Modelling Energy Balance and Storage in the Design of Smart Microgrids

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Abstract—**This paper introduces and demonstrates appropriate and realistic modelling approaches for smart microgrids, with a focus on local energy balance. There is an increasing interest in microgrids, as the nature of large-scale electricity generation and distribution changes, with a conscious shift to more sustainable and renewable energy sources. However, the modelling and design techniques traditionally used have tended to be based on economics and design criteria more suited to the top-down planning for power generation and distribution typical of legacy grids, than to bottom-up energy balance incorporating localised distributed generation and storage, significant characteristics of these new systems. Several aspects of microgrid design and specification are modelled using an example based on an installation incorporating solar photovoltaic panels and battery storage. Important features of each of the models shown are the associated visualisations, which lead to improved understanding of design implications, compromises, and consequences, and the true context of a renewable-energy based microgrid.**

Keywords-energy balance; smart microgrid; solar PV; battery capacity; Grid-lite

I. INTRODUCTION

There are recent significant shifts of interest to new renewable energy sources, as concerns relating to greenhouse gas emmisions, climate change, and finite fossil fuel resources grow [1][2]. The electricity supply industry world-wide has been characterised for the past 100 years by national and international grids, operated with the goal of balancing *power* generation with demand in real-time [3]. The industry has become very skilled and adept at managing this challenge, and it is this which has determined the complexities, the risks, and the costs, of present day power systems [3]. In this context, longer term seasonal variations in *energy* demand have generally been accomodated by ensuring sufficient reserves of energy are held – fossil fuels in the case of oil, gas and coal systems, water in the case of hydro systems. The design and management of such systems can be characterised as one of top-down planning of power generation, driven by economic considerations, load anticipation, resource availability, and the need for grid-wide security of supply.

But also fueled by those environmental concerns and rapidly advancing technology, dramatic changes are occuring through the combination of new renewable energy sources (solar, wind, tidal), energy storage technologies (at this stage mainly batteries), and automation systems, which enable effective and tolerable distributed load matching/shifting. Two specific technologies – solar photovoltaics (PV) and lithium batteries – are of particular interest because they lend themselves to a significant degree of distribution, which coupled with load matching/shifting technology in microgrids [4], challenges many of the notions of the traditional, or *legacy*, grid [5]-[8]. Concerns with long-distance hierarchal/radial energy transfer and real-time load following from centralised generating systems, grow less and less relevant and appropriate when microgrids, with their highly distributed generation, storage, and load management, become more prevalent [3][9][10].

New renewables in themselves bring challenges under the traditional model, since their contributions tend to be non-deterministic and variable, so adding further complexity to that real-time load-following approach. However, when such generation is combined with short-term storage, and located close to the point of consumption, then these technologies have the potential to radically change the nature of the grid in the longer term [3]. Although the integration of renewable sources into the legacy grid has been the subject of much research, discussion and debate [11][12], to fit with the on-demand delivery and economic models, typical renewables require significant, and unrealistic, energy storage capacity. A range of storage concepts have been explored, including the exploitation of electric vehicle batteries (V2G) [13], but for centralised renewable generation, such as wind or solar farms, the distributed nature of such storage in contrast to the generation, places increased energy transfer demands on the grid.

However, microgrids have the potential to lead to an entirely fresh approach to planning, a bottom-up technique based on localised energy balance, maximising the balance between local generation and local load, and minimising the dependence and impact on the remote resources of the grid. The effect then of such an installation on the legacy grid is not so much one of increased non-deterministic generation capacity, but one of reduced load. Coupled with this approach go a new set of imperatives for consumers, typified by a growing bourgeois off-grid population; a great deal can be learned from the experience and motivations of these people, in terms of shifted demands and expectations, and modified behaviour [14][15].

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This paper explores design approaches to smart microgrids based on energy-balance techniques, and shows how such perspectives result in and project far more realistic specifications and expectations, and can be presented in such a manner that leads to a better understanding of the design compromises, and that will in turn lead to a more enlightened next-generation grid development.

Section II introduces a representative microgrid example, which is then used in Section III to explain the Net Zero Energy Balance concept, and the strengths and weaknesses associated with that concept. Discussion in Section IV turns to the implications of non-deterministic generation, and to the limitations of the short-term storage typified by batteries. Finally, in Section V, the paper develops an argument for reducing grid dependency in such installations, and introduces and explains the Grid-lite concept.

II. A REPRESENTATIVE MICROGRID INSTALLATION

The data and graphs used in this paper are based on a representative residential installation located in New Zealand, at approximately -38° lattitude. Real electricity consumption data for a family home, at hourly intervals, has been captured over a year. The analysis explores the effect of local generation. For this purpose, a real data set using actual solar radiation at this location, at hourly intervals over a year, combined with characteristics of a representative contemporary PV panel, has been used [16]. Different parts of the following analyses assume different configurations in relation to the grid. However, the energy balance terminology that is used in relation to the energy flows between the major functional components of the system is shown in Figure 1. While the inclusion of the battery flows in both the *local consumption* and *local generation* totals may appear to account for the stored energy twice, this is necessary in order to examine flows over short time scales, where in one interval the battery may be charging, and in another, discharging, using energy produced in the previous interval [17].

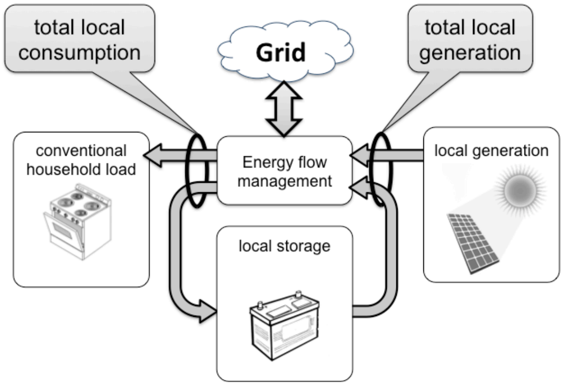


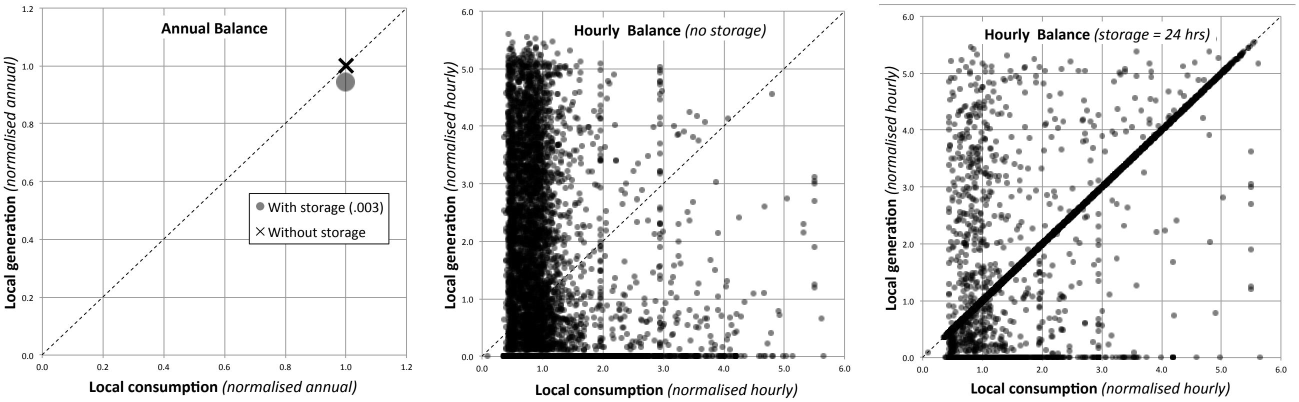
Figure 1. Energy flows within the smart microgrid, and the definitions of local generation and local consumption.

For this example installation, the total annual electricity consumption is 6.446 MWh, equating to a daily average of 17.661 kWh, and an hourly average of 736 Wh. Many of the subsequent figures in the paper use normalised values; these have been normalised to the relevant load figure, be it annual, daily or hourly, as indicated in the axis labels.

III. NET ZERO ENERGY BALANCE (NETZEB)

A useful starting point in considering smart, renewable-energy based microgrids is the concept of *Net-Zero Energy Buildings* [18][19], buildings with an annual total energy consumption of zero. The total energy used over a year is equal to the total renewable energy generated on the site. A NetZEB buiding is by necessity a grid connected one, since it is the annual balance which is of concern, and to accomodate short-term (hourly or daily) or even seasonal variations in balance between generation and load, necessitates both grid feed-in at times of excess generation, and grid-supply in times of excess load, even with local battery storage. For the example configuration (see Section II) to achieve NetZEB, solar PV has been chosen to exactly match the total load over a full year, requiring panels with a name-plate capacity of 4.03 kW.

Figure 2 illustrates the apparent contradictions of the NetZEB approach. These three graphs use the *interval energy balance space* [17] to show the balance between local generation and local consumption, as defined in Figure 1, over different intervals. In each of these graphs, total local generation over the interval in question, is plotted against total local consumption over the same interval; each point on the graph identifies one such interval during the year. Points on the leading diagonal are those where for that interval, perfect balance is achieved between generation and consumption. Figure 2(a) represents the interval of a whole year, so just a single point is shown, and as expected from the design specifications mentioned, NetZEB is achieved over this period without any need for battery storage – the X on the balance diagonal. Reliance on the grid to both store and supply energy enables this balance, as Figure 2(b) highlights. Here, with an interval of just one hour, it can be seen that in very few of the 8760 hours of the year is perfect balance achieved. In many of these intervals there is zero generation but some load (those points on the horizontal axis, invariably night-time hours), and in others there is relatively low load (0.4 to 1.1), but much higher generation (the stack of points parallel to the vertical axis, invariably representing hours of high sunshine). Figure 2(c) however, shows that the introduction of local battery storage can improve the situation. With a storage capacity equal to 1 average day's consumption (in this case 17.661 kWh, equivalent to 1.3 Tesla Powerwall 2s – a normalised energy capacity of 24 on this hourly plot), many of the previously scattered points are now located on the balance diagonal. Since some of the locally generated energy now passes through the battery, then the annual goal is slightly compromised because of battery losses, as is seen from the shaded circle point on the annual balance plot of Figure 2(a) (here the normalised battery capacity for annual data is 1/365 ~ 0.003). This could be readily corrected by a small increase (<10%) in PV capacity. A battery efficiency of 90% has been used in these calculations, the indicated efficiency associated with the Tesla Powerwall [8].



(a) (b) (c)

Figure 2. Interval energy balance plots for the example configuration; (a) the annual balance, with and without storage; (b) hourly balance without storage; and (c) hourly balance with storage equivalent to an average day's consumption. Note that all energy values have been normalised, as indicated.

The difference in grid dependency between the no-storage and storage scenarios can also be seen from the *balance duration* plots of Figure 3. These duration plots take the 8760 hourly balance values over the year from Figures 2(b) and 2(c), and show them sorted, largest to smallest. Again it can be seen that for the no-storage scenario, almost none of the hours lie on the balance line, but now for the storage scenario, it can be seen that for only 5% of the time, is generation in excess of load, and grid feed-in required, and for 17% of the time, load exceeds generation so that grid supply needed. For the remaining 78% of the hours of the year, the central horizontal band, perfect balance is achieved.

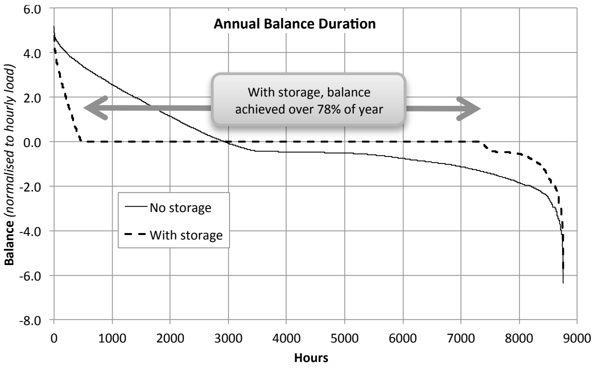


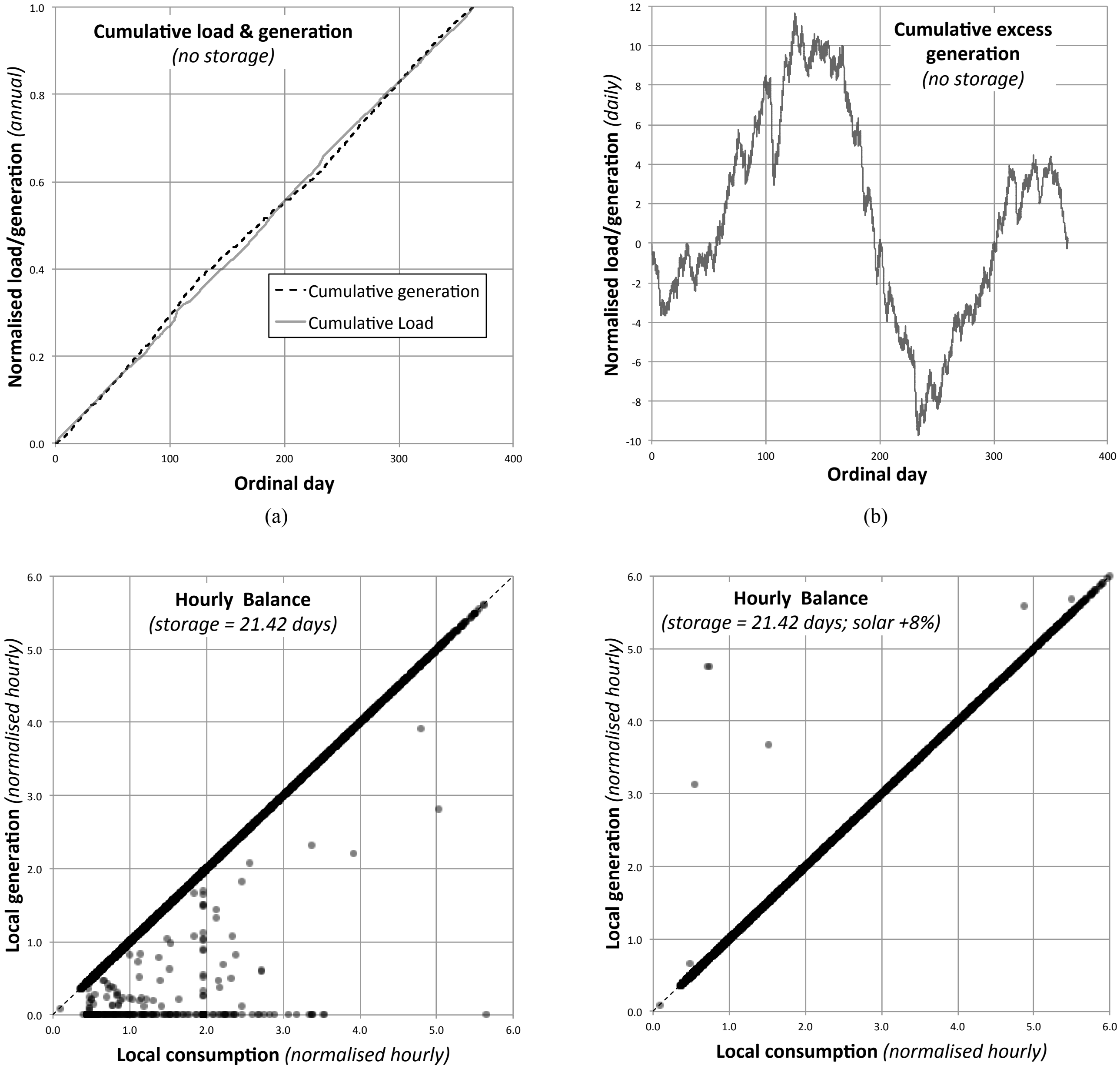
Figure 3. Balance duration plots for the storage and no-storage scenarios of Figure 2.

Although the figures used here are hourly ones, so that within a balanced hour there may well be periods of imbalance, it can be safely assumed that battery storage of one day's duration will normally smooth this, or in extreme cases, load management technology can be utilised to avoid peaks in either direction.

IV. IMPLICATIONS OF NON-DETERMINISTIC GENERATION AND FINITE BATTERY STORAGE

It is apparent from Figures 2(c) and 3 that the battery capacity used in this example (1/365 = 0.0027 of annual load) is insufficient to produce continuous balance over the whole year for this specific installation. In fact, balance is achieved for only 78% of the year. In general, batteries are really viable only for short-term storage. If one considers a solar PV microgrid installation, there are three levels of fluctuation in the generation capability that must be accommodated before load variations are even considered. (i) The first is the daily cycle attributable to the rotation of the earth. No energy is generated during the night-time hours, and during the day, output begins at a low level as the sun rises, peaks in the middle of the day, and fades away to nothing as the sun sets. (ii) The second is related to weather events – when cloud cover and precipitation are present, the ouput at any time of day is reduced, from relatively minor impact for high cloud, to significant reduction for low cloud or precipitation. Such events may last from just minutes (cloud in front of the sun) to several days (major weather event). (iii) The third is the seasonal variation. With the sun at a lower angle in the winter, peak daily output can be significantly lower than in the summer, with the effect increasing with lattitude. For a residential installation, the reduced winter generation is compounded by what is normally an increased winter demand because of longer darkness hours and lower temperatures.

Figure 4 illustrates an approach to determining the effectiveness of battery storage solutions [20]. Figure 4(a) shows the cumulative load and generation patterns over a year for our example, without any battery storage. It can be seen that accumulated generation (on a daily basis) generally exceeds accumulated consumption until day ~200 (mid-winter). Figure 4(b) then shows the difference between the generation and load lines, essentially the same data used in the balance duration plot of Figure 3, but arranged chronologically rather than sorted by decreasing value. The distance between the maxima and minima of this plot gives the battery capacity that would be required to achieve continuous energy balance throughout the year, without any grid dependency (21.42 average days' consumption, equivalent to 28 Tesla Powerwall 2s). The *hourly* interval energy balance plot with this battery capacity provided is shown in Figure 4(c), where it can be seen there remain a



(a) (b)

(c) (d)

Figure 4. An approach to battery sizing: (a) Cumulative load and generation; (b) cumulative balance; (c) interval energy balance with the large battery resulting from interpreting this difference; and (d) the further effect of a small increment in PV size.

number of hours where there is excess load. However, an increase in the solar capacity of just 8% can correct this, as shown in Figure 4(d), which demonstrates that these exceptions were caused simply by the battery losses.

Clearly the battery capacity proposed here is impractical, and in fact, not a lot is typically gained, in terms of balance hours, as the battery capacity is increased beyond just a few days. Much smaller increases in the PV capacity are usually more fruitfull. Weniger [21] provides useful contour plots showing the tradeoff between battery and PV capacity in terms of self-sufficiency (proportion of load delivered by locally produced electricity). Their analysis, however, is based on annual totals, so assumes that any excess can be accomodated by the grid.

For the previous example, a more satisfactory grid-load-free solution can be achieved by starting with a 38% increase to the solar capacity, and using just 6 days' battery storage.

The cumulative generation curve shown in Figure 4(a) does demonstrate the typical seasonal sigmoidal shape. At increased lattitudes, this effect becomes much more pronounced, with signficantly reduced winter output. With the type of analysis just described, this can be best dealt with by increasing to solar capacity to provide adequate winter generation, accepting that there will be increased excess in

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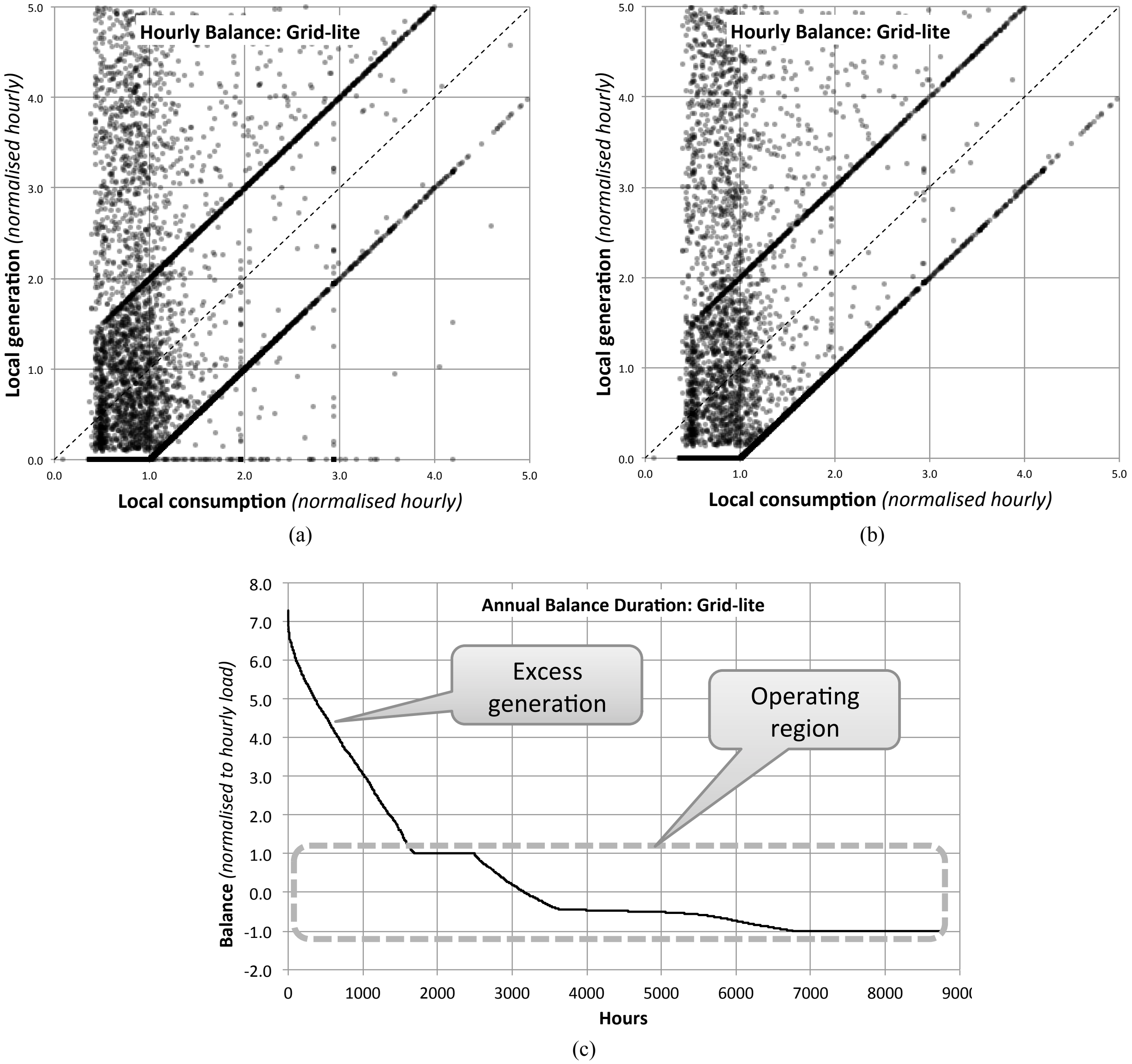
the summer months, but certainly not by trying to increase battery storage to carry excess energy from summer through to winter [22].

V. REDUCING GRID DEPENDENCY

One approach to reducing the grid dependency of a microgrid installation is to plan for a restricted capacity grid connection – say a maximum X kW load and a maximum Y kW generation feed [17]. The advantages of this *Grid-lite* approach are (i) to ensure a level of self-sufficiency for the consumer, but more importantly (ii) to allow the grid and the electricity provider to plan their systems with a greater confidence. This notion is consistent with the idea that microgrids incorporating PV and battery storage are best not treated as non-deterministic generators, but rather as reduced loads. Grid-lite puts some numbers on this concept.

Figure 5(a) shows the hourly energy balance for a Grid-lite implementation based on our example system. Here the maximum grid flow has been set to 1 (normalised hourly) in both directions, the battery capacity to 1 day, and the PV capacity also to 1 (normalised). The goal of the smart management system is to keep the balance within the limits that clearly show in the plot. While there are some hours where the balance falls below the limit, these can be eliminated by increasing the solar capacity by 38% and doubling the battery capacity. This modification is shown in Figure 5(b). The positive imbalance hours need to be



(a) (b)

(c)

Figure 5. The Grid-lite model: (a) Hourly balance with grid-flow restricted to 1; (b) with increased solar capacity and storage to eliminate excess load; and (c) the balance duration plot for this latter configuration showing 18% of hours with excess or wasted generation.

regarded simply as wasted generation, and the effect can be assessed from the balance duration plot of Figure 5(c), which shows there are 1650 hours of excess generation (18%).

VI. CONCLUSION

This paper has explored and demonstrated a range of approaches to modelling microgrids incorporating solar PV and batteries. While other renewable generation technologies are equally applicable (they differ mainly in the extent and manner of their variability) the focus has been on solar because (i) it is the obvious distributed choice for urban environments, where by far the greater proportion of the population of the world resides, and (ii) its rapid penetration has caused the electricity supply industry to seriously consider its implications.

The approach has highlighted the need to primarily consider local energy balance, using the particular model for energy balance defined in Figure 1, where local supply is considered to come from both the solar PV and the battery, and where battery charging is also considered to be a part of the local load.

With a better appreciation of the motivations for local balance, microgrids incorporating solar PV and storage can be seen to contribute to the longer-term planning of electricity grids, not because of the generation capacity the solar PV provides, which is considered of dubious value by some, but because of the load such systems, if well designed, remove from the grid.

While the analysis is this paper has been based on a single household, because of the success of the approach in demonstrating the possibilites of local energy balance, the situation for multiple households (say a street) can be no more challenging, and is likely, because of parallel generation patterns, but probably different consumption patterns, to be complimentary, with balance able to be achieved with slightly less total storage. The wasted excess generation from one house may contribute to the shortfall of another, so effectively implementing grid-edge transfers within the microgrid.

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