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A SIMPLE MODEL OF DOMESTIC PV SYSTEMS AND THEIR INTEGRATION WITH BUILDING LOADS

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ABSTRACT

Photovoltaic systems can reduce the CO₂ emissions associated with the consumption of electricity in dwellings. One key issue that affects both the economic case for home installation and the integration with the mains electricity grid is the match between the instantaneous production and demand for power. This initial study considers a sample of 10 dwellings which were monitored under the UK Government's Photovoltaic Domestic Field Trial. A simple PV system model is introduced and used to examine the variations in the balance between the imported and exported electricity of the monitored households. There are cases where a large proportion of the electricity generated by a PV system is used directly by the household and instead is exported to the mains electricity grid. The possibility of using the model to explore the effects of PV system size on the import and export balance, and the benefits of sharing production and consumption between nearby dwellings, is discussed.

INTRODUCTION

This paper presents the initial findings of a study investigating the integration of solar photovoltaic (PV) systems on domestic buildings in the UK. Of particular interest is the relationship between the amount of electricity generated by the PV system, the amount of PV generated electricity which is used directly by the building and the amount of PV generated electricity which is exported to the main electricity grid. This work is based on fine-grained monitoring data from 10 domestic PV systems.

Grid-connected PV systems installed on buildings can supply electricity directly to the electrical appliances within the building or export electricity to the mains electricity grid (Figure 1). Export of electricity only occurs when the supply of PV generated electrical power is greater than the power demand of the building's electrical loads. This situation can often arise around midday in dwellings when the PV generation is high, as the available solar energy is highest in the middle of day, and the dwellings electricity consumption is low as the occupants may be, for example, out at work. PV generated electricity which is supplied directly to the building loads (termed 'direct-use') reduces the need

to import energy from the mains electricity grid and therefore reduces the electricity bill of the building owner. Exported PV electricity does not reduce the electricity bills but can be sold to the mains grid operator for an agreed price. Domestic PV systems therefore offer two different financial incentives; offsetting electricity bills and sale of exported electricity. It is essential to be able to estimate the expected proportions of these two incentives when studying the economics of proposed PV system installations.

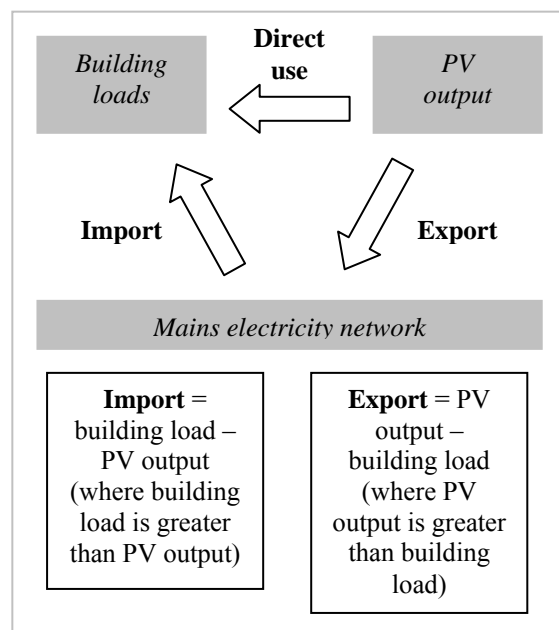


Figure 1: Electricity flows in a grid-connected building-integrated PV system

The mains electricity grid was originally designed as a distributor of electricity from large centralised power stations to distributed consumers. The addition of small-scale power generation systems on the mains grid (such as grid-connected solar PV systems) may have some adverse effects on the grid, such as fluctuation in voltage levels. In particular, if PV systems are installed in large quantities on the UK mains grid, this may lead to difficulties in load matching.

Theoretical models of the electricity generated by PV systems are available and are used by the PV community to predict electricity generation for proposed installations (for example PVSYST, 2009). These models will make estimates for any shading that is present at the site, and will allow the designer to test the effect of different components and positions of a PV system. The physical principles of the sunlight to energy conversion process, together with the expected energy losses within the PV systems, are used in these models. An alternative approach is taken in this work based on an empirical model developed using measurements of installed PV systems. This simple model has the advantage that it is easy to understand and to use, and implicit in the results are the energy losses that occur in installed PV systems under actual operating conditions. The model is based on the relationship of solar irradiance to overall system efficiency and provides a straightforward method of simulating PV electricity generation data, for different sizes of PV systems, from solar irradiance data.

Modelling the electrical demand from households is a more challenging task and there are many determining factors including: the number of appliances in a home; the electrical power used by each appliance; and the amount of use of appliances determined by the behaviour of the occupants in the home. This is more complex to model task than, say, space heating demand where a single energy consuming device (the boiler) and a single control strategy (the boiler controls) are in use. Available electricity demand models include BREDEM-8 which makes predictions for household electricity consumption at the monthly level based on empirical relationships (Anderson et al., 2002). This approach gives the average electricity use for a given house and does not represent the potential variation in demand, which may be significant depending on the occupants use of appliances. Stokes (2005) developed an electricity demand model based on one-minute intervals for houses using a probabilistic approach to trigger appliance-usage events. This model was intended to simulate large numbers of buildings over a city-wide scale. Richardson et al. (2008) have developed a probabilistic model to determine the occupancy patterns within a building, with the aim of using these to produce electricity use patterns. All of these models are based on field studies of electricity consumption in housing and their results are influenced by the sample size and characteristics of the households which the data originated from.

Current standard building simulation models are largely focussed on the thermal energy flow within the building and do not attempt to dynamically model the electricity consumption. In these models the appliances within the modelled building are listed individually and the profile of use of each appliance has to be explicitly given by the programme user.

This creates an estimate of electricity use but without any of the variation which will always occur in real buildings due to the hard-to-predict behaviour of the occupants.

This paper presents an initial exploration of the dynamic use of electricity in UK homes and the effects of grid-connected PV systems on the building electricity flows. The work is based on a monitoring study of 10 dwellings, sampling whole-house electricity consumption at five-minute intervals, over a two-year period. The results from two sample months (30 days considered for each), January 2008 and June 2008, are discussed in this paper. A simple model of PV system performance is then used to simulate the electricity generation of a grid-connected domestic PV system situated at the same location as the monitored households. The simulated electricity generation data is matched with the electricity use measurements of each dwelling to determine the effect on the import and export of electricity from the dwellings. As the same PV generation data is used for each dwelling, any variation in the import and export characteristics is caused by differences in electricity use across the dwellings.

DATA COLLECTION AND PROCESSING

Description of study households

The dwellings were located in the South-West of the UK and were two-storey social housing units, constructed in 2004 each with a grid-connected PV system installed at the time of construction. The PV systems were funded by the UK Government's Photovoltaic Domestic Field Trial (DFT). The DFT funded around 500 domestic PV system installations in the UK between 2002 and 2004 and each system was monitored for a two-year period. The authors have gathered data from around 100 DFT PV systems at six UK sites and present a proportion of this dataset in this work. Previous work using this dataset includes an investigation of the trends in appliance usage of the households (Firth et al., 2008).

Description of monitoring systems

Each dwellings had eight parameters measured, averaged and recorded over at five-minutely intervals for a two-year monitoring period:

- Horizontal solar irradiance (W/m^2)
- In-plane solar irradiance (W/m^2)
- Ambient air temperature ($^{\circ}\text{C}$)
- PV module temperature ($^{\circ}\text{C}$)
- DC electrical power from the PV array (W)
- AC electrical power from the inverter (W)
- Imported electrical power from mains grid (W)
- Exported electrical power to the mains grid (W)

Solar irradiance was measured by reference PV cells and temperatures with sensors using PT100 platinum temperature sensing resistors. The DC and AC electricity generation of the PV system were measured by sensors in the PV inverter and the electrical flows to and from the house by additional electricity meters. All the data was recorded by on-site data loggers with modems connected to the public telephone network. The recorded data was then downloaded on a regular basis to a central PC.

Data processing

The monitored data was downloaded as a series of Excel workbook files. This raw data was cleaned and pre-processed using Excel VBA scripts to automate the process. Negative values and error values were removed from the datasets. Missing data was identified and estimated values substituted in its place (this comprised less than 0.05% of data set in this work). Matlab was used for the analysis of the datasets and to generate the plots. Household use of electricity was not directly measured and so is calculated at each five-minute interval using the following equation:

$$P_{EU} = P_{PV-AC} + P_{IMPORT} - P_{EXPORT}, \quad (1)$$

where P_{EU} is the electrical power used in the dwelling (W); P_{PV-AC} is the AC electrical power generated by the PV system (W); P_{IMPORT} and P_{EXPORT} are the electrical power imported from and exported to the mains grid respectively (W).

ANALYSIS OF BUILDING LOADS

The whole-house electricity use is plotted for two example dwellings in Figure 2 for one day out of each month considered in this study: June 1st 2008 (Summer, on the left) and January 1st 2008 (Winter, on the right). Two houses for each of these days give an appreciation of the variation in the demand characteristics between the households: House 1 in the upper plots has a representative ‘low’ demand and House 9 in the lower plots has a fairly high consumption by comparison. On each of the plots two vertical dotted lines indicate the times of 08:00 and 22:00 to reference typical activity hours of ‘morning’/‘breakfast’ time and ‘late evening’/‘bed’ time.

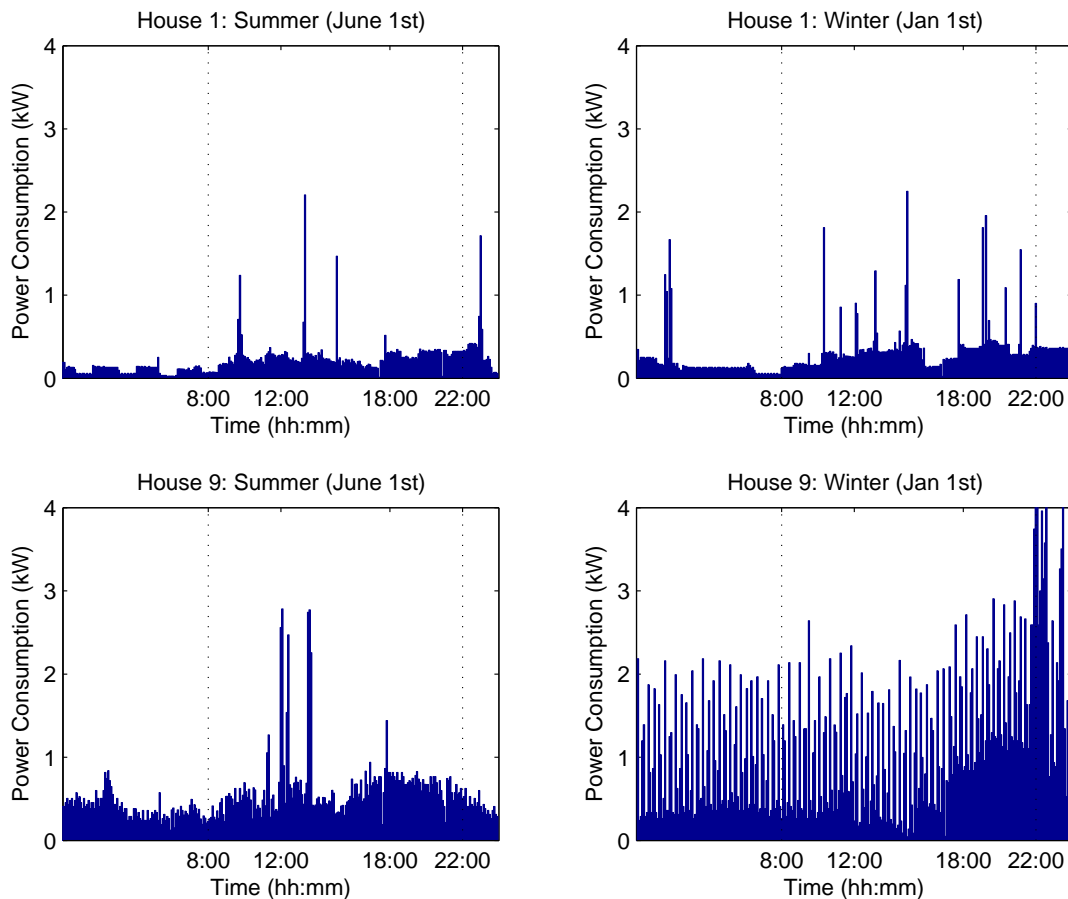


Figure 2: Depicts the power consumption a summer and a winter day for two of the houses monitored, selected to demonstrate the diversity in demand and demand profile

In Figure 2 the refrigerator cycling is clearly visible during the summer night time period in House 1. There are a number of high peak loads throughout the day which could be caused by kettles, electric showers and other high power appliances. Establishing the detailed appliance activity would be required to fully describe these characteristics and requires further investigation. Regardless of reason however, the household load profiles are vary considerably as do the total consumption. Table 1 gives the total monthly consumption per household for each dwelling studied for both winter and summer months. In each case the winter electricity consumption is higher than the summer consumption and the percentage increase varies across the dwellings from 12% (House 4) to 140% (House 9) The observed changes in electrical usage are in part likely due to the winter period requiring more lighting but also indicate large variations in changes in behaviour which requires more appliance usage. This could be a greater use of 'entertainment' appliances (such as TVs, video games, computers etc.) as the occupants spend more of their time indoors in winter.

Table 1: Total monthly consumption data for the summer (June 2008) and winter (January 2008) monitoring periods.

House	Total monthly electricity consumption (kWh)		% increase (summer to winter)
	Summer	Winter	
1	160	193	21
2	186	315	69
3	291	449	54
4	187	210	12
5	306	385	26
6	133	182	37
7	265	414	56
8	374	681	82
9	414	992	140
10	230	326	42

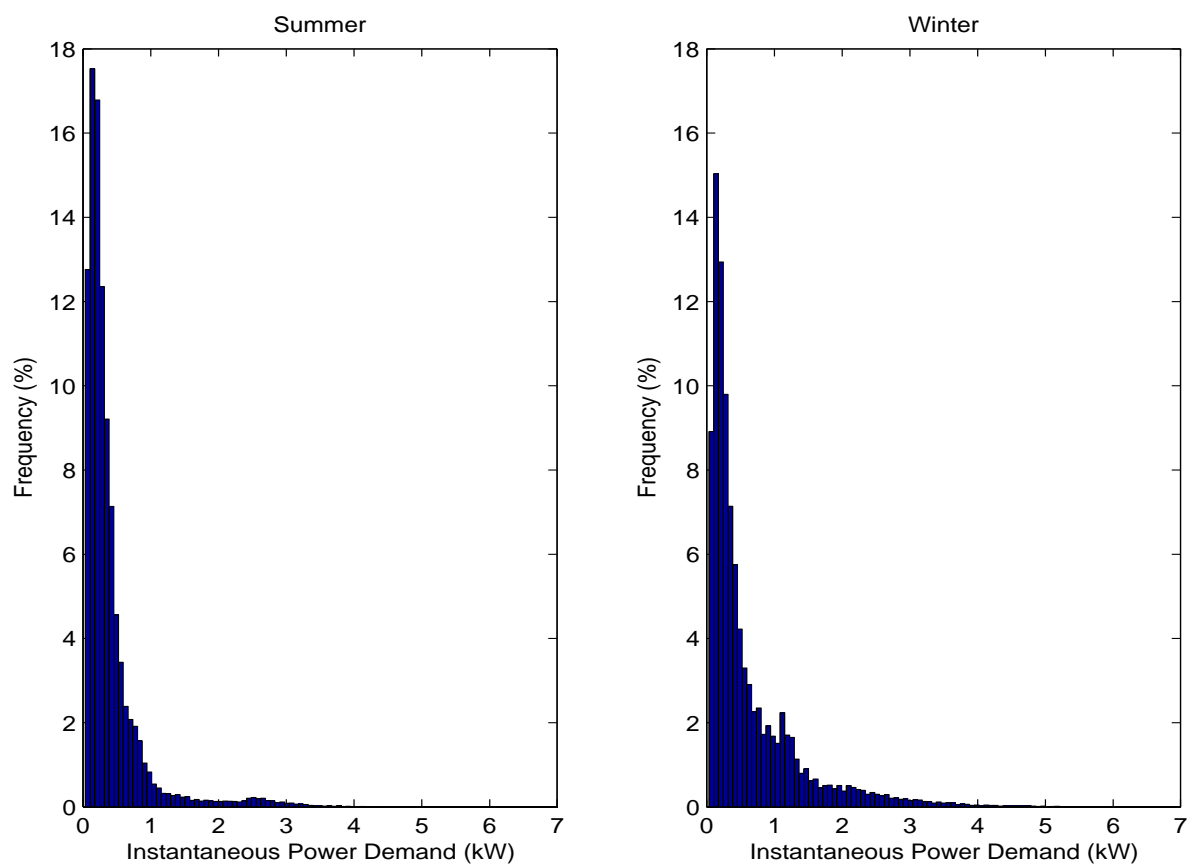


Figure 3: Frequency distribution of five-minutely electrical power for all 10 dwellings for Summer (June 2008) and Winter (January 2008), using bins of approximately 80W

Figure 3 shows the frequency distribution of the monitored five-minutely electrical power loads for all dwellings in June 2008 and January 2008. The frequency of the load occurrence is plotted in bins of approximately 80W. The maximum recorded load was 6.7kW occurring once in summer, although this is not clearly visible on the plot. Most of the demand is low: around 67% of the demand is less than 500 W in summer. In winter there is a greater occurrence of higher loads and around 55% of demand is less than 500 W. There is a slight rise in the summer demand occurrence around 2500 W region and in the winter demand occurrence around the 1200 W region. The explanation for this is unclear but it represents repeated use of high power appliances.

THE PV SYSTEM MODEL

The simulated PV system generation data is generated using a simple empirical technique which has been described previously (Firth et al., 2005). The PV system model is based on five-minutely data recorded for a 1.44 kWp, 11.7 m² grid-connected PV system with 12 Astropower 120Wp PV modules and a 1100W SMA inverter. For each five-minutely recording interval the overall PV system efficiency is calculated as:

$$\eta_S = \frac{E_{AC}}{G_i \times A} \quad (2)$$

where η_S is the five minutely PV system efficiency; E_{AC} is the electrical energy output from the inverter recorded over a five minute period (Wh); G_i is the in-plane solar irradiation received on an unshaded surface of the same location, orientation and tilt as the PV array over a five minute period (Wh/m²); and A is the area of the PV array (m²)

Figure 4 shows the relationship between the five-minutely in-plane solar irradiance and the five-minutely calculated system efficiency values for the PV system when operating well. Only solar irradiances above 50 W/m² are shown on the figure and occurrences of low system efficiencies due to faults have been excluded (see Firth, 2006 for further details). A boomerang-shaped cloud of points is formed by the system efficiency values. At solar irradiances above around 300 W/m² the system efficiency forms a constant band of values between 0.07 and 0.10. As irradiance increases the upper boundary of this efficiency band decreases, from around 0.10 to 0.08, due to energy losses caused by high temperatures at high solar irradiances. At low solar irradiances below 300 W/m² the system efficiency falls rapidly to zero.

The measured system efficiency values are used to generate a ‘system efficiency curve’ which forms the basis of the empirical model of PV operation. The solar irradiance values are separated into a number of variable-width bins. The first bin starts

at 50 W/m² and each bin is sized to contain 300 values. This means that at low irradiance the irradiance bins are narrow and occur close together (as there is a high number of low irradiance values) and the bins here can track the rapidly changing system efficiency values. At high irradiance, the irradiance bins are wider and more spaced apart as there are fewer occurrence of high irradiance values. In total 114 irradiance bins were generated for the measured data in Figure 4.

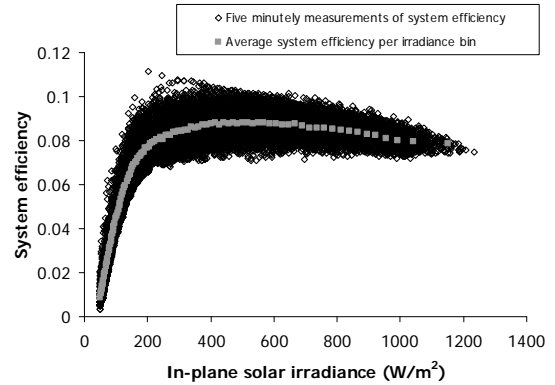


Figure 4: Five minutely solar irradiance against system efficiency measurements and the system efficiency curve of average efficiency per irradiance bin

Within each irradiance bin a normal distribution curve is fitted to the frequency distribution of system efficiency values. This provides an expected mean value and upper and lower boundary of system efficiency within each irradiance bin. The mean values for each irradiance bin are shown as the grey points in Figure 4. These mean system efficiency values form the system efficiency curve for the system and represents the solar irradiance to system efficiency relationship for a well-operating PV system. The simple PV model used in this paper is based on the system efficiency curve. To simulate the output of a PV system, using a solar irradiance dataset and a defined PV array area, Equation 2 is rearranged as:

$$E_{AC,S} = G_i \times A \times \eta_{SEC} \quad (3)$$

where $E_{AC,S}$ is the simulated electrical energy output from the inverter at time intervals τ (Wh); G_i is the in-plane solar irradiation recorded at time interval τ (Wh/m²); and η_{SEC} is the system efficiency at irradiance G_i as given by the system efficiency curve shown in Figure 4.

Using five-minutely solar irradiance data recorded at the site of the 10 monitored households, the PV model is used to generate five-minutely PV electricity output for a 10 m² PV system for the summer and winter months presented in the previous section. This represents the simulated

output of a 10 m² PV system and is used to simulate the same PV system being installed on each of the monitored households. The simulated PV generation output for 3 sample days in both summer and winter are shown in Figure 5. In summer the days are longer and the PV system generates from around 06:00 to 20:00 with a peak in output around midday. The maximum output in summer is around 800 W. The modelled PV output power is variable and there are many fluctuations between high and low power outputs. These will match the fluctuations in the solar irradiance and represent the effects of clouds obscuring the direct solar irradiance throughout the day. As the simulated data is based on the system efficiency curve of a well-operating PV system, these fluctuation in power output are not the result of faults. In winter the PV output power is much

reduced, with a maximum peak of around 300 W for the sample days shown in Figure 5. The period of PV power output is also reduced, from around 09:00 to 17:00, as the days are shorter in winter.

Figure 6 shows the frequency distribution of the simulated PV output power for summer and winter. Values of zero PV power output, which occur during the night time, are excluded from these plots. During the summer, 45% of PV power output is zero and this rises to 82% in winter, due to the shorter day lengths that occur during winter. In summer there is a fairly even distribution of PV power output up to around 750 W. In winter the PV power output is significantly reduced with low power generation at much lower frequency than summer.

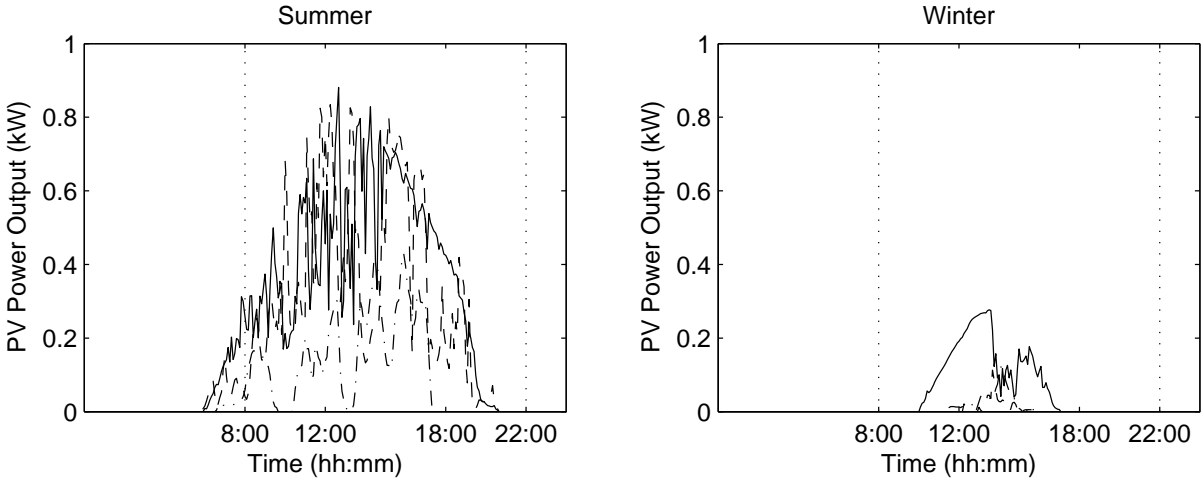


Figure 5: Examples of the simulated PV power generation of a 10m² PV system against time of day for 3 days in summer left, and 3 days in winter, right. The 1st, 15th, and 30th day of each month are plotted.

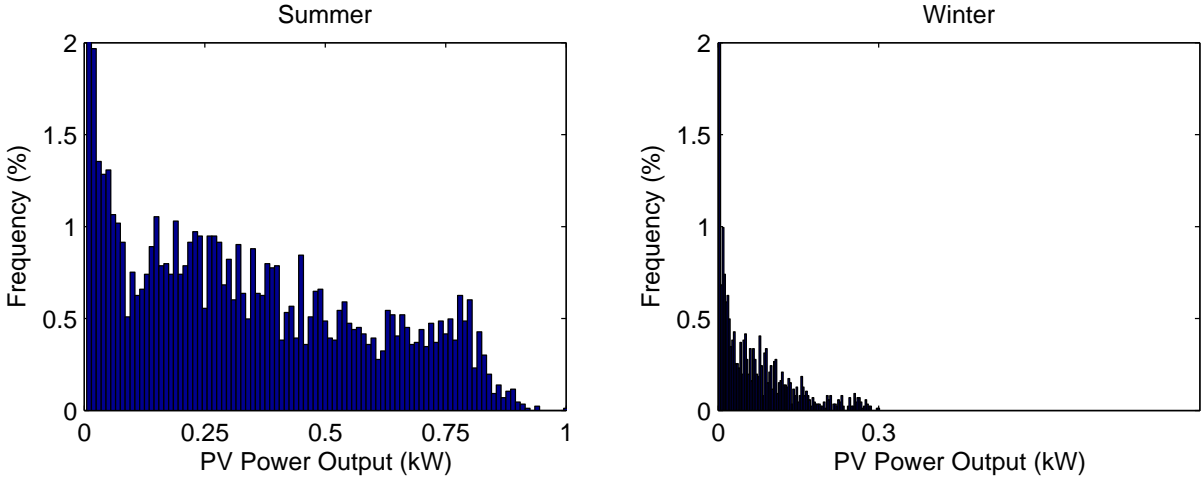


Figure 6: Frequency histograms of the simulated PV power generation of a 10m² PV system for summer, left and winter, right. Zero PV power output are excluded in these plots.

SUPPLY / DEMAND ANALYSIS

The examples of household electricity demand (Figure 2) and PV electrical power generation (Figure 5) show the PV power is not always generated at the exact moment it is needed by the household. If there is an excess of PV generation then the proportion not used directly by the household is exported to the mains electricity grid. The amount of export and direct use of PV generated electrical energy is calculated for each five-minutely interval as:

$$E_{EXPORT} = E_{AC,S} - E_{EU} \quad (4)$$

$$E_{DIRECT_USE} = E_{AC,S} - E_{EXPORT} \quad (5)$$

where E_{EXPORT} is the electrical energy exported from the dwelling (Wh); E_{DIRECT_USE} is the electrical energy generated by the PV system used directly by the dwelling (Wh); $E_{AC,S}$ is the simulated PV electrical AC energy output (Wh); and E_{EU} is the electrical energy used by the dwelling (Wh).

Figure 7 shows the monthly direct use and export against the monthly household electricity consumption for each of the monitored households for the summer and winter period. In each case, the sum of the monthly direct use and export will equal the total PV electricity generated in the month (which is the same for each household as the same simulated PV generation data is used). In summer the households with high monthly electricity consumption export a lower amount of PV generated electricity, as they are using more of the PV generation directly. The households with low monthly electricity consumption have higher monthly export as the PV generation exceeds the household electrical demand in these dwellings. If there is a financial penalty for the export of electricity (for example if a lower price is paid for the sale of export electricity than the purchasing of imported electricity) then the higher consuming households benefit most as they export less and use the PV output directly to offset electricity imported from the mains grid.

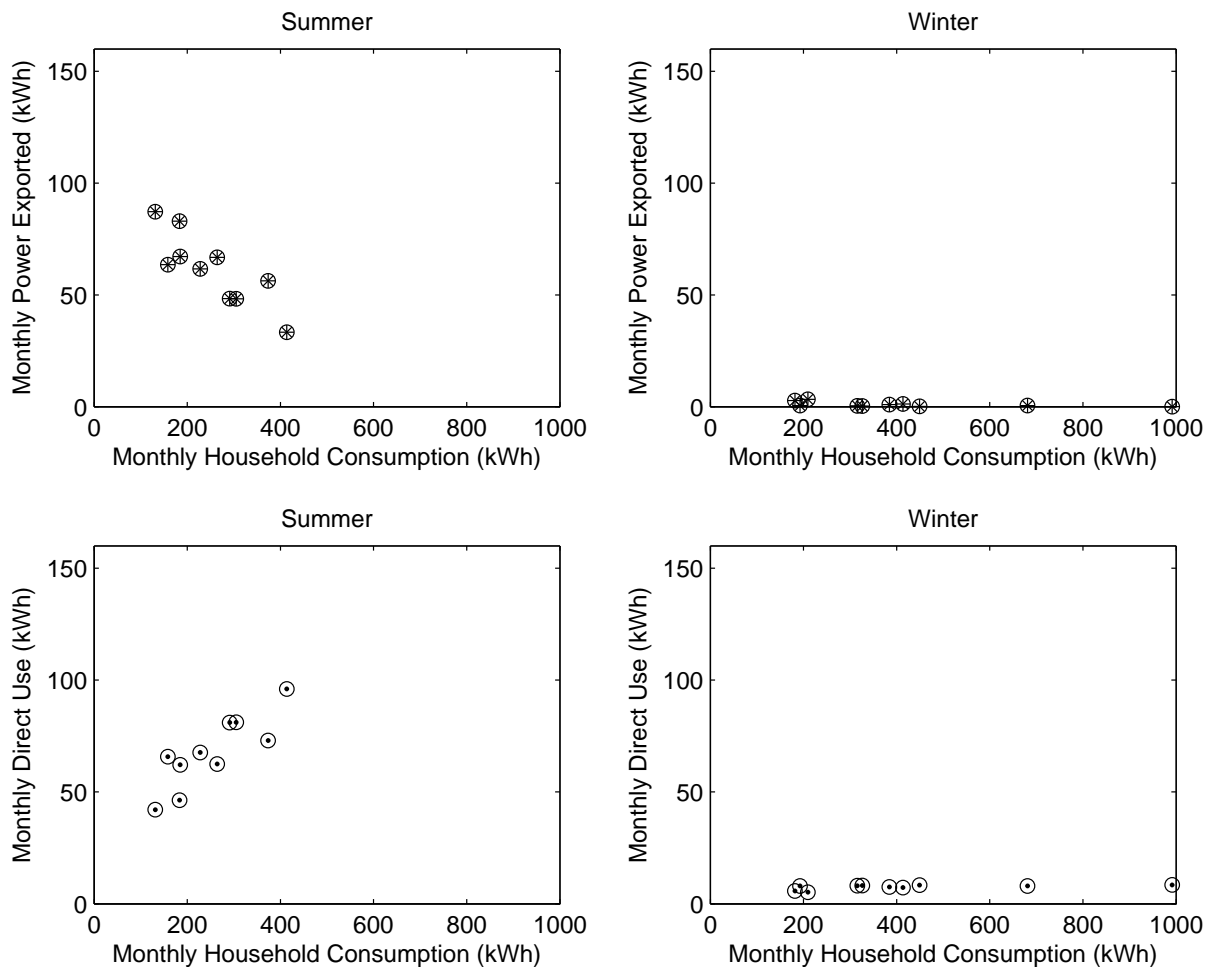


Figure 7: Summer (June 2008) and winter (January 2008) monthly direct use and monthly export against monthly household consumption for the 10 monitored dwellings

In winter the PV output is significantly reduced and almost all of the generated electricity is used directly by the households. This avoids the export of electricity and potentially selling this export at a low price. However the PV output in winter is very small compared to the total electricity consumption of the dwellings and therefore the PV system is only making a minimal contribution to offsetting the electricity requirements of the dwellings.

The effects of occupant behaviour of appliance usage can be observed in the summer plots of Figure 7. For example, there are several households with a monthly consumption around 200 kWh. Some of these households use less than 50 kWh of the PV output directly, whilst other use around 70 kWh. The households with higher direct use are using their electricity at times which better suits the PV generation, and therefore export less PV electricity to the mains grid. Further investigation of this issue could lead to standard advice to the householders to adapt their behaviour to improve the direct use of PV generated electricity.

The PV model could be used to simulate different sizes of PV systems. A larger PV system will generate a larger contribution of a household electricity demand, although the proportion of export may also increase. Different households with different consumption will suit different sizes of PV systems and the optimum match will also depend on the electricity tariff and the price paid for exported electricity. The exported electricity may be used by neighbouring dwellings and an area of further work is to investigate, for communities of dwellings, then smoothing of the overall electrical demand and if this improves the match with PV system generation.

CONCLUSION

This paper has presented a initial study of the dynamic electricity consumption of UK dwellings and the effects of grid-connected PV systems on the balance of imported and exported electricity. The study was based on five-minutely data recorded from a sample of 10 dwellings for a summer month (June 2008) and a winter month (January 2008). A simple model of PV system operation was developed and used to generate PV power output data for a 10 m² PV system. This simulated data was matched to the dwellings' consumption and the effects on imported and exported electricity was analysed.

Further work will extend the analysis to cover the entire two-year monitoring period and for the complete sample of 100 dwellings for which data is available. Different sizes of PV systems will be simulated to determine the optimum design for maximising the financial benefits. This will include the use of economic scenarios of different electricity import and export prices. The effects of considering a community of dwellings, as well as

the differences between individual dwellings, will also be investigated.

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