An Islanded Community Solar Microgrid with Capability of Future Fractal Growth

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***Abstract*— A design for a non-grid-connected (islanded) smart community microgrid is developed and elaborated. This focuses on a real community, and the design is developed in such a way as to take into account current energy demands, and future expansion (given that currently there is no formal electricity supply to the community), but also, since the community is located on an island with a number of neighbouring communities and industries, the design is developed to enable future fractal growth of the micro-grid. To meet these requirements, the development covers needs analysis, the micro-grid configuration, and the initial sizing of the various components. Configuration and sizing are then optimised for the initial microgrid, taking into account the particular community social infrastructure characteristics and dynamics.**

Keywords-community microgrid; fractal microgrid design.

I. INTRODUCTION

This paper describes the development of a design for a smart electricity microgrid in Aotearoa New Zealand, for the community of Motairehe on Aotea/Great Barrier Island, a remote island approximately 100km northeast of Auckland. There is no reticulated power system on Aotea. The entire population of the island (~1000) live off-the-grid, running their own solar/battery power systems, which are supplemented by petrol or diesel powered generators, natural gas and wood fires, and in almost all cases, the solar/battery systems do not provide nearly enough of the households' energy needs, so there is a heavy reliance on the fossil-fuel powered back-up generators.

This absence of existing infrastructure provides an opportunity to improve the lives of the island's population, and contribute to New Zealand's efforts to reduce carbon emissions and expand clean energy use [1]. The community on which this design focuses contains the majority of the indigenous Māori population of Aotea, approximately forty households and 90-100 people. The initial design is for the central part of the community, ten households together with a *marae*, but it is intended that through a phased approach, the microgrid would be extended over time to include the remainder of the households, and then on into neighbouring communities. A *marae* is a place where traditional *Māori* ceremonies and meetings are held. It normally comprises a meeting space, *marae ātea*, a meeting house, *wharenui*, and a kitchen/dining room, *wharekai*. The *marae* can accommodate *hui*, either short, smaller meetings, or larger *iwi* (tribal) events that may run for several days, with accommodation being provided in the *wharenui*.

To accommodate this anticipated expansion, focussing on the use of non-dispatchable and distributed renewable energy generation (solar panels), and to some extent exploiting the absence of any existing legacy grid, the design described is based on a fractal grid model [2]. Considerations in this design include distributing both generation and storage across the community, in such a way as to ensure maximum local consumption of locally produced energy, to enable and support community utilisation of all energy produced, yet to minimise the required inter-node transmission capacity. A further aspect is to ensure community engagement, and essentially "ownership" of the microgrid [3].

While there is a growing body of literature on the design of community microgrids e.g., [4][5][6], the work described here essentially begins from first principles in order (i) to recognise the islanded environment, (ii) to base the design principally on solar power and batteries, and (iii) to acknowledge the social context of the development.

The paper is structured in the following way. Section II develops appropriate household and *marae* load profiles, necessary because there is no existing reticulated power system. These load profiles are then used in Section III to establish what would be an adequate or appropriately sized solar/battery configuration for a household, and for the *marae*. This configuration is then adjusted in the context of a fractal microgrid design in Section IV, which clearly demonstrates the advantages of this concept. Section V provides a discussion of the optimal configuration and distribution of resources in the microgrid. The overall design, and the current state of the development, is then discussed in the concluding Section VI.

II. LOAD PROFILE ESTIMATION

Annual load profiles were established for ten individual households. As there is currently no grid supply to the community, then these profiles were derived from real households with appropriate occupancy and appliance utilisation characteristics, located at a similar latitude on the New Zealand mainland. Those adopted were selected on the basis that the houses did not have electric hot-water systems, nor did they use electricity as their primary form of heating. These were also households comprising a range of occupant

 ISBN: 978-1-68558-054-4

numbers, both adults and children. The consumption profiles for these houses varied considerably, in terms of average daily use, hourly use over the day, and seasonal differences. The data used was hourly data over a whole year – 8760 data points for each house [7].

While the variation between households was retained, the profiles were scaled to give an average daily base load (across the ten houses) of 7.5 kWh. This data is summarised in Table 1.

TABLE I. SUMMARY OF HOUSEHOLD BASE LOAD DATA

ID	#Adults	#Child	Daily average	Scaled Average	Comments
A1	2	0	11,714	7,994	Gas heating
A2	2	0	10,981	7,493	Fossil heating
A3	2	0	8,956	6,112	Gas heating
A4	2	0	14,047	9,586	Gas heating
A5	1	0	5,840	3,985	Gas heating
A6	4	1	13,509	9,219	Gas heating
A7	2	0	11,150	7,609	Gas heating
A8	3	1	10,249	6,994	Gas heating
A9	2	0	6,990	4,770	Gas heating
A10	2	0	16,461	11,233	Gas heating
Average daily consumption			**10,990**	**7,500**	

A load profile for the *marae* was also established using similar techniques, based on the occupancy level. One of the household profiles (A4, Table 1) was used as the starting point, but the scaled data was doubled to represent 4 adults (estimated permanent *marae* occupancy), meaning the base load daily average is 19.171 kWh. To this base profile was then added a randomly generated *hui* load. Fourteen *hui* were added over the year, with their start dates randomly generated, and with randomly allocated durations of 1 to 3 days. This was based on suggestions from the community of typical *hui* frequency and size. An estimated supplementary load profile was created for a *hui*, which included additional cooking, lighting, and heating during the event. This added load runs from 2.00pm to 2.00pm, so assumes that even a 1-day *hui* involves an overnight stay for the non-local participants.

For the *marae*, the addition of these *hui* increases the annual average daily consumption to 24.275 kWh, and the maximum consumption in any one hour over the year from 6.051 to 9.465 kW.

III. INDIVIDUAL HOUSEHOLD DESIGN

Based on these load profiles, and standard design guidelines for solar installations in New Zealand:

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

an initial analysis was carried out for the ten households and the *marae*.

For this initial analysis, with each household, and the *marae*, operating as an independent unit, the standard configuration used was solar panels of 4 kW capacity, plus a battery of 22.5 kWh capacity, for each site. Annual solar data for Aotea was used to calculate the solar panel output for each hour of the year [8], and key points from this analysis of the non-networked configuration are shown in Table 2.

A discretionary or divertible load was added in for this analysis. In reality, this might, for example, represent hot-water heating or EV charging, 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 household) of 5 kWh, and was invoked only when the 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 9 days in which no discretionary load was possible at all.

TABLE II. SUMMARY OF INITIAL NON-NETWORKED SIMULATION

ID	Average Daily Base Demand (W)	Peak Daily Base Demand (W)	Average Daily Discretionary Load (W)	Total Surplus Hours	Total Failed Hours	Average Daily Failed Supply (W)
A1	7,994	16,406	3589	1604	16	13
A2	7,493	15,281	3779	1704	12	14
A3	6,112	9,087	4016	1939	0	0
A4	9,586	27,908	3093	1365	143	217
A5	3,985	11,730	4364	2200	0	0
A6	9,219	17,160	3364	1374	127	142
A7	7,609	19,738	3735	1663	58	47
A8	6,994	14,018	3778	1750	0	0
A9	4,770	11,893	4229	2057	0	0
A10	11,233	31,066	2899	1129	317	591
Marae	24,275	106,162	808	274	2184	8908

It is interesting to note (Table 2) that under this autonomous mode of operation, and with this configuration, for four of the households there were no base load supply failures 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 House 10 showing the most extreme case of 317 hours of failed base load supply. The *marae*, because of its very high peak demands during *hui*, showed 2184 hours in which the system was unable to meet its demands, and with this shortfall averaged over the whole year, that amounts to nearly 9kWh per day. By contrast, all sites, including the *marae*, showed a significant number of hours in which there was an unused surplus of solar energy.

Of course the failure 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. For all of those failed hours across the ten households shown in Table 2, these were spread across 355 hours of the year.

To give an idea of the energy balance situation, in Figures 1 and 2 the annual hourly balance is shown for two extreme houses, House 5 (zero failed hours) and House 10 (317 failed hours). For these energy balance plots, the consumed energy includes battery charging as well as the actual domestic loads, and the produced energy comprises both solar generation and anything delivered from the batteries [9]. Perfect balance is shown by points on the diagonal. For House 5 (Figure 1), perfect balance is achieved 75% of the time. The very evident stack of points close to the vertical axis represent hours of sunlight (high generation) at times of low load, when the batteries are fully charged. The other vertical cluster of points at a load of 2.2kW represent those daylight hours when the discretionary load has been activated, but there is still some surplus. House 10 (Figure 2) actually achieves perfect balance 83% of the time, but of course, as can be seen from the graph, there are 317 hours (3.6%) when the full demand is not met.

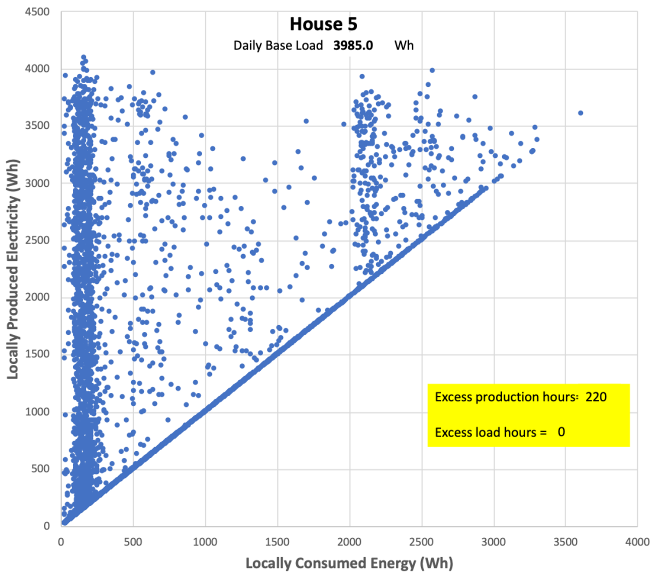

Figure 1. Hourly energy balance over the full year for House 5 in the non-networked mode.

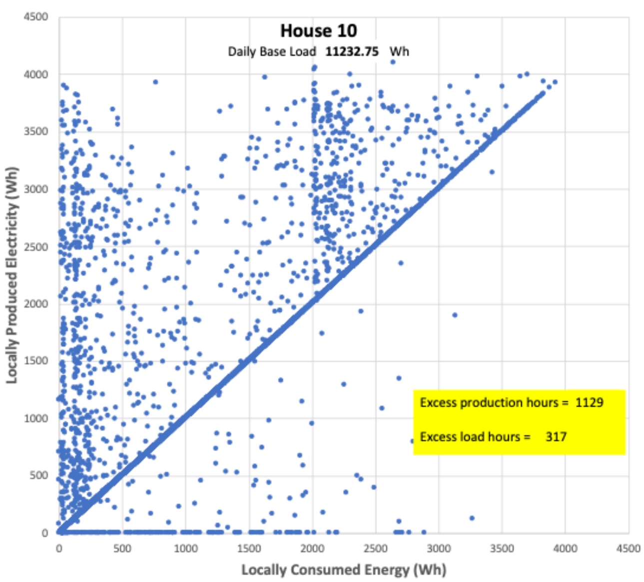

Figure 2. Hourly energy balance over the full year for House 10 in the non-networked mode.

These two houses represent the extremes of generation/load balance using this basic design; all of the others lie between these in their energy balance characteristics [9].

IV. Fractal Microgrid Design

Clearly with demands and surpluses varying between households, and the occasional peak demand from the *Marae* during *hui*, community sharing has potential to achieve a greater degree of balance between generation and demand. A fractal microgrid design [2] as represented in Figure 3 will now be considered.

In this model, any terminal node (A to F, and I in Figure 3) can comprise any combination of load, generation, and/or storage. Typically, these would represent individual households such as those being considered here, but they could also represent a community solar panel array (generation only), a community service, such as street lighting or EV charging (load only), or a community battery (storage only). Some of the households might not include solar panels and/or storage. The non-terminal nodes (G, H, and J in Figure 3) will always present themselves as intelligent and active to the higher level grid they are connected to, and will comprise a combination of load, generation and storage, but from the perspective of the higher level grid, will appear as a single entity with these properties, hence the term, *fractal* microgrid [10].

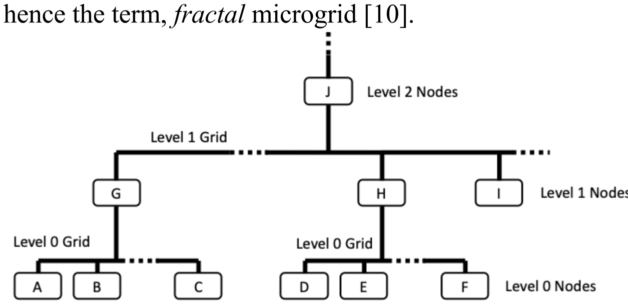

Figure 3. The fractal microgrid concept.

The fractal microgrid proposed here initially comprises just a single level 0 grid (Figure 3) and no higher levels. The *marae* forms the level 1 node (node G in Figure 3), and the community households the level 0 nodes (nodes A, B, C in Figure 3). A more specific representation of this Motairehe fractal microgrid is shown in Figure 4.

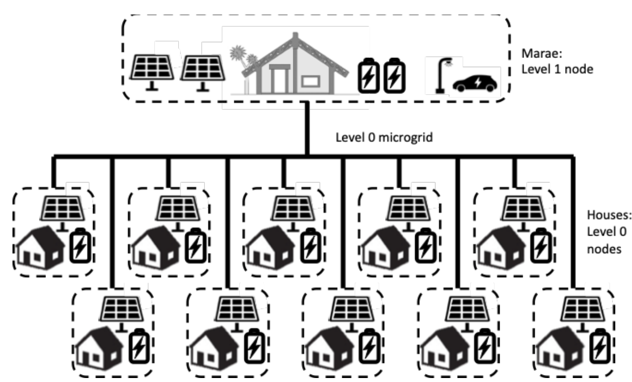

Figure 4. The proposed Motairehe fractal microgrid comprising ten houses and the *marae*.

In this model, it can seen that each household retains local solar generation and battery storage, but is also connected to the microgrid. This means that at times of surplus, the household can contribute to the microgrid, potentially supporting neighbours, and/or the *marae*, and at times of shortfall, it may be able to draw from neighbours or the *marae* surplus. The *marae* similarly is connected to the microgrid, and retains its local solar generation and storage. Also shown in the *marae* set up is the notion of community services – in this case, street lighting and EV charging. Such services could also be simply connected to the microgrid itself (rather than be part of the *marae* node), as could, for example, additional community solar panels.

Although shown here as a single community system, and not explicitly demonstrating a fractal structure itself, it has been developed in this way consistent with the fractal microgrid concept, in order that it could in the future be readily extended to:

- multiple community grids within the same general area, each connected to the *marae* as the upper-level node; or
- the *marae* itself could be connected to a higher level node, potentially bringing together more distant groupings.

Possible future extensions to the microgrid of this nature would follow the general fractal model of Figure 3.

The approach taken with the initial design of the microgrid is to consider overall the same total solar generation and the same total battery storage as was used for the non-networked analysis of Sections II and III. At this stage, it is assumed:

- All houses will have the same sized system of solar panels and batteries;
- The *marae* may have a different configuration, and the design will attempt achieve a distribution which minimizes the overall energy transfer between the *marae* and the community, in either direction;
- It is anticipated that the fractal microgrid should achieve an overall better utilisation of the generated electricity, reducing over the entire site both the wasted excess production and the failed supply.

Initially, it is a simple matter 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 [9]. However, once that analysis has been carried out, then the distribution of generation and storage between the houses and the *marae* needs to be explored to minimize the overall grid flow, since a higher grid flow will require a more substantial cable, and/or imply greater transmission losses.

The results of the initial analysis are shown in the energy balance plot of Figure 5. 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. What is remarkable, is that by considering the total generation, the total load, and the total battery capacity, the overall number of shortfall hours over the year for the whole community have been reduced to 64, significantly less than the 2184 previously experienced by the *marae*, and the 355 by all of the houses together. In fact, only 16 of the shortfall hours actually coincide with *hui*.

Of course, this plot (Figure 5) does represent just the base load; any discretionary load would need to be taken during those hours of surplus, above the diagonal. Referring back to Table 2, it can be seen that these 1870 hours of overall surplus are more than those experienced by some of the houses in the non-networked mode. The impact of the fractal network on discretionary load is discussed later, in relation to Figure 8. However, each site (both Level 0 and Level 1) would need "smart" control to prioritise demand in the following sequence:

(i) Local base load;
(ii) Local battery charging;
(iii) Microgrid (community) needs;
(iv) Household discretionary load.

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

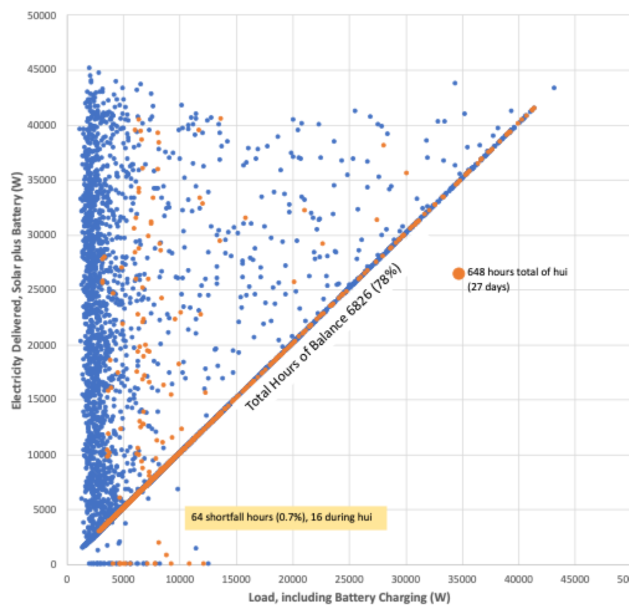

Figure 5. The overall energy balance for the fractal microgrid model.

It is clear from this initial analysis of the fractal community microgrid model, that overall a much better utilisation of the generated electricity has been achieved, reducing, across the entire site, both the excess production and the failed supply. This has utilised the same overall total solar panels, and the same overall total battery storage, as with the original non-networked model of Section III. These numbers are:

- *Solar panels:* For the non-networked model, each house, and the *marae*, was fitted with ten 400W panels, giving a total of 110 x 400W.
- *Batteries:* For the non-networked model, each site was provided with 22.5 kWh of battery, leading to a total battery capacity of 247.5 kWh.

ISBN: 978-1-68558-054-4

Before proceeding to optimise the configuration by attempting to minimise grid flow, it is worth considering other aspects of this fractal microgrid model. Figure 6, for example, shows the daily variation in total base load for the community, and highlights those days which correspond to *hui*. While it can be seen that there are daily peaks corresponding to *hui*, there are also peaks which are not associated with *hui*.

In Figure 7, the nine days over the year in which supply shortfall occurs are shown, again with correspondence to *hui* highlighted. Three of these days do coincide with *hui*, but there are three quite significant shortfall days which do not. Those days are in the middle of winter, and in this data set represent days of very low solar radiation.

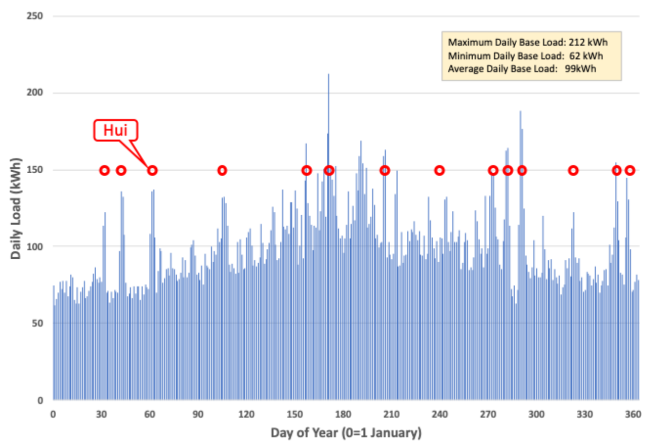

Figure 6. Overall daily base load variation for the whole community, with *hui* days highlighted.

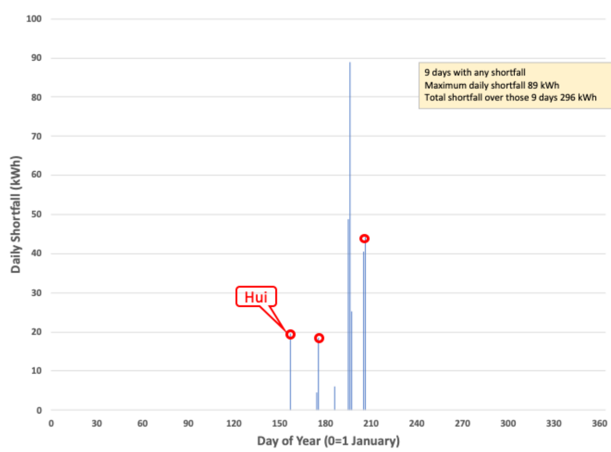

Figure 7. Days of overall shortfall for the community over the year, showing some coincidence with winter *hui*.

Figure 8 shows the daily baseload surplus, which is, of course, highly relevant in relation to discretionary loads. Here, it is evident that the surplus is quite variable, and also that there are periods during the winter where there is no surplus for several days in sequence. For comparison, *hui* are also identified on this plot. For the earlier non-networked configuration, there were just nine days when no discretionary load was available; under the fractal model, there are 60 days. However, the average daily availability of discretionary power is 91 kWh; the allocated average daily load for the non-networked model was 30 kWh. Not surprisingly then, the fractal model offers this option to the whole community on fewer days of the year, because it is making more effective use of surplus generation in providing base load for the whole community, but in total, over the year, there is more than adequate discretionary capability.

It should also be noted that many of the houses, and the *marae*, already have back-up generation resources, and are likely to retain those when the fractal solar microgrid comes into existence. While the household back-up systems are likely to be used only for the individual households, the *marae* back-up would potentially benefit all when needed, covering those days of community shortfall shown in Figure 8.

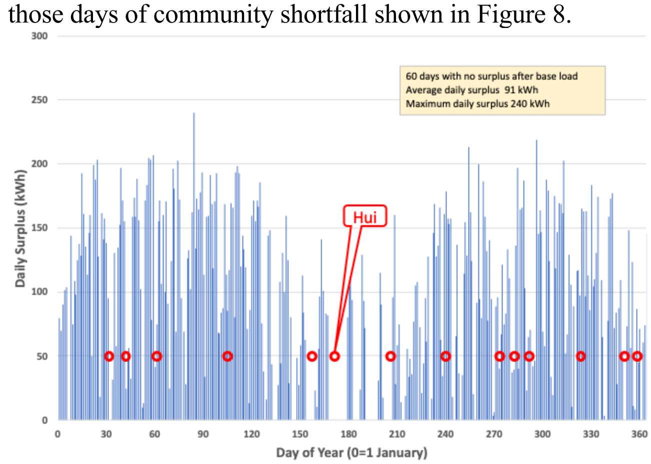

Figure 8. Daily baseload surplus for the community.

This analysis has shown the real adbvantage of the community microgrid approach, in that each houshold is fitted with the same configuration of panels and batteries, and in all cases has a more stable supply of electricity.

V. Resource Distribution for Optimal Microgrid Operation

Now that the positive aspects of the fractal microgrid approach have been established, it is necessary to consider the optimal configuration of solar panels and batteries. As suggested earlier, it is assumed that all houses have the same configuration, and that the distinction will be between the houses and the *marae*. It is the electricity flow in the microgrid connection which will be the determining aspect of the distribution of resources. For this analysis, it is necessary to explore both:

- the peak flow, since this will dictate the size of cable required, and
- the average flow, since this will determine the overall energy losses in the cable.

The overall resources on which the results shown in Section IV were established, comprise a total of:

- 110 x 400 W solar panels, and
- 247.5 kWh of battery storage.

As an example of the nature of the energy flows between the *marae* and the houses, Figure 9 shows the hourly flow over

 ISBN: 978-1-68558-054-4

a year with 20% of the panels and 20% of the battery capacity held at the *marae*. It is evident from this graph that at different times, energy flow can be in either direction, and that the peak flows (largest is ~9.5 kW) occur *to* the *marae*, although overall, more energy appears to flow *from* the *marae*. Almost all of the flows to the *marae* do coincide with *hui*, as can be seen from the graph.

In order to determine the optimum allocation of resources to the *marae*, an analysis was carried out with various proportions of those resources, ranging from 18% to 30%. The results of this analysis, shown in the parallel coordinate plot of Figure 10, reveal clearly that a 20% allocation produces a minimum of both peak grid flow, and daily average grid flow.

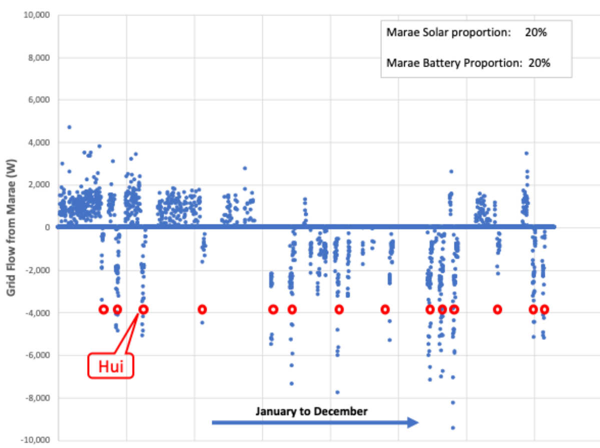

Figure 9. Hourly grid flow from the *marae* to the houses with 20% of generation and storage allocated to the *marae*.

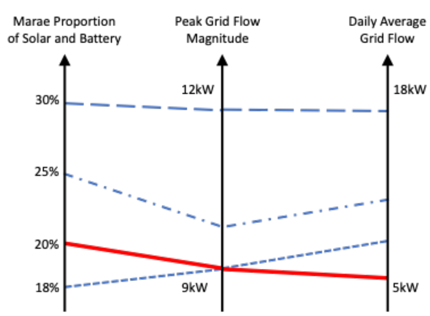

Figure 10. Parallel coordinate plot showing the relationship between the proportion of the resources located at the *marae* and the peak and daily average grid flows.

Finally, to give a better picture of these grid flows, Figure 11 shows (for this 20% *marae* allocation) the distribution of the hourly grid flows over a year.

It can be noted that the grid flows to the *marae* (negative in Figures 9 and 11) occur on far fewer hours than the *marae* showed a shortfall in the non-networked model (see Table 2). But of course, under this optimised fractal microgrid model, the *marae* does have a larger allocation of solar generation and batteries. It should also be noted that this analysis has examined the flow between the *marae* and the houses as a group (refer to Figure 3), not the flow between the houses themselves. These latter flows are likely to be less, and it is reasonable to use the *marae* flow as the basis for cable sizing.

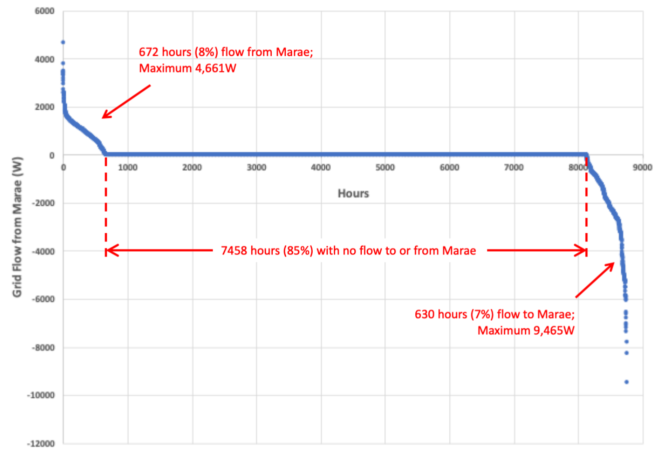

Figure 11. Duration plot of grid flow from the *marae* over a year.

This proposed configuration is elaborated in more detail in the following concluding section.

VI. CONCLUSION AND FUTURE WORK

The analysis of the preceding sections has clearly shown that the suggested fractal solar microgrid model for the Motairehe *marae* and community provides a superior outcome to isolated individual systems, for exactly the same overall solar panel and battery resources. A more resilient and reliable electricity supply for the community ensues, with far fewer hours overall of electricity shortfall.

Based on the numbers from this analysis, the suggested configurations are:

Marae:	8800 W solar panels
	49.5 kWh battery
Houses:	3520 W solar panels
	19.8 kWh battery

These numbers, of course, need to be rounded up for sensible use of currently available technology.

In addition to this basic technology, the houses and the *marae* need to be connected by an appropriate cable capable of carrying at least the calculated 10kW load with minimal losses. A preliminary calculation, taking into account the relatively close proximity of the households and *marae* at Motairehe, suggests that the cost of the interconnecting microgrid cables to handle this 10kW load could have provided ~15% increased solar panel capacity across the site, if no microgrid was included. However the advantages of the microgrid interconnection shown in this analysis, far outweigh the benefits of increased, but isolated, generation. Additional control logic will need to be incorporated within each node of the microgrid, to manage the interaction, particularly in relation to grid needs and offers, and local discretionary demands.

It should also be re-iterated that the adoption of a fractal microgrid model readily enables future expansion, without significant reconfiguration, for example:

- Addition of further community facilities, such as community lighting, shared solar arrays, community EV charging, and community storage, on the level 0 grid.
- Addition of other close-by communities or groups of houses into the system, either as an extension of this level 0 microgrid, or as another level 0 microgrid (refer to Figure 3).
- Expansion of the fractal structure to Level 2 or higher (Figure 3) potentially linking it with more distant communities.

The system as described is currently under development, with support from the MBIE *Mãori Housing Renewable Energy Fund* [11].

ACKNOWLEDGEMENTS

The research described in this paper has been supported in part by the MBIE Endeavour Programme, *Public Housing and Urban Regeneration: Maximising Well-being* (Grant ID:20476 UOOX2003), and also the the MBIE Strategic Science Investment Fund grant, *Ahuora: Delivering sustainable industry through smart process heat decarbonisation* (Grant ID: CONT-69342-SSIFAETP-UOW).

REFERENCES

[1] *Emissions reduction targets*. Ministry for the Environment; https://environment.govt.nz/what-government-is-doing/areas-of-work/climate-change/emissions-reduction-targets/ Accessed 2023.02.13.

[2] M. Apperley, “Modelling Fractal-Structured Smart Microgrids: Exploring signals and protocols”, *Energy 2019 Conference Proceedings*, IARIA, pp. 13–17. 2019.

[3] A. L. Berka, J.L. MacArthur, and C. Gonelli, “Explaining inclusivity in energy transitions: Local and community energy in Aotearoa New Zealand”, *Environmental Innovation and Societal Transitions*, **34**, pp. 165-182, 2020.

[4] L. Che, X. Zhang, M. Shahidehpour, A. Alabdulwahab, and A. Abusorrah, "Optimal interconnection planning of community microgrids with renewable energy sources." *IEEE Transactions on Smart Grid* **8**, pp. 1054-1063, 2015.

[5] M. A. Hossain, H. R. Pota, S. Squartini, F. Zaman, and J. M. Guerrero. Energy scheduling of community microgrid with battery cost using particle swarm optimisation. *Applied Energy*, 254, p. 113723, 2019.

[6] N. Tomin, V. Shakirov, A. Kozlov, D. Sidorov, V. Kurbatsky, C. Rehtanz, and E.E. Lora, (2022), Design and optimal energy management of community microgrids with flexible renewable energy sources, *Renewable Energy,* pp. 903-921, 2022.

[7] M. Apperley, P. Monigatti, and J. Suppers, “Grid-Lite: A network integrated semi-autonomous local area electricity system”, In *Proceedings of the 4th International Conference on Green IT Solutions (ICGreen 2015)*, Milan, Italy, SciTePress, pp. 27-33, 2015.

[8] J. Suppers and M. Apperley, “Interactive solar panel simulation tool - from GHI to PV output”. In C. Beckmann & T. Gross (Eds.), *INTERACT 2015 Adjunct Proceedings: Fostering Smart Energy Applications Workshop*, pp633–642. Bamberg, Germany: University of Bamberg Press. 2015.

[9] M. Apperley, “Modelling energy balance and storage in the design of smart microgrids”, *Energy 2017 Conference Proceedings*, *IARIA,* Barcelona, pp. 40-45, 2017.

[10] B. B. Mandelbrot, *Fractals: form, chance, and dimension*, W. H. Freeman: San Francisco, CA., 1977.

[11] *Māori and Public Housing Renewable Energy Fund.* https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/low-emissions-economy/energy-efficiency-in-new-zealand/maori-and-public-housing-renewable-energy-fund/maori-housing-renewable-energy-fund. Accessed 2023.02.13