LOW ENERGY COMMUNITIES: THE AUTOMATIC SIZING OF HYBRID RENEWABLE ENERGY SCHEMES AND THE GENERATION OF A SIMULATION INPUT MODEL FOR PERFORMANCE APPRAISAL

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ABSTRACT

Integrated building performance simulation (IBPS) provides an appropriate means to appraise the performance of low energy communities featuring cooperating technologies for demand management and low carbon heat/power delivery. Only by addressing such communities in a holistic and dynamic manner can the performance characteristics of the individual technologies be discerned and overall, well-found solutions established.

This paper addresses a major issue confronting the utilisation of IBPS in such a role: how to generate the initial input model in terms of the capacity levels of each technology that are likely to give an effective demand/supply match in practice. In the described work this is accomplished by using a search engine to locate the best quantitative match between demand (which could be represented by actual or anticipated data) and potential supply profiles and then using the outcome to synthesise an ESP-r model for use to ensure that the identified hybrid supply will perform well in practice. The approach outlined ensures that the final design to emerge is arrived at through a rational process as opposed to the refinement of some initial design hypothesis based on arbitrary sizing considerations.

INTRODUCTION

In response to government policies relating to energy utilisation and supply, attention is being directed to developing energy efficient, low carbon communities attained through the deployment of local supply technologies sized to best match local load profiles. To this end, IBPS is a potentially powerful tool for the assessment of proposed schemes. Specifically, IBPS can be used to assess if the deployment of low-carbon technologies will deliver the energy required, while also identifying detrimental impacts on conventional HVAC and electrical distribution systems.

To realise the potential of the approach, two significant barriers have yet to be overcome:

1. For a given community, existing or planned, a method is required to identify the mix of supply technologies (by type and capacity) that best match either the measured or anticipated demand profiles. Such a method equates to a rational sizing procedure for hybrid new and renewable energy supplies as opposed to the more constrained and often arbitrary selection of a technology mix based on exogenous factors such as roof area, net annual energy use or peak demand.
2. Once a best technology mix is located, a method is required to (semi-automatically) generate the required model for detailed simulation – typically comprising several hundred buildings with the selected supply technologies imposed. This model may then be used to appraise the feasibility of the embedded generation scheme in terms of relevant criteria such as indoor comfort, system controllability, heat and power quality, and carbon emissions. This step is required because it is unlikely that the profession would invest the effort to make one-off, detailed simulation models of whole communities.

This paper describes how these issues have been resolved by an approach based on two existing modelling tools when operated in co-operative mode: MERIT (2013) for demand/supply matching assessment and ESP-r (2013) for building simulation.

SIZING HYBRID SUPPLIES

A MERIT model will typically comprise several power profiles representing the heat and electricity demand over time of some target scheme (single building, community, city district *etc*.). A supply scenario is then established as a collection of technologies of interest (PV, wind turbine, CHP, heat pump, biomass, fuel cell *etc*.) and in terms of anticipated technology capacities arrived at on the basis of appropriate but external considerations. During the subsequent simulation all possible combinations of supply and demand profiles are assessed in terms of statistics that quantify the energy match. This process gives rise to a rank ordered list of best demand/supply profile combinations. For example, assuming a demand scenario comprising a heat and electricity profile and a supply scenario comprising 3 supply technologies, MERIT would undertake 21 combinatorial match assessments.

The problem with this procedure in the present context is that the capacity of each supply technology must be *a priori* defined by the user on the basis of exogenous considerations. The real need is to inform the user of the mix of technologies (by type and capacity) that best matches the demand without imposing arbitrary external factors – such as available roof area in the case of PV – which serve only to inappropriately constrain the solution space. This requirement has been met by implementing a 'chunking' procedure in MERIT as follows.

First, the user identifies the supply technologies of interest. Often this list will be speculative and might include technologies that are only of marginal interest. The starting point for the purposes of the case study described in this paper is that the demand profile is known. Where the community exists, this profile may well be available in the form of utility data. Where it corresponds to a new build, estimates of demand may be available from the design process. If no data are available it would be necessary to estimate the demand via an extended energy audit or modelling study (perhaps based on the semi-automated approach to estate model formulation as described in the next section). The important point is that the method commences with full knowledge of the community energy demands that are to be serviced via a hybrid supply system.

Second, MERIT sets the capacity of each technology to an initial value equal to or greater than that required to match the peak demand if that technology were deployed alone (and the renewable source was simultaneously available which is unlikely to occur in practice). Note that the final outcome is independent of these initial capacity value assignments.

Third, the capacity of each technology is 'chunked' as a function of the minimum feasible contribution. For example, 1 MW of wind might be represented as 11 turbines of cumulative capacity (50 kW, 150 kW, 250 kW, 350 kW, 450 kW, 550 kW, 650 kW, 750 kW, 850 kW, 950 kW and 1 MW) because the rated power will affect the Capacity Coefficient; while 1 MW of PV might be represented as 100 separate modules each of 10 kW because outputs are additive. The user has control of the chunk size, which will depend on the scale of the scheme being processed: as with the discretisation process applied within a numerical representation of a building, chunks size can vary as a function of the required accuracy. This initial search is designed to be as broad as possible with the subsequent simulation analysis used to establish the operational feasibility and efficacy of the best fit supply technology mixes.

Fourth, a demand/supply profile match assessment is undertaken but now involving substantially more combinations because of the virtual technologies relating to the chunking process. This results in a rank ordered set of matches arrived at on the basis of two criteria as follows.

- A Rank Correlation Coefficient (*RCC*; Scheaffer and McClave 1982) that describes the correlation between demand and supply by calculating the degree to which the profile variables fall on the same least square line:

$$RCC = \frac{\sum_{t=0}^{n}(D_t - d)(S_t - s)}{\sqrt{\sum_{t=0}^{n}(D_t - d)^2 \sum_{t=0}^{n}(S_t - s)^2}} \quad (1)$$

  where D_t is the demand at time t, S_t the supply at time t, d the mean demand over time period n and s the mean supply over time period n. *RCC* describes the trend between the time series of two data sets and does not consider the relative magnitudes of the individual variables. Thus, if a supply system were doubled in size *RCC* would remain the same even though the excess supply would be greater. Additionally, two profiles perfectly in phase with one another, but of very different magnitudes, would result in a perfect correlation, but not a perfect match.

  An *Inequality Coefficient* (IC; Williamson 1994) that describes the magnitude inequality due to three sources – unequal tendency (mean), unequal variation (variance) and imperfect co-variation (co-variance). *IC* ranges between 0 and 1, with 0 indicating a perfect match and 1 denoting no match.

$$IC = \frac{\sqrt{\frac{1}{n}\sum_{t=0}^{n}(D_t - S_t)^2}}{\sqrt{\frac{1}{n}\sum_{t=0}^{n}(D_t)^2} + \sqrt{\frac{1}{n}\sum_{t=0}^{n}(S_t)^2}} \quad (2)$$

- A Percentage match (*PM*) is then given by

$$PM = (1 - IC)100 \quad (3)$$

with *PM* indicates the overall match between demand and supply, ranging from excellent (90-100%) to very poor (0-10%).

The rank ordered matches to emerge from the process represent the hybrid system supplies that deliver the best quantitative match to the demand. However, the above criteria do not reflect the feasibility of the matches so identified. This requires that the user now tests the operational performance of schemes of interest based on heat and power usability considerations.

TESTING SCHEME FEASIBILITY

A scheme selected from the matching stage must be transformed to a model suitable for detailed simulation. In the present case the target program is ESP-r, requiring the explicit definition of multiple buildings – in terms of geometric, constructional, operational and environmental parameters – and multiple supply technologies – in terms of system layout, building interaction and control parameters. Whilst this ESP-r input model could be created in a conventional manner, with each building/system model explicitly defined, the scale of an embedded generation community scheme, perhaps comprising several hundred dwellings, will render this approach infeasible. To reduce the model creation workload, an alternative approach based on pre-existing prototype models was established. These prototype models represent all conceivable dwelling configurations, now and in future, within a national housing stock, thus allowing the ESP-r input model for a community to be generated semi-automatically. Because the approach to prototype model formulation is detailed elsewhere (Clarke and Samuel 2011), only a summary is included here. Note that the approach has not yet been extended to non-domestic application.

Within the approach it is assumed that the energy performance of a given dwelling is a function of a finite number of principal parameters: exposure, insulation level, air tightness, thermal capacity location, solar ingress level, occupancy level, and living area fraction. A housing stock is then decomposed to distinct prototypes on the basis of discrete levels of each parameter with the number of levels per parameter set to capture the range likely to be experienced in practice. Application of the approach to the Scottish Housing Stock for example resulted in 18,750 prototypes corresponding to 5 levels for each of the parameters indicated above with the exception of solar ingress, which had 3 parameters, and thermal capacity position, which had 2.

An ESP-r estate model can therefore be formed by combining prototype models selected on the basis of the descriptive parameters related to the targeted community – age of dwellings, construction types *etc*. To this model is added the supply technologies identified from the demand/supply matching state, and electricity/heat flow network models to connect technology outputs to dwelling loads. A model calibration exercise is then carried out to ensure that model outputs are aligned with the initial demand profile of the community. Note that this estate model could have been formed at the beginning of the appraisal process to determine the demand profile of the community prior to the matching process. In this case the calibration exercise is not required.

In this way, a simulation input model is semi-automatically synthesised by selecting from a large database of pre-formed models which represent a national housing stock and all possible retrofits to an adequate level of resolution as determined from comparison with data contained in national house condition surveys. While this model could of course be replaced by a user generated model, this is exactly what the reported method is trying to avoid because of the complexities then introduced associated with the vastly increased size of the problem domain.

EXAMPLE APPLICATION

The above two-part procedure is now demonstrated through application to a real case: a community at Upton in Northampton, UK (Figure 1). The objective here is to size a hybrid renewable energy supply system to serve existing demands.

The site, originally farming land, was acquired by Northampton Development Corporation before passing to the Commission for New Towns in 1985. It is now under the control of *English Partnerships*, a national regeneration agency. The development is regarded as one of the best examples of sustainable design due to the commitment of the partners involved and one of the first applications of the Enquiry-by-Design method (EST 2006) for master planning. Based to its size and structure it is considered a model for future sustainable community development in the UK.

The presented case study focuses on Site A, a developed residential neighbourhood occupying a total area of 3.7 hectares and accommodating 214 dwellings subdivided into 110 semi-detached houses (1 2-bed, 13 3-bed, 88 4-bed, 7 5-bed, 1 6-bed) and 104 flats (14 1-bed, 83 2-bed, 7 3-bed).

The total measured annual electricity and heating energy demand of the site is 817,187 kWh and 3,106,098 kWh respectively, with corresponding peak demands of 311 kW and 1,278 kW. The detailed hourly electricity and heating profiles for a winter week are as shown in Figure 2.

The low carbon supply technologies considered here to meet the existing demand are PV and wind turbines for electricity, and solar thermal and heat pumps for heating. According to the chunking procedure described previously, different supply technologies are treated differently. Considering electricity as an example, the PV was chunked into 700 x 500 W capacity units, while wind power was chunked into multiple turbines of increasing capacity: 10 kW, 30 kW, 50 kW… 290 kW, 310 kW and 330 kW. Because of the chunking process, the number of supply/demand permutations to be searched by MERIT was 131,771 cases.

Figure 3 depicts the top two rated matches for electricity resulting from the MERIT search, while Table 1 summarises the match statistics and required hybrid capacities for both cases.

At this stage, and as described above, an ESP-r estate model is constructed by selecting prototype models based on available information about the dwellings comprising the targeted community. To this is added the hybrid supply model represented in terms of individual technology models and heat/electrical network models to connect these technologies to the loads.

Within ESP-r heat network models are typically used to represent HVAC systems within individual buildings. The approach can also be extended to the modelling of community heating. Similarly, an ESP-r electrical model can be used to analyse the performance of electrical networks of varying scales and levels of complexity: from distribution inside a building to micro grids.

Two options exist for the creation of this supply model: as a community scheme by which the supply is connected to aggregate load profiles, or as a building-integrated scheme by which the hybrid supply is apportioned to individual dwellings. Here the ESP-r network model represents the low voltage distribution system associated with the estate and is used to analyse the network impacts of the building-integrated electrical supply technologies. The network consists of a series of supply cables, each of which accommodates approximately 50 dwellings connected radially to a local supply substation, which is the boundary of the analysed system.

The following discussion considers an individual dwelling selected from the multi-dwelling community model: a 2002 standard dwelling with 140 m^2 of floor area. Attributing this dwelling with a portion of the generation suggested by the MERIT match results in a 6.6 m^2 PV (0.5 kW_e capacity) installation and a 1 m diameter wind turbine (1.3 kW_e capacity). Of interest here is the potential impact of this level of microgeneration on the local electrical supply: specifically local voltage levels.

The voltage at the substation has a mean value of 230 V but which is subject to random perturbation (with normal distribution about the mean and a standard deviation of 1.9 V); these values were derived from monitored low voltage network data (Thomson and Infield 2007). The random substation voltage variation represents the influence of the wider electricity system on the local network.

Table 1: Match statistics and resulting hybrid supply capacities.

	MATCH STATISTICS	
	Match 1	Match 2
RCC	0.07	0.07
IC	0.34	0.37
PM	65.7	63.4
Solar PV capacity (kW)	100	50
Wind turbine capacity (kW)	350	300

Figure 4 illustrates the net electrical power flows associated with the selected dwelling over a week in spring. The negative values shown in the graph indicate that electrical power is exported to the local network from PV and wind turbine (supply > demand), positive values indicate that the building draws from the network (demand < supply). Also shown is the local network voltage, which is taken from the electrical systems model; this is heavily influenced by the performance of the dwellings' local generation and its demand. As the demand increases, the local voltage drops below the nominal network supply voltage of 230 V. Conversely, as the supply from the local generation increases, the voltage rises.

Figure 5 shows the variation in the local network voltage level plotted against the calculated power exchange between the dwelling and the local electricity grid over the simulated week. Superimposed on the graph are the voltage constraints for electricity supply in the UK (230 V +10%/-6%); the results demonstrate that with the suggested MERIT generation scheme the voltage excursions are relatively minor and the supply voltage stays within limits: in terms of power quality, the suggested technology mix is feasible and does not result in any specific problems.

Whilst the detailed analysis described here produced a positive outcome, affirming the feasibility of the MERIT match, this may not be the case for all possible local generation schemes. Figure 6 shows the voltage variation with power import and export for an alternative suggested match comprising a PV-only scheme featuring an array of some 30 roof-mounted panels with a capacity of approximately 3 kWe. The graph shows that in this case the upper voltage constraints for the dwelling are frequently breached (this would also be true for the other dwellings in the estate connected to that branch of the low voltage network).

This example has considered PV and small scale wind and their effect on the electrical system, specifically looking at a single building within an estate. However, where appropriate, other electrical metrics may be considered, for example at the larger scale phase balancing and cable overloading may be an issue. Further, the detailed modelling approach can be applied to assess other technologies and actions such as heat pumps (Hong *et al* 2013) and thermal load shifting where thermal performance is key, requiring that a different set of supply metrics be used such as the impact availability of hot water temperatures and ability to provide thermal comfort.

CONCLUSIONS

This paper has outlined a procedure to automatically size hybrid energy supply solutions at the community level. The approach is based on a search engine that processes all possible combinations of demand and supply profiles after the latter have been quantised. The feasibility of identified schemes may then be tested by simulation on the basis of an input model formed from pre-established prototypes. The approach was elaborated via an example application.

The approach demonstrated here, which balances the quantitative and qualitative aspects of demand/supply matching, illustrates that detailed simulation can highlight potential operational problems from local generation schemes emerging from MERIT supply sizing studies.

REFERENCES

Clarke J A (2001) 'Domain integration in building simulation', *Energy and Buildings*, V33(4), pp303-8.

Clarke J and Samuel A (2011). 'Housing upgrades policy development', *Proc. eSim 2011*, Halifax, Canada.

BRE (2009) *Standard Assessment Procedure for Energy Rating of Dwellings*. Building Research Establishment Publication.

EST (2006) 'Creating a sustainable urban extension - a case study of Upton, Northampton', *Energy Saving Trust Report*.

ESP-r (2013) www.strath.ac.uk?Programs/ESP-r.htm (viewed February 2013).

Hong J, Kelly N J, Thomson M and Richardson I (2013) 'Assessing heat pumps as flexible load', *J. Power and Energy*, 227(1), pp1-13.

Kotsiantis S and Kanellopoulos D (2006). 'Discretization Techniques: A recent survey', *International Transactions on Computer Science and Engineering*, 3 (1), pp.47-58.

MERIT (2013) 'User information', www.strath.ac.uk/Programs/Merit.htm (Viewed February 2013).

Thomson M and Infield D (2007) 'Impact of widespread photovoltaics generation on distribution systems', *J. Renewable Power Generation*, (1), pp33-40.

Williamson T J (1994) 'A confirmation technique for thermal performance simulation models', University of Adelaide.

Figure 1. The Upton low carbon community development.

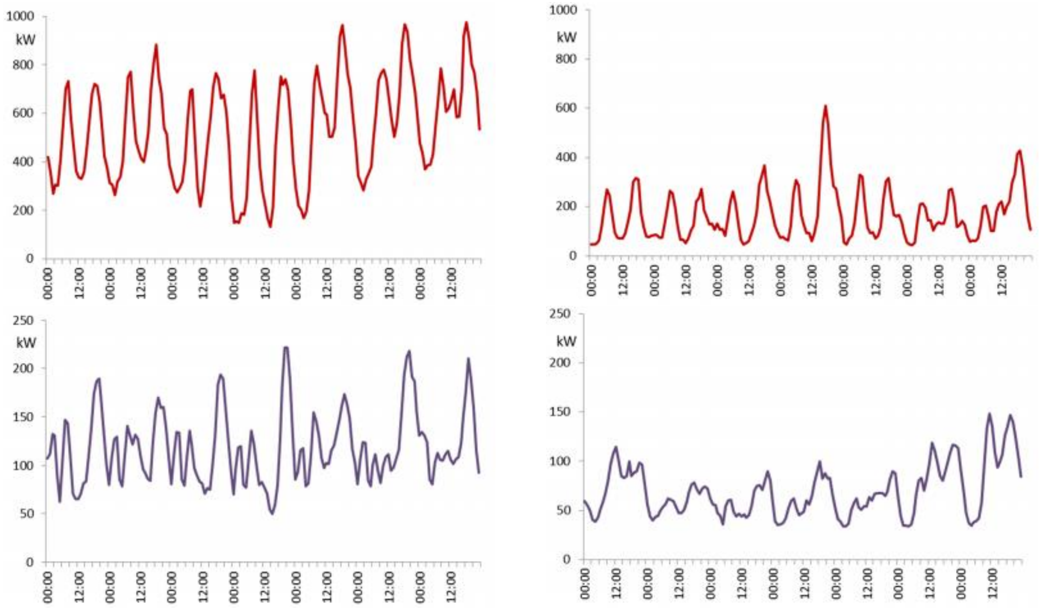

Figure 2: Upton Park Estate Demand profiles for heating (top) and electricity (bottom), for January (left) and June (right) weeks respectively.

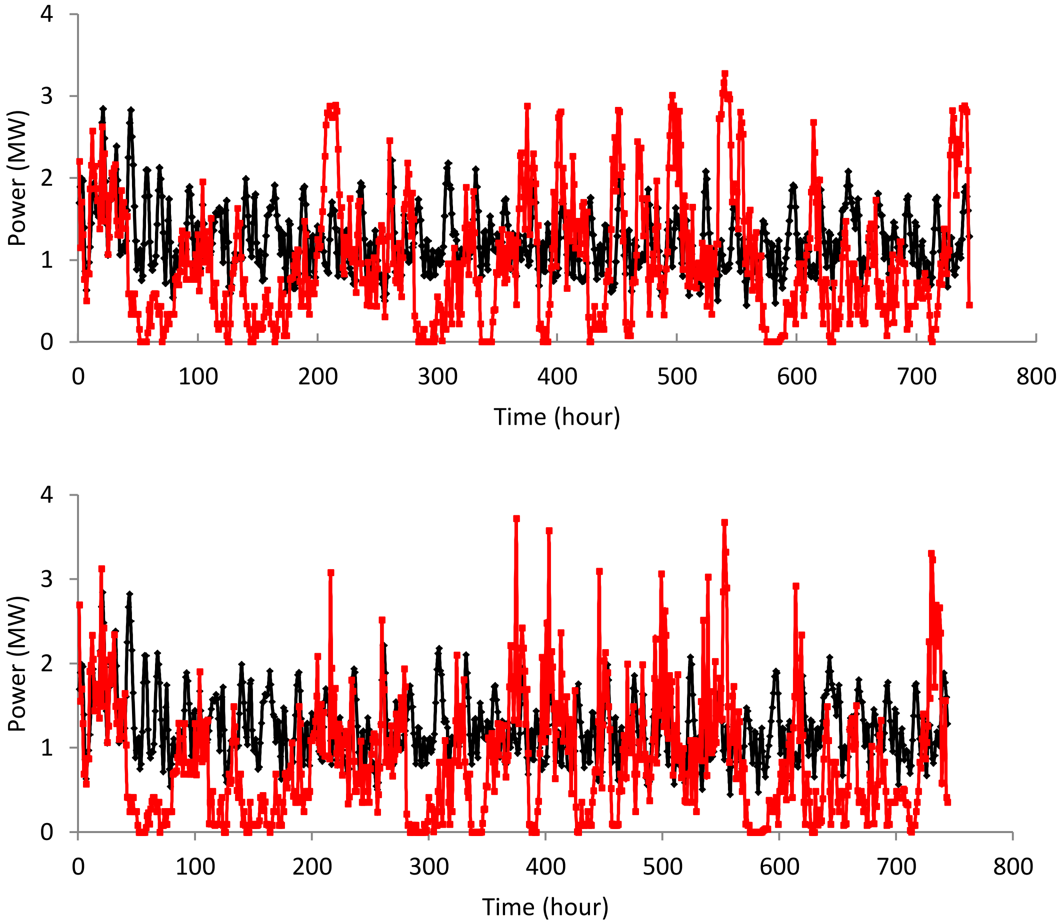

Figure 3: Top 2 matches from the chunking process over a one month period.

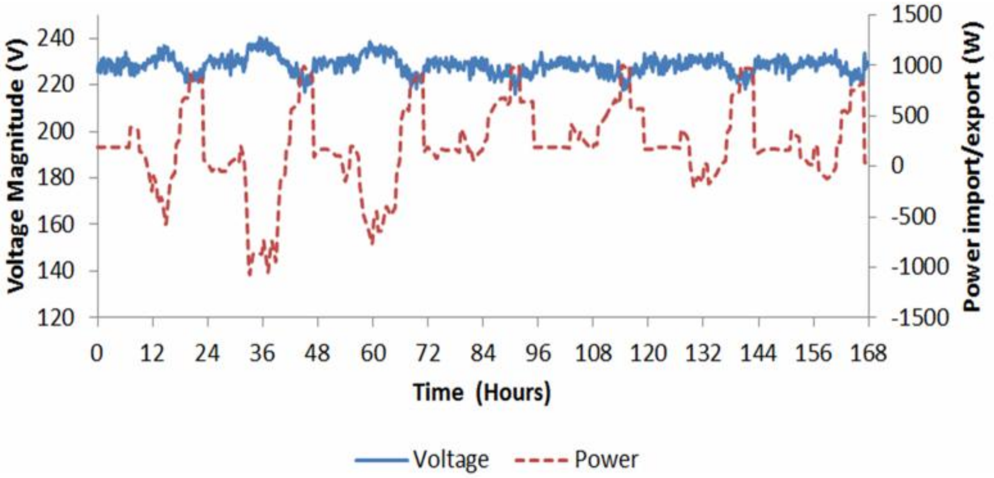

Figure 4: Voltage levels and power import/export for dwelling with hybrid supply.

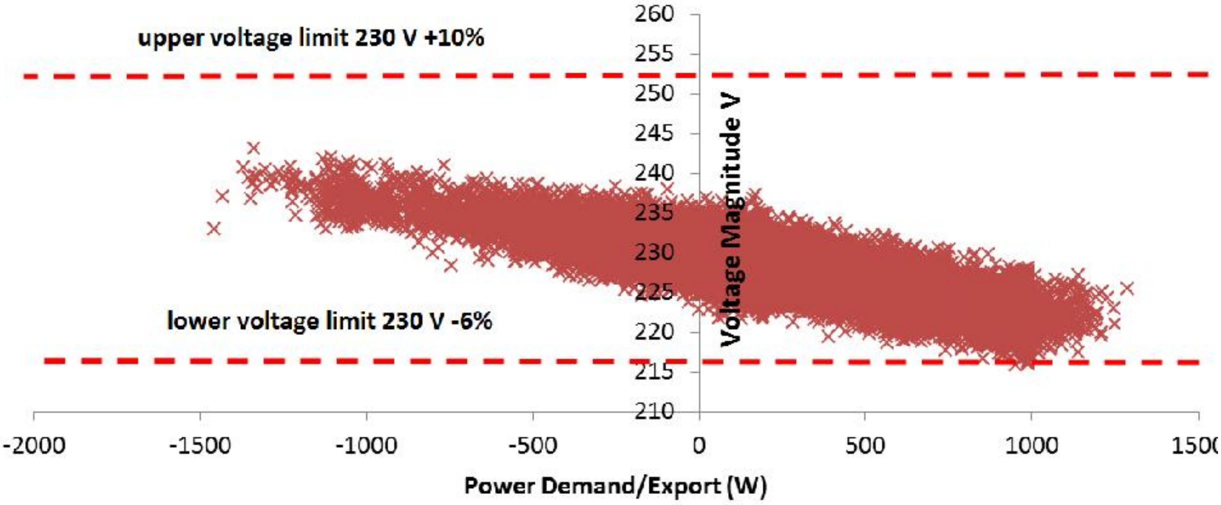

Figure 5: Voltage variation against power import and export (MERIT-sized system).

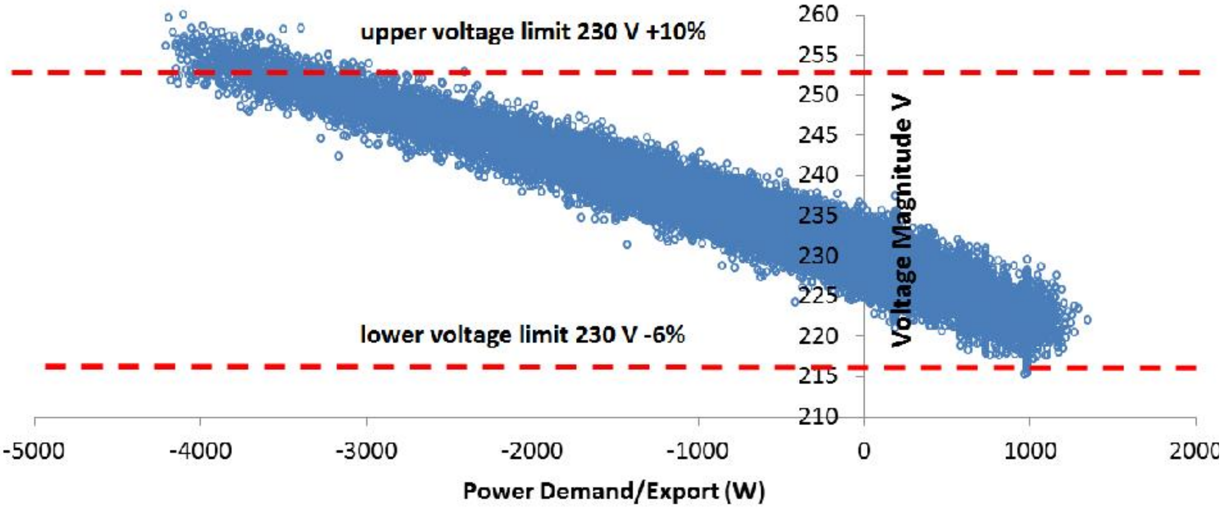

Figure 6: Voltage variation against power import/export (PV system covers electrical net demand).