large enough to service a town of 10,000 people. This electricity load of 28.8 GWh/year has a daily cycle, peaking near the middle of the day, with lower demands on weekends, and reaches a maximum peak of 7.5 MW in winter.

The transport load is based on a regular pattern of charging during the day and at night for 6000 EVs and 10 electric stock trucks. This contributes a load of 26.1 GWh/year.

The combined electricity load for the entire factory-centred energy community then comes to 168 GWh/year, with a peak demand of 34 MW arising during the winter. As expected, there is a regular day/night pattern to this profile, a week/weekend pattern, and two periods of low demand when the factory is closed in winter and summer. This is evident from the combined load profile shown in Figure 7.

A spreadsheet model for this microgrid was developed, analysing the balance between electricity supply and demand, with and without batteries and thermal energy storage (TES) (Tito et al. 2023). With no energy storage, the zero battery and zero TES case, local renewable electricity is preferentially used to meet electrical loads, followed by

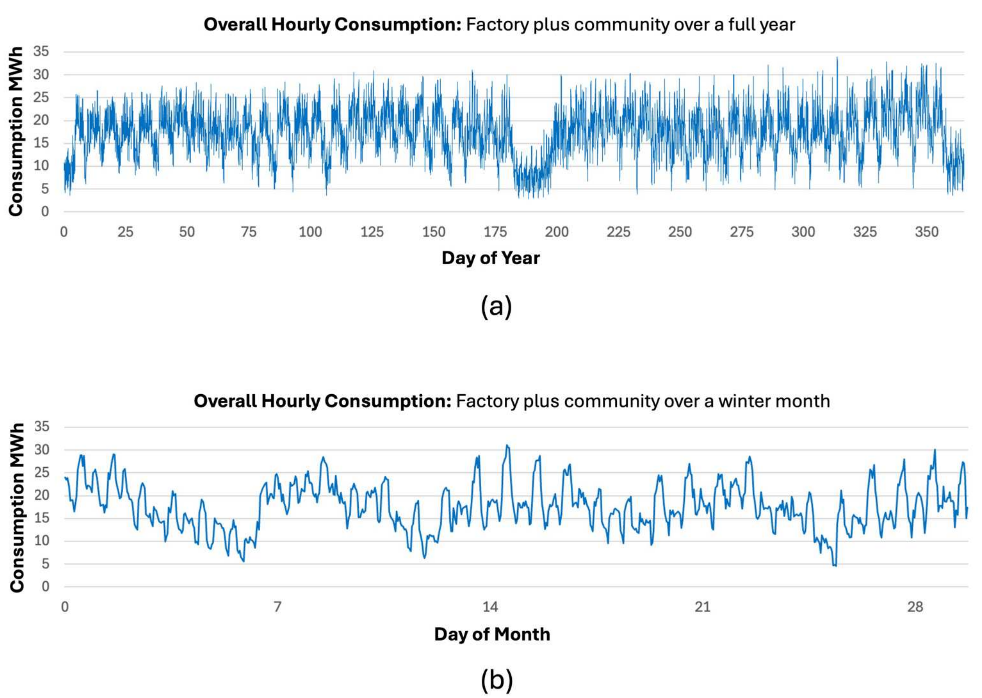

Figure 7. The combined electricity load profile for the factory-centred energy community, **A,** for the full year, and **B** for a winter month.

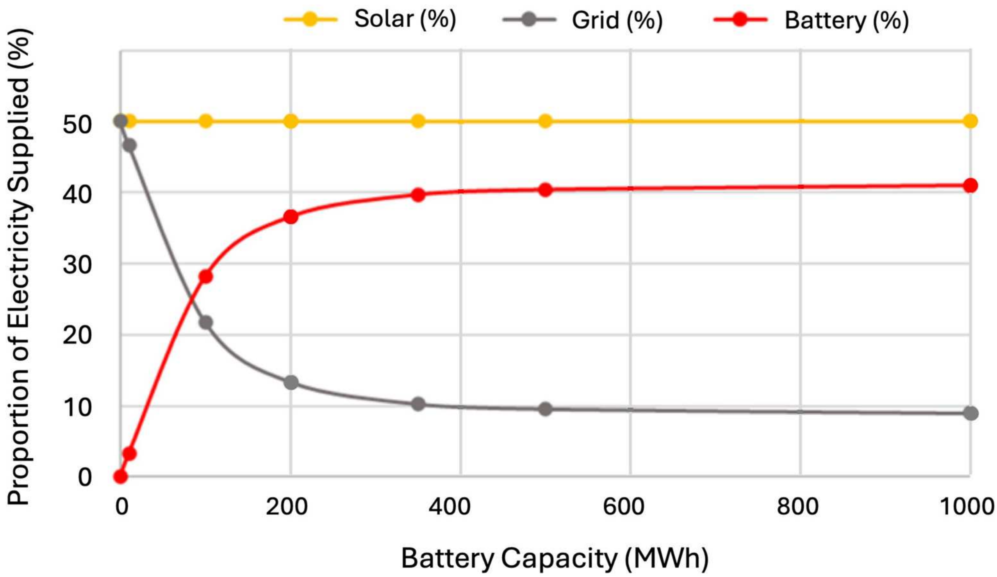

Figure 8. The impact of battery capacity on grid demand for the factory-centred energy community.

thermal electric loads, with any excess local generation exported to the grid. During times when local generation is in deficit, electricity is imported from the grid to meet electrical and thermal electrical demands. For the case with both batteries and TES, similar energy flows arise, except excess local renewable electricity is sent to the battery first, then TES, and only if both batteries and TES are full does the local renewable energy get sent to the grid as electricity export. When local renewable energy is insufficient to meet the thermal electric load, additional heat is transferred from TES, and electricity is imported from the grid for heating only once TES is empty. Various battery and TES capacities have been evaluated, as shown in Figure 8.

With the particular configuration used here, effectively a NetZEB (Net Zero Energy Balance) model (Apperley 2017) with the solar panels sized to produce 168 GWh per year, equal to the factory-centred community's total annual load, it can be seen from Figure 8 that with a battery capacity of ~400 MWh, grid demands are minimised to ~10% of the supply. The combination of a variety of loads, industrial, residential, and commercial, enhances the ability of this microgrid to achieve effective balance between local generation and load.

Benefits of community microgrids

The example microgrids described show a range of real advantages of this technology, which were suggested in the earlier introductory section. The examples cover a range of scales, from a small residential community, to a larger town incorporating industry and commerce. In each case the microgrids provide a means of effectively incorporating distributed, often non-dispatchable, renewable energy sources into the overall electricity network. This effectiveness is highlighted by a number of characteristics which these examples demonstrated, across the wide variation in scale which they represent:

- Local consumption of locally generated electricity reduces the need for costly expansion of the backbone grid capacity in providing this additional energy, and significantly reduces transmission line losses.
- The full exploitation of renewable generation accordingly contributes significant benefits for the environment.
- The diversity of loads within the microgrid provides a means of load balancing and helps manage the non-dispatchable nature of the generation. The islanded microgrid described earlier showed a significant reduction in shortfall hours through intra-community trading.
- For a given load profile, the microgrid examples have shown substantial reduction in overall grid load and also reduction in peak loads.
- Microgrids can contribute to resilience given the extent to which grid load is potentially reduced in the two grid connected examples given earlier. Clearly, in the event of backbone grid failure, these systems could continue to provide electricity to their communities, even for quite long periods, if in the circumstances, loads were reduced and the systems appropriately isolated.
- There is the potential for greater awareness and community engagement and sharing with a microgrid, which can lead to modified patterns of behaviour and usage of the electricity, through a sense of cooperation and collaboration.
- Because of the many advantages of microgrids, particularly those relating to reduced demand on backbone grid capacity, and promotion of the sense of community cooperation and resilience, overall microgrids can deliver less expensive electricity, and contribute to both well-being and sustainability.

Community microgrid challenges

While clearly there are strong arguments for the adoption of community microgrids as a means of expanding the use of renewable electricity and reducing the use of carbon-emitting energy sources in housing, transport and industry, there are also a number of challenges associated with their adoption.

- At the present time, the regulatory and business models associated with the electricity industry tend not to provide motivation, guidance, nor realistic planning pathways to the development of community energy systems (McCabe et al. 2018; Milis et al. 2018; Syed and Morrison 2021). More integrated support from regulatory systems and funding/guidance bodies could significantly reduce the planning burden on individual communities.
- There are a range of technical and economic issues related to microgrid planning, which will inevitably develop and change over time, but which do need to be recognised. These include:
  (i) The legacy grid approach to load balancing and grid stability is often seen as a technical obstacle to grid-edge generation. However, modern technology does make grid management, including microgrids, much simpler, and the overall grid potentially more resilient (Cagnano et al. 2020; Souza and Freitas 2022; Fazal et al. 2023). The potential microgrid management of grid load, grid feed

and grid connect/disconnect, are all shown to be relatively straightforward utilising modern smart-grid techniques in the 20 example microgrids of the survey included in Cagnano et al. (2020).

(ii) A realistic assessment of capital outlay and operational costs will always be challenging, in the sense that these will be constantly evolving, and are potentially influenced by a range of factors in addition to technology developments, including climate concerns, incentives and subsidies and changing business models (Milis et al. 2018). A microgrid to be implemented today ideally should be able to take advantage of any future positive developments in these areas. Steps need to be taken to ensure that the most up-to-date advice is available to communities, and that potential providers of the microgrid systems are also offering the best currently available solutions.

(iii) At any time there will be cost trade-offs which will need to be considered, such as the balance between solar panel size and battery capacity to ensure supply stability (Donkoh et al. 2020; Panamtash and Mahdavi 2020; Kichou et al. 2022). The potential life span of batteries, and their optimum usage patterns, balanced against their cost, is also an issue (Shabani et al. 2023), as is the potential utilisation of other forms of storage, such as thermal, pumped hydro, or hydrogen production, for example (Kear and Chapman 2013; Ali et al. 2023; Tito et al. 2023).

(iv) While the three case studies described cover a wide range of scales, the question of the optimum scale for a microgrid remains, and will be influenced by local factors such as load diversity, GXP capacity, and energy flow optimisation in relation to transmission cable capacity and cost, although the fractal structure concept (Apperley 2019; Apperley and Toki 2023) does potentially provide future flexibility for expansion and integration for any implemented microgrid.

- A community microgrid requires clear planning and processes concerning ownership, management, governance, maintenance and costing and benefit sharing. This is likely to require adjustment to the regulatory framework applying to the electricity system, to accommodate the notion of a community facility, and to encourage the engagement of the communities concerned (Montoya et al. 2013; Wagemans et al. 2019; Berka et al. 2020; Norouzi et al. 2022; Eklund et al. 2023). These adjustments and processes will take time to be realised. An imminent issue for regulators is to determine at what size of generation a community microgrid becomes a commercial entity. Current taxation guidance over whether energy rebates count as income for tax purposes threaten some community-based projects (Aperahama et al. 2025). This issue may become more problematic as the line between community energy solutions and commercial generation activities blurs with increasingly complex community-based solutions.
- The need for decision making to take place at the micro-grid level implies that there must be a community, or delegated authority, to make those decisions. Although rural areas, *marae*, and public housing may have a pre-existing sense of community, in other situations there will likely be need for community formation or building before any micro-grid projects can be attempted.
- Equity considerations need to be explicitly included early in the planning processes to ensure that neither early nor late adopter households/communities end up with disproportionate costs or benefits.

Conclusions – microgrids and our energy future

This paper has clearly established the value and role of renewables-based community microgrids in the energy future of Aotearoa. The concept provides a potential pathway to cost-effectively and equitably expand the country's electricity production to the level required to meet future demands while minimising carbon emissions associated with existing energy generation for heating, transport and industry. However the current business models, regulatory framework, and legacy grid concepts relating to the electricity sector do little to encourage or motivate such moves, and in some respects place obstacles in the implementation path of community microgrids. Further, in order to progress along the desired transition path, long-term planning is needed, not just developing microgrids for tomorrow, but developing ones which can confidently evolve as new opportunities relating to generation, smart control, and electricity storage systems develop further over the coming 25 years.

What will be required to encourage, support and enable the development of such systems, which are clearly in the interests of Aotearoa's people, the country as a whole, and the global energy transition, is a very clear pathway forward. This needs to involve regulatory experts, as well as the electricity sector, and associated business and technical partners who can navigate an inclusive path forward (Broska et al. 2022). While the community challenge remains, if the pathway is clear and open, and equitable, then there are many who will willingly work towards it, particularly if there are good demonstration systems available based in real communities.

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