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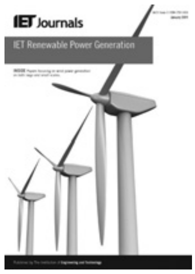

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Photovoltaic metering configurations, feed-in tariffs and the variable effective electricity prices that result

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Abstract: Occupants of dwellings with photovoltaic (PV) systems can often benefit financially by time-shifting their use of electricity in relation to the times when the PV is generating. This financial benefit is owing to differences between the import and export prices, which in some cases can be a factor of four or more. Quantifying the exact financial benefit in terms of the dwelling's effective electricity prices is, however, not trivial; it depends on the physical meter arrangement, the dwelling's electricity tariffs (including any feed-in-tariff), the instantaneous levels of PV generation and household demand. This study reviews typical metering and tariff configurations for the UK, and Germany, and systematically considers how the effective price may be calculated. This study reviews and expands upon general advice for occupants aiming to reduce electricity bills: demand should be kept below generation; external irradiance is a useful proxy for determining effective electricity prices. Furthermore, designers of feed-in tariffs should consider that focusing on generation payments encourages consumption typically around mid-day, which may be counterproductive from a grid-balancing and environmental perspective. Conversely, a focus on export payments discourages mid-day consumption but may increase the risk of over-voltages in local networks.

1 Introduction

It is often the case that the occupants of dwellings with grid-connected PV systems can benefit financially by time-shifting their use of electricity within the dwelling in relation to the times when their PV systems are generating. This generally occurs when the occupants own the PV system and are responsible for paying the electricity bill for the dwelling. In the UK, for example, the Energy Saving Trust (EST) – an independent consumer advice body – advises the PV system owners to shift the use of their appliances to the middle of the day, when the PV system is generating, in order to maximise their return on investment [1]. In Germany, in contrast, the owners of PV systems installed before 2010 can achieve a better return by avoiding consumption during the middle of the day, in order to maximise the income they receive for electricity that is exported to the grid.

The occupants both in the UK and in the Germany evidently experience a price signal that encourages time-shifting of demand, but what exactly creates this price signal, and why is it reversed in the two countries, even though both have 'feed-in' tariffs?

To conceptualise and quantify this price signal, this paper introduces the concept of an 'effective price' of electricity, which describes the variation in the price that the occupants of dwellings with PV will have to pay for the electricity they consume owing to their specific metering configuration, feed-in tariff, instantaneous levels of demand and PV generation.

Even though somewhat unusual, the effective price consolidates the price signals of the various metering and feed-in tariff arrangements into a single variable. More broadly, this approach also conceptually aligns this variable effective price with the real-time prices used in demand-response schemes. As a result, this paper provides a framework for future investigations of the behavioural responses of occupants with PV to be applied more generally to the study of demand response in low-carbon power systems.

Although there are numerous studies on the value of PV to a household in terms of consumer behaviour change [2, 3] and impact on electricity bills [4–8], none of these quantify the benefit in terms of a variation in effective price of electricity throughout the day. The work that comes closest analyses how income from PV systems varies throughout the day, and how this variation in income produces a 'signal' that can encourage the occupants to time-shift their consumption [9]. Although the present work is also interested in price signals produced by PV systems, it differs from previous studies by focusing on the variation in the effective price of electricity consumed within the dwelling, rather than on the overall income that the owner may receive from generated electricity.

The following presents a general framework for the calculation of effective electricity prices for dwellings with PV systems. Data from PV systems on dwellings in the UK are then used to expand upon the general advice given to the occupants aiming to reduce electricity bills. Typical metering and tariff configurations for the UK and Germany are then reviewed along with their associated price functions. The paper concludes with a discussion of the broader implications of this work.

2 Calculating the variable effective electricity price

The aim here is to find the effective price of electricity consumed in dwellings that have grid-connected PV systems. For the purposes of this paper, a time interval of 5-minutes has been chosen, principally due to the availability of data at this resolution from monitoring campaigns of dwellings with PV, but also because it is in keeping with the timescales that the occupants' demand-response actions could be considered. Before setting out a formal description, the following example will serve to introduce the underlying concepts and terminology.

2.1 Example calculation

Consider Fig. 1, which shows the typical metering configuration of a PV system that meets the recommended design guidelines for the UK [10]. Note the direction of the power-flow arrows, which indicates the sign conventions used in this paper: both consumer demand (P_d) and PV generation (P_{pv}) are positive. A list and description of the variables is provided in Table 1.

For the purposes of this example, the PV system is assumed to be on a UK feed-in tariff, with a generation price of 21 p/kWh, an export price of 3.2 p/kWh [11], and a flat-rate import price of 11.8 p/kWh, which is a typical value for a domestic consumer on a 'standard' flat-rate demand tariff [12]. The generation price in this example is applicable to PV systems installed on the existing dwellings after 3 March 2012 and before 1 August 2012, while the export price is applicable to all installations before 1 August 2012. Note that installations after 1 August 2012 in the UK will have slightly higher export prices (4.5 p/kWh) and lower generation prices (16 p/kWh). These changes do not however affect this paper's conclusions.

Using data from a real 2.03 kW_{peak} PV system located in Gloucestershire, UK, Fig. 2*a* shows the PV output and demand profile over a single day in June 2006. The other plots shown in Fig. 2 will be discussed later.

In order to commence the price calculations, consider the two time intervals detailed in Table 2.

In the first interval, the dwelling's demand is greater than the PV generation. Of the 3.18 kW being consumed, 1.04 kW is met by the PV generation while the remaining 2.14 kW has to be imported from the grid. The occupant pays the standard import price (11.8 p/kWh in this case) on the 2.14 kW imported.

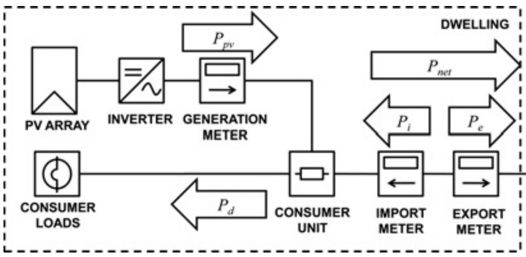

Fig. 1 *'Fully metered' domestic PV system*

Table 1 Description of the fundamental and derived variables used in this text

Variable	Description
P_{pv}	PV generation, kW
P_e	PV output exported to grid, kW
P_i	electricity demand imported from the grid, kW
$P_{net} = P_e – P_i$	dwelling's net power flow, kW
$P_d = P_{pv} – P_{net}$	consumer electricity demand, kW
$P_{self} = \min(P_{pv}, P_d)$	'self-consumed' power, i.e. PV generation that is consumed on-site within the dwelling, kW
P_{pv}/P_d	PV fraction (> 1 when exporting, < 1 when importing)
M	income from electricity generated by PV system and exported to grid (£ or p)
p_{gen}	price paid for a unit of electricity generated by PV system, 'generation price', p/kWh
p_i	price paid for a unit of electricity imported from the grid, 'import price', p/kWh
p_e	price paid for a unit of electricity exported to the grid, 'export price', p/kWh
p_{eff}	effective price of electricity, p/kWh
p_{mar}	marginal price of electricity, p/kWh
t	time, hours

There is also, however, a cost associated with the 1.04 kW that is being generated by the PV and consumed on-site ('self-consumption'). Every unit of electricity that is generated could contribute towards the occupant's income, as it could be exported at the export price (3.2 p/kWh in this case). The occupant's income in the first interval is 1.04 kW × 1/12 h × 21 p/kWh = 1.82 p. If all the electricity generated had been exported, then this would have resulted

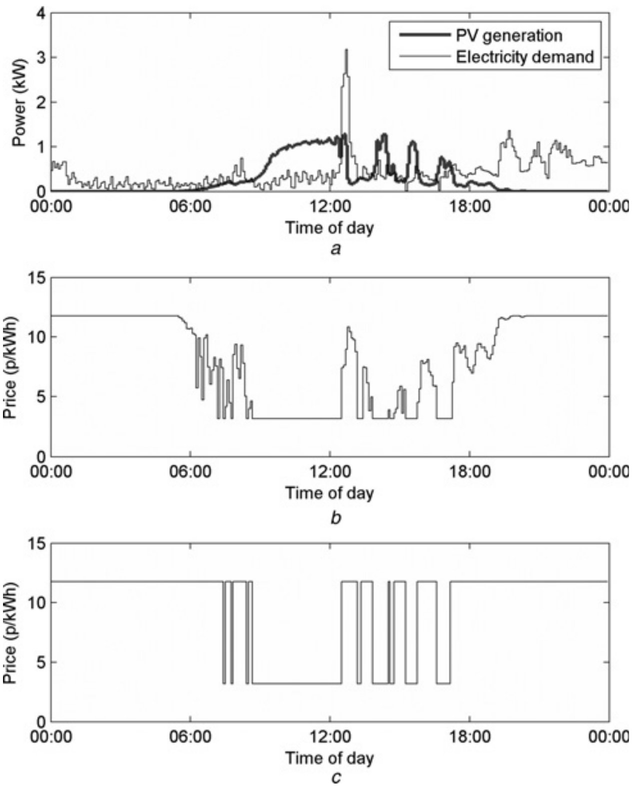

Fig. 2 *PV generation, demand and resulting price profiles for a PV system on 8 June 2006*

a PV generation and electricity demand
b Effective (average) price of electricity
c Marginal price of electricity

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Table 2 Power flows and electricity prices for two 5-minute intervals

	Time interval 1	Time interval 2
time	12:40 to 12:45	14:10 to 14:20
P_d (demand)	3.18 kW	0.33 kW
P_{pv} (PV generation)	1.04 kW	1.27 kW
P_{net} (net power flow)	–2.14 kW	0.94 kW
P_i (import)	2.14 kW	0 kW
P_e (export)	0 kW	0.94 kW
P_{self} (self-consumption)	1.04 kW	0.33 kW
m (income)	1.82 p	2.47 p
p_{eff} (effective price of electricity)	8.99 p/kWh	3.2 p/kWh

in a larger income for the occupant: 1.82 p + 1.04 kW × 1/12 h × 3.2 p/kWh = 2.10 p. Self-consumption, therefore, incurs a real cost to the occupant – economists call this an 'opportunity cost'. The opportunity cost is the difference between the occupant's actual income and what it could have been. In this case, the difference is 1.04 kW × 1/12 h × 3.2 p/kWh = 0.28 p. It can be seen that the opportunity cost is dependent on both the export price and the occupant's self-consumption.

The effective price during the first interval is therefore (see equation at the bottom of the page)

During the second interval, the demand is less than the PV output. No electricity is being imported; everything that is being consumed is being met by the PV system. Of the occupant's total costs, there is no import cost, only the opportunity cost. In this interval, the occupant's income was 1.27 kW × 1/12 h × 21 p/kWh + 0.94 kW × 1/12 h × 3.2 p/kWh = 2.47 p. Their income could have been higher, if all the electricity generated had been exported: 1.27 kW × 1/12 h × 21 p/kWh + 1.27 kW × 1/12 h × 3.2 p/kWh = 2.56 p. The opportunity cost was 0.09 p, and the effective price is

$$p_{\text{eff}} = \frac{\text{Total costs}}{\text{Total consumption}} = \frac{\text{Opportunity cost}}{\text{Total consumption}} = \frac{3.2\ \text{p/kWh} \times 0.33\ \text{kW} \times (1/12)\text{h}}{0.33\ \text{kW} \times (1/12)\ \text{h}} = 3.2\ \text{p/kWh}$$

Evidently, there are two important prices in determining the effective price: the import price and the export price. A unit of electricity imported from the grid has a value set by the import price, whereas a unit of electricity that is generated by the PV and consumed on-site has a value set by the export price. The effective price of electricity depends on how much electricity is imported, and how much is self-consumed. Note that, perhaps surprisingly, the generation price is not relevant to the calculation of the effective price. This is because the effective price is associated with electricity consumption, and this can only influence what the import and export meters record, not what the generation meter records.

2.2 Clarification of terminology

The metering configuration shown in Fig. 1 records power that is generated by the PV array, power that is exported to the grid and power that is imported from the grid. Since all the major power flows are either measured, or can be calculated using the measured power flows, this configuration will be referred to as a 'fully metered' system. The occupant receives payments from (or makes payments to) the utility depending on the power flows recorded by the meters, and the tariffs that apply to the meter readings. The term 'occupant' is used here to refer to the person or persons occupying the dwelling with the installed PV, and this paper only considers the situation where the occupant is the owner of the PV system and pays the electricity bills.

The terms 'tariffs', 'prices' and 'rates' are often used interchangeably, but in this paper we will use 'price' to refer to the value in p/kWh of a unit of electricity, and this will be used in preference to 'rate'. We then use 'tariff' to refer to a set of electricity prices that is agreed between the occupant and the utility, and which applies to the metered power flows.

A 'demand tariff' is associated with electricity imported from the grid. Demand tariffs can be a simple constant price (often called a flat-rate or flat-tariff), or have two prices (such as the Economy-7 tariff in the UK, which has a low price at night, and a higher price in the day), or have multiple prices such as in a 'real-time pricing' scheme, where the price can change every hour of the day.

'Feed-in tariff' is an umbrella term with different meanings in different countries. In the UK, for example, at the time of writing, a feed-in tariff has two prices: a 'generation price' and an 'export price' [13, 14]. The generation price is paid for every unit of electricity produced by the PV system, and the export price is paid for every unit of electricity that is exported to the grid. Payments for generated and/or exported electricity are made by the utility to the PV system owner.

2.3 Income from a PV system

The financial benefits of installing a PV system are often framed in terms of the income generated by the system. For example, the income (m) from a PV system with UK feed-in tariff is given by the following income function

$$m = p_g \overline{P_{pv}} t + p_e \overline{P_e} t$$

where $\overline{P_{pv}}$ and $\overline{P_e}$ denote averages over a time interval t

The focus of this paper is, however, on the additional financial benefit of reduced, effective electricity prices. These are formally described in the following sections.

2.4 Effective prices (weighted mean average)

The example in Section 2.1 illustrated that the effective price of electricity consumed in dwellings that have grid-connected

$$p_{\text{eff}} = \frac{\text{Total costs}}{\text{Total consumption}} = \frac{(\text{Opportunity cost} + \text{Import cost})}{\text{Total consumption}} = \frac{3.2\ \ \text{p/kWh} \times 1.04\ \ \text{kW} \times (1/12)\text{h} + 11.8\ \ \text{p/kWh} \times 2.14\ \ \text{kW} \times (1/12)\ \text{h}}{3.18\ \ \text{kW} \times (1/12)\text{h}} = 8.99\ \ \text{p/kWh}$$

PV systems is a weighted mean of the export and import prices. This can be written as

$$p_{\text{eff}} = \frac{p_e P_{\text{self}} + p_i P_i}{P_d} \tag{1}$$

It may be more intuitive, however, to work with variables for consumer demand (P_d) and PV generation (P_{pv}), and to express the function as follows.

When exporting

$$P_{pv} > P_d \text{ therefore } P_{\text{self}} = P_d \text{ and } P_i = 0$$

$$p_{\text{eff}} = \frac{p_e P_d + p_i 0}{P_d} = p_e$$

When importing

$$P_{pv} \le P_d \quad \text{therefore } P_{\text{self}} = P_{pv} \text{ and } P_i = P_d - P_{pv}$$

$$\begin{aligned} p_{\text{eff}} &= \frac{p_e P_{pv} + p_i P_i}{P_d} = \frac{p_e P_{pv} + p_i\left(P_d - P_{pv}\right)}{P_d} \\ &= \frac{p_i P_d + (p_e - p_i) P_{pv}}{P_d} \end{aligned} \tag{2}$$

$$p_{\text{eff}} = p_i - (p_i - p_e)\frac{P_{pv}}{P_d}$$

Equation (2) shows that the effective price is equal to the import price minus a quantity relative to the ratio P_{pv}/P_d, which is commonly known as the PV fraction. Fig. 3 shows this relationship in graphical form for several typical PV metering and tariff configurations. Currently, we are considering the situation for a fully metered system (the full line in Fig. 3) – the other systems are considered later in Section 3.

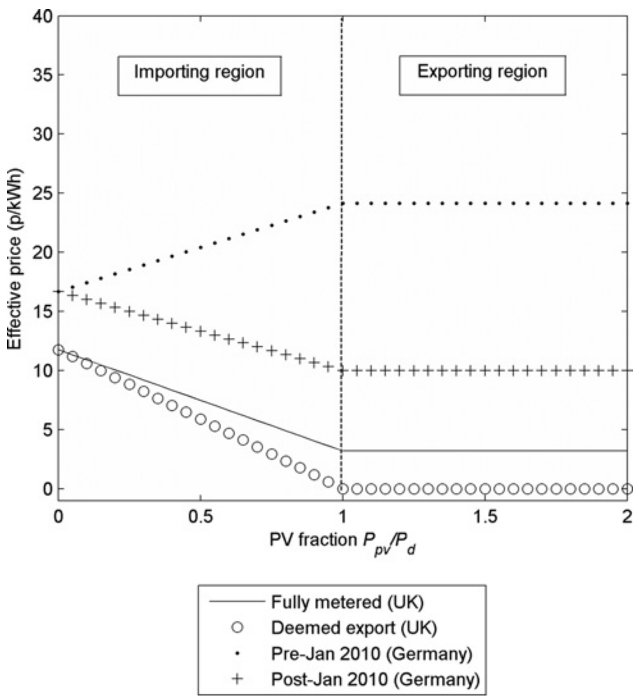

Fig. 3 *Relationship between effective price and PV fraction, for some typical PV configurations*

An important determining factor in these calculations is the dwelling's net power flow – whether it is exporting or importing power. When exporting, the effective price is equal to the export price. When importing, however, the effective price will depend on the relative amounts of demand and generation. If the PV generation is nearly equal to the demand, then the effective price will be close to the export price. As the proportion of electricity that is imported increases, however, the effective price increases towards the import price. At the extreme, when all of the electricity is imported, then the effective price is equal to the import price.

2.5 Marginal prices

As an alternative to the effective (weighted mean average) price discussed above, it also interesting to consider the marginal price, which is the price the consumer would have to pay to increase their demand by a small quantity – that is, the price of the next Watt. Returning to the earlier example, during the first time interval, the consumer's demand is greater than the PV generation: the dwelling is importing power from the grid, and so any further increase in demand would also have to be imported. The marginal price is therefore equal to the import price: 11.8 p/kWh in this case. Whereas in the second interval, the demand is less than the generation and the system is exporting; an incremental increase in demand in this case would reduce that export and the marginal price is therefore equal to the export price: 3.2 p/kWh.

The important point here is that the marginal price is different in the first interval, when the dwelling is importing, than in the second interval, when the dwelling is exporting. In other words, the cost of increasing demand by a small amount, such as turning on a light bulb, is different.

The marginal price of electricity therefore depends only on the status of the dwelling's net power flow, as follows

$$p_{\text{mar}} = \begin{cases} p_e, & \text{when exporting} \\ p_i, & \text{when importing} \end{cases}$$

2.6 Variation in effective and marginal prices

Figs. 2*b* and *c* show the variation in effective and marginal prices that result from the power flows over the course of the day shown in Fig. 2*a*. It is clear that both prices varied considerably throughout the day.

Also in Fig. 2, it can be seen that this particular day was divided into two periods where effective prices were broadly different. During daylight hours, when the PV was generating, from approximately 06:00 to 19:00, the price of electricity was lower than it was during the rest of the day. There was therefore a general separation of the day into low- and high-price periods.

There was, however, significant price variability within these general periods. From 06:00 to 09:00, the prices fluctuated rapidly. From 12:30 to 18:00 also, the prices fluctuated, although less rapidly, with periods of high and low costs that were more sustained. Returning to the power profiles in Fig. 2*a*, we can see that these

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volatile periods coincide with periods when the dwelling was importing, and the PV generation was low, but not zero.

The occupants of dwellings with PV systems therefore have an 'opportunity window' during the day, when the PV is producing electricity, in which the effective price of electricity for their consumption is relatively low. The extent of this reduction is determined by how much demand is met by the PV generation. A single, large peak in demand during the middle of the day, for example, will still be quite expensive, as most of this demand will have to be imported. Indeed, this can be seen happening in Fig. 2 just after noon, when the demand peaks to around 3 kW. During this period, the PV generation is, at least for a brief moment, at a maximum, ~1.25 kW in this case. The result, however, is that the effective electricity price is still quite high, around 10 p/kWh in this case.

Fig. 4 shows the electricity and price profiles for the same consumer as in Fig. 2, taken some weeks later. It can be seen that effective price profiles are now different. On this day, prices were generally higher, and more volatile throughout the day. This demonstrates that the variation in electricity prices for a dwelling with PV will not necessarily be regular, or predictable, from day to day. This is because one of the principal factors driving price variability is the PV generation, which is in turn dependent on the irradiance. As a result, the opportunity window can be expected to vary, in both magnitude and length, on a seasonal and even daily basis.

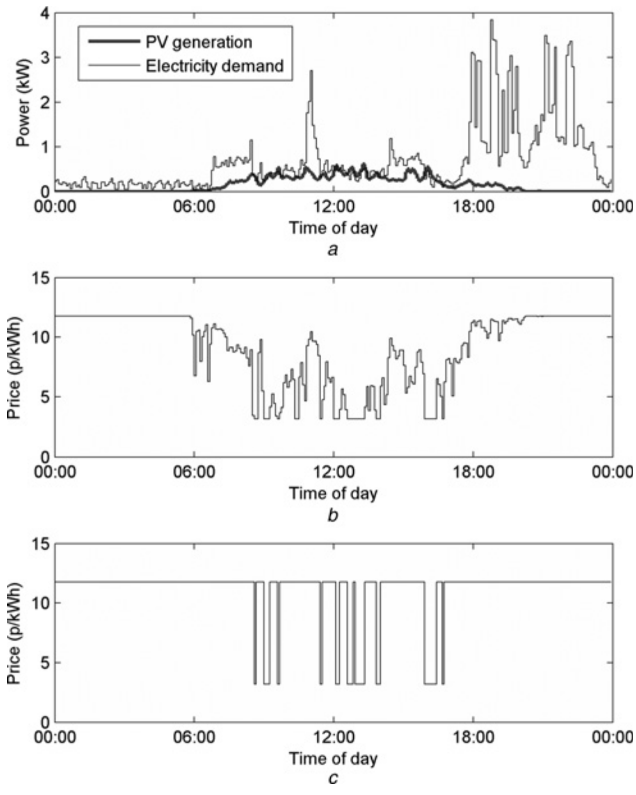

Fig. 4 *Electricity and price profiles for the same dwelling on the 18 June 2006*

a PV generation and electricity demand
b Effective (average) price of electricity
c Marginal price of electricity

3 Reducing electricity bills: reviewing the general guidelines for the UK

This section uses measured data from UK dwellings with PV systems as input to the effective price functions presented earlier. The purpose is to determine whether the results of the previous section can be generalised, and to review and expand upon the general advice given to the occupants aiming to reduce their electricity bills.

The data used is from the UK Photovoltaic Domestic Field Trial [15], in particular from a group of 15 dwellings in Gloucestershire, UK. The sizes of PV systems on this site ranged from 2.03 kW_{peak} to 3.20 kW_{peak}. All systems were co-located, had identical inclinations (30°), and similar orientations (within 12° of due South). Note that this is a hypothetical exercise: the actual metering configuration and tariffs for these dwellings are not known. For consistency with the previous section, however, it is assumed that all systems are fully metered systems (as in Fig. 1), and had import rates of 11.8 p/kWh, and export rates of 3.2 p/kWh.

In order to account for the different capacities of the PV systems, Fig. 5*a* shows the average yields for the systems, as well as average demand for the 15 dwellings for the month of June 2006. The load factor, or capacity factor, for the PV systems for this month was 11.4%, with a standard deviation of 4%. The average daily demand for these dwellings during this month was 7.38 kWh, which is lower than the national average daily demand for UK domestic unrestricted consumers of 8.87 kWh for a summer weekday [16]. Fig. 5*c* displays the effective price of electricity for the same dwellings for the same month. For simplicity, only effective (weighted mean average) prices are considered, not marginal prices. To calculate this price profile, the effective price profile for each dwelling was calculated for each day of the month (in a similar way to

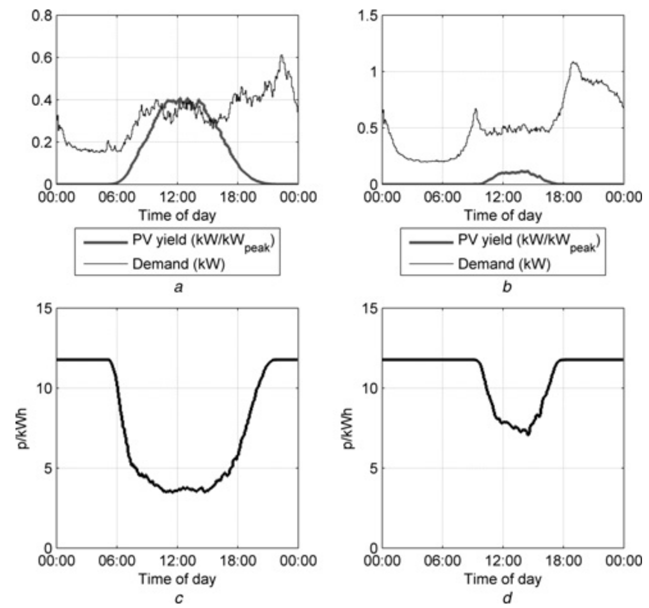

Fig. 5 *Site averages of PV yield, demand and effective price of electricity for 15 dwellings in June 2006 (A and C) and January 2006 (B and D)*

a PV yield and demand (June 2006)
b PV yield and demand (January 2006)
c Effective (average) price (June 2006)
d Effective (average) price (January 2006)

that shown earlier in Figs. 2 and 4). These effective price profiles were then averaged over all dwellings, and finally averaged over all days in a month. The result is a price profile that is 'smoother' than those shown in Figs. 2 and 4. Note that the same profile would not be achieved if the averaging was carried out before calculating the effective price profile.

Figs. 5*b* and *d* display similar plots, although for January 2006. The load factor for the PV systems for this month was 2.2%, with a standard deviation of 1.0%. The average daily demand for this period was 12.47 kWh, which is similar to the national average for a winter weekday of 12.29 kWh [16].

Figs. 5*c* and *d* demonstrate the extent to which electricity is cheaper, on average, for occupants during the summer and winter months. Clearly, as a general rule of thumb, the EST's advice – that PV owners should run appliances during the middle of the day – is sound, even during the winter.

An important caveat, however, is that consumers should try to keep the demand below generation. As a result, large appliances should not be run generally all at once. Both Figs. 2 and 4 demonstrate that sharp 'spikes' in demand incur relatively high effective prices. If, during the days depicted in these figures, the occupant had 'smoothed' the demand spikes over a longer time period, ideally such that the demand did not exceed the PV generation, then the price of electricity would have been considerably lower, possibly near to 3.2 p/kWh. Naturally, this will be more difficult during winter months, when the PV generation is relatively low, compared to the summer months.

From Figs. 5*c* and 5*d*, it is also evident that the effective price profiles mirror the PV generation profile, which, in turn, is closely related to the external irradiance. This correlation is explored further in Fig. 6, which plots hourly effective price against hourly in-plane irradiance for the 15 dwellings for the whole of the year 2006. Note that the figure plots hourly averages of the 5 min effective price and irradiance data. In order to focus attention on those hours of the day when the Sun is shining, the figure only shows the data between the hours of 09:00 and 15:00, and where hourly irradiance values are greater than zero. Owing to the large sample size (25 366 points), the data have been binned, and each bin is coloured to indicate the number of data points contained within it. The figure shows that for low irradiances, prices tend to be clustered near the

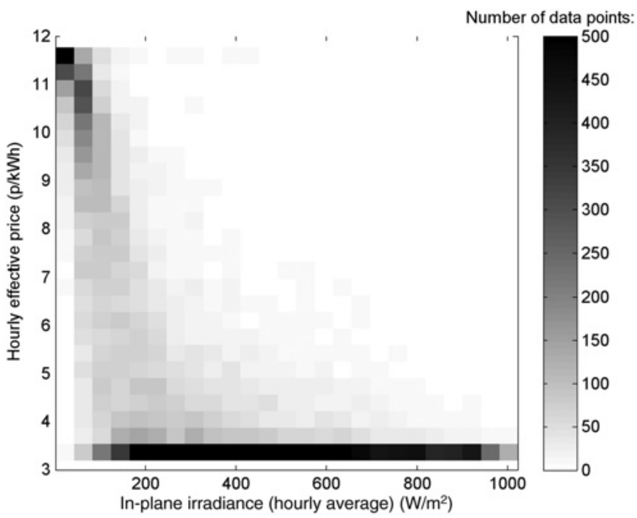

Fig. 6 *Effective price against in-plane irradiance for 15 dwellings for 2006 (hourly resolution)*

11.8 p/kWh level. With increasing irradiance, the effective price decreases until the export price (3.2 p/kWh) is reached, at which point the data clusters again.

The data are evidently non-linear, and polarised by the high number of data points at the 'floor' and 'ceiling' prices. There is, however, a clear negative relationship between price and irradiance. In terms of the correlation between these two variables, Pearson's product-moment correlation coefficient is -0.63 for the data shown in Fig. 6, whereas Spearman's rank correlation coefficient is -0.72. Both coefficients are significant at the 99% confidence level.

The same procedure was also performed using the data for horizontal irradiance rather than in-plane irradiance. This produced a similar plot to Fig. 6, although with slightly less of a negative correlation between the variables (Pearson's coefficient was -0.62 and Spearman's coefficient was -0.69, both significant at the 99% confidence level).

Fig. 6 shows the data for dwellings with PV systems ranging in size from 2.03 to 3.29 kW_{peak}. To test the dependency of the results on system size, the effective price was plotted against in-plane irradiance for the seven dwellings with 2.03 kW_{peak} PV systems and compared with the same plot for the four dwellings with 3.29 kW_{peak} PV systems. Both plots produced similar distributions to that shown in Fig. 6, and so these are not reproduced here. The correlation values were also similar. For the 2.03 kW_{peak} systems, Pearson's coefficient was -0.64, and Spearman's coefficient was -0.71. For the 3.29 kW_{peak} dwellings, Pearson's coefficient was -0.61, and that of Spearman's was -0.74. All correlation coefficients were significant at the 99% confidence level.

As a general rule of thumb, therefore, it would seem reasonable for the occupants to judge whether the effective price of electricity is high or low, based on the level of sunshine outside. Given the data considered here, this can be said to be valid for typical domestic PV systems sized 2 kW_{peak} and above. In-plane irradiance is a slightly better proxy for price than horizontal irradiance; so, ideally, the direction of the Sun should also be taken into account. This is significant because, while information regarding PV generation and dwelling demand might be relatively inaccessible (e.g. meter in the loft or garage), external irradiance, and solar direction is, in contrast, relatively easy for the occupants to determine.

In summary, the EST's advice to occupants is to 'use any appliances during the day when the solar PV modules are generating the electricity' [1]. In light of this paper's results, this advice can be reviewed as follows:

- The EST's advice is broadly true, and is applicable even during the winter, and for days with low irradiance.
- The reduction in effective electricity prices is considerable – for the dwellings analysed here, the occupants can expect, on average, a two-third reduction in effective price of electricity during the daylight hours on a summer day, and a one-third reduction on a winter day.
- The demand should be kept below generation. As a result, spikes in the demand should be avoided. Rather, the demand should be 'smoothed' in order to match the PV generation profile, as this results in lower effective electricity prices. Larger appliances should be run consecutively during the day, not all at once.
- It should also be noted that the availability of cheap electricity offered by UK PV systems might encourage wasteful use of electricity. It should be emphasised

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therefore that appliances should only be run during the day if they were going to be run anyway.

- The effective price of electricity is broadly correlated with the outside irradiance. As a rule of thumb, the occupants can determine when it is likely to be a good time to use electricity by considering how sunny it is outside, as well as the direction of the Sun. Given the data analysed in this paper, this is true for typical domestic PV systems sized 2 kW_{peak} and above.

The above comments apply to the occupants on a UK feed-in tariff with a fully metered system. Other metering and tariffs configurations will now be considered.

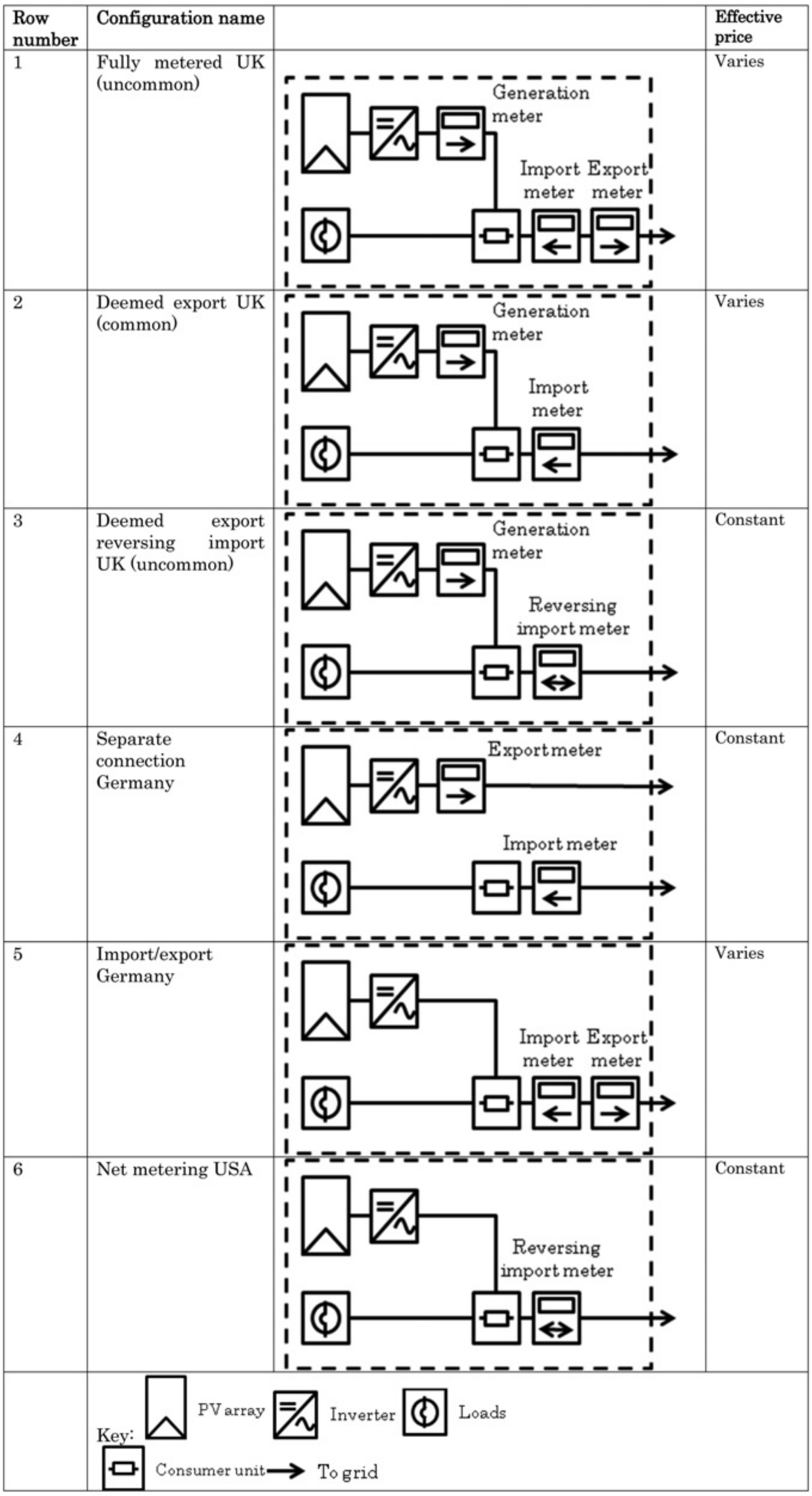

Fig. 7 *Typical PV system connection and metering configurations*

4 Typical metering and tariff configurations and their effect on price

The effective and marginal prices of electricity consumed in dwellings that have grid-connected PV systems depend greatly on the physical types and configuration of meter(s) and on the tariff arrangements applied. These vary in different countries and often depend on when the meter(s) and PV system were installed. This section presents a selection of typical metering and tariff configurations used in the UK, Germany and the USA, and which are shown in Fig. 7.

4.1 Feed-in tariff (UK)

The first three configurations shown in Fig. 7 are eligible in the UK to claim payments under the UK feed-in tariff [14], provided that the system as a whole is installed according to Micro-generation Certification Scheme standards [13].

The top row is the 'fully metered' system, which was used in the example earlier in this paper, and shown to have the following price and income functions

$$p_{\text{eff}} = \begin{cases} p_{\text{e}}, & \text{when exporting} \\ p_{\text{i}} - (p_{\text{i}} - p_{\text{e}})\dfrac{P_{\text{pv}}}{P_{\text{d}}}, & \text{when importing} \end{cases}$$

$$p_{\text{mar}} = \begin{cases} p_{\text{e}}, & \text{when exporting} \\ p_{\text{i}}, & \text{when importing} \end{cases}$$

$$m = p_{\text{g}}\overline{P_{\text{PV}}}t + p_{\text{e}}\overline{P_{E}}t$$

This configuration serves well as an illustration of the concepts and calculations, but in practice it is relatively uncommon in the UK today due to the cost of the export meter.

The second row in Fig. 7 illustrates the 'deemed-export' system, which is by far the most common configuration used in the UK today. It avoids the cost of installing an export meter by simply deeming the amount exported to be a percentage of the amount generated: 50% in the case of domestic PV systems [17].

Mindful of the impending roll-out of 'smart' meters, the deemed-export system is favoured by the UK electricity 'suppliers' (energy retail companies) who are reluctant to install new conventional export meters that could have a very short life in service [18]. Export meters are the responsibility of electricity suppliers, whereas generation meters (required in all UK systems – first 3 rows of Fig. 7) are the responsibility of the PV system installer [13].

For the deemed-export systems, electricity that is exported to the grid is not metered at all, and any potential payments for electricity exported are lost. Since the occupant does not get paid for exports, the export price is effectively zero, in which case the price functions are as follows

$$p_{\text{eff}} = \begin{cases} 0, & \text{when exporting} \\ p_{\text{i}} - p_{\text{i}}\dfrac{P_{\text{pv}}}{P_{\text{d}}}, & \text{when importing} \end{cases}$$

$$p_{\text{mar}} = \begin{cases} 0, & \text{when exporting} \\ p_{\text{i}}, & \text{when importing} \end{cases}$$

Notice that in comparison to the fully metered system, the effective price when exporting is now zero: consumers may enjoy 'free' electricity up to the limit set by the PV generation. Therefore note that the occupants with the deemed-export systems experience electricity prices that vary in time similar to the fully metered system described previously, although with more exaggerated price variations, as the 'floor' price is 0 p/kWh rather than 3.2 p/kWh. This is indicated by the line with circle markers in Fig. 3, which is both steeper and lower than the full line for the fully metered system. Thus, we see that the electricity prices for the occupants with the deemed-export systems are therefore lower, on average, than those on fully metered systems.

The income function for the deemed-export systems is given by

$$m = \left(p_{\text{gen}} + \alpha p_{\text{e}}\right)\overline{P_{\text{PV}}}t,$$

where α is the % that is deemed to be exported

Occupants will therefore receive 22.6 p/kWh (21 p/kWh + 50% × 3.2 p/kWh) for every unit generated by their PV. Note that the mean percentage exported for the 15 dwellings analysed in Section 3 was in fact 56.2%, which indicates that these occupants would receive higher incomes with fully metered systems than with deemed-export systems.

In the future, when smart meters are installed, the deemed-export systems will become fully metered, and the price functions will change accordingly.

The third row of Fig. 7 illustrates a relatively uncommon configuration: a 'deemed-export reversing-import' system. In the UK, all domestic import meters should have a backstop fitted that prevents them from going backwards. In practice, however, there are still some legacy reversing-import meters installed in domestic dwellings. Where these are present, a unit of electricity that is exported has the same value as a unit that is imported. The export price is therefore effectively equal to the import price, and as a result, the price functions are as follows

$$p_{\text{eff}} = p_{\text{i}}, \quad \text{when importing and exporting}$$

$$p_{\text{mar}} = p_{\text{i}}, \quad \text{when importing and exporting}$$

In contrast to the fully metered system, therefore, an occupant with a 'deemed-export reversing-import' system does not experience a time-varying price of electricity.

The income function with reversing-import meters is the same as for the deemed-export systems shown above.

4.2 Feed-in tariff (Germany)

The fourth and fifth rows of Fig. 7 show the two typical metering configurations for PV systems in Germany [19]. These are referred here as 'separate connection systems' and 'import/export systems'. With a separate connection system, the PV is connected separately from the dwelling's connection, such that all the electricity that is generated by the PV is exported straight to the grid – presumably to maximise income from the high export price. The dwelling pays the import price for all electricity consumed, and so, under this arrangement, the occupant does not experience a time-varying effective electricity price.

The alternative to the separate connection system is the import/export system, shown in row 5. Unlike the fully

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metered system (row 1), the import/export system lacks a generation meter. Consumers with import/export systems will, however, have price functions that are the same as for a fully metered system (see beginning of Section 4.1), because the configuration of import and export meters are the same for the two systems – the generation meter has no effect on the effective price.

In addition to the two physical meter configurations described above, however, Germany also has two variants of feed-in tariff. For PV systems installed before January 2010, the German feed-in tariff consists of a high export price (~30 c€/kWh–40 c€/kWh, euro–sterling exchange rate €1.2;£1), which is paid for electricity exported to the grid [20]. The generation price for the German feed-in tariff is zero. This contrasts with the UK feed-in tariff, where the export price is low (~3.2 p/kWh) and the generation price is high (~21 p/kWh).

The marginal price for self-consumed power on a German import/export system pre-2010 was equal to the export price. Since the export price was high (~30 c €/kWh–40 c€/kWh), certainly compared to a typical import price of around ~20 c€/kWh, the occupants on such tariffs experience high prices for the electricity they consume during the periods when their PV is generating, and lower prices outside these periods. They are incentivised therefore to minimise their consumption and maximise their export during these periods. It is important to note that this is the opposite case to consumers on the UK feed-in tariff, who are incentivised to export as little power as possible. This is indicated in Fig. 3 by the dotted line, which slopes in the opposite direction to the line for the fully metered system.

The variant German feed-in tariff was introduced for PV systems installed after January 2010. For these systems, the feed-in tariff was changed in order to provide an explicit incentive for self-consumption. Under these new arrangements, the occupants receive payments for any electricity that is generated and consumed on-site [20].

Owing to the introduction of the self-consumption payment, the marginal price for self-consumed power is now the export price minus the self-consumption payment. The exact values of the export price and self-consumption payment depend on the size of the PV system and the overall percentage of self-consumption [20]. For a typical domestic system installed in 2011, however, the export price is around 29 c€/kWh and the self-consumption payment is around 17 c€/kWh. The payment for self-consumption is less than the payment for exported electricity, but high enough so that the consumer is incentivised to shift consumption to periods where their PV is generating. This is because the marginal price of self-consumed power is 29 c€/kWh–17 c€/kWh = 12 c €/kWh, which is 8 c€/kWh cheaper than a typical import price of 20 c/kWh.

A consumer in Germany import/export system and self-consumption payments will therefore experience effective prices that vary similarly to a UK feed-in tariff. The variations will, however, be less exaggerated, as the 'floor' price will be 12 c€/kWh (~10 p/kWh) rather than 3.2 p/kWh (see the slope of the line in Fig. 3). The price functions will be as follows

$$p_{\text{eff}} = \begin{cases} p_{\text{e}} - p_{\text{self}}, & \text{when exporting} \\ p_{\text{i}} - (p_{\text{i}} - p_{\text{e}} + p_{\text{self}})\dfrac{P_{\text{pv}}}{P_{\text{d}}}, & \text{when importing} \end{cases}$$

$$p_{\text{mar}} = \begin{cases} (p_{\text{e}} - p_{\text{self}}), & \text{when exporting} \\ p_{\text{i}}, & \text{when importing} \end{cases}$$

where p_{self} is the self-consumption payment. Income from this system is given by

$$m = p_{\text{e}}\overline{P_E}t$$

Note that in order to be able to accurately calculate the relevant payments, a PV system with German feed-in tariff and self-consumption payments requires a fully metered system [21].

4.3 Feed-in tariffs and price signals

Feed-in tariffs that focus on payments for exports typically have export prices that are high compared to import prices. In these cases, the high-price period is during the middle of the day, when the PV is generating. As a result, the occupants will be incentivised to maximise exports, for example, by shifting the demand away from the middle of the day, perhaps to the early morning or evening periods. This is the situation for import/export systems (Fig. 7, row 5) in Germany that were installed prior to 2010.

In contrast, feed-in tariffs that focus on generation payments typically have export prices that are low compared to import prices. The low-price period will, as a result, be during the middle of the day, and consumers are incentivised not to export. This is the situation for UK systems (Fig. 7, top three rows), and German import/export systems post-2010 (Fig. 7, row 5).

The important point to note is that, although the support mechanisms for PV in Germany (pre-2010) and the UK might appear to be similar, in fact they produce price signals that are opposite in terms of the behaviour that they might encourage in consumers. One group of consumers is incentivised to minimise day-time consumption, whereas the other is incentivised to maximise it.

4.4 Net metering

The last row in Fig. 7 shows a 'net metering' system. 'Net' simply refers to the fact that the occupant is charged only for the net energy consumption of the dwelling over a given period, which is the total electricity imported minus the total electricity exported. Net metering is the standard metering configuration in the USA, although there is diversity in terms of how this is actually implemented at the state level [22].

The metering configuration for net metering is simple (final row of Fig. 7), as it only requires a reversing-import meter. Note that if the occupant does not have a reversing-import meter, then a net metering system can also be achieved with the import/export system shown in Fig. 7, row 5. The import and export meters explicitly record imported and exported power, which can then be used to calculate the dwelling's net energy consumption.

5 Discussion: comparison with time-of-use and real-time pricing tariffs

Time-of-use and real-time pricing refer to demand tariffs in which prices vary throughout the day in order to deliberately influence electricity consumption and thus provide demand response. With time-of-use tariffs, prices follow a prescribed profile known to consumers well in advance, whereas with real-time pricing, prices can vary unpredictably with very little notice to consumers. At present, simple time-of-use schemes such as Economy-7 are quite common around the world but there are very few schemes using prices that vary hourly or similar. Nonetheless, it is anticipated that such schemes will play an increasingly important role in assisting grid balancing and managing network constraints in the future [23]. It is interesting therefore to compare the variable pricing typical of these dedicated demand-response schemes against the variable effective pricing that occurs, almost as a by-product, with PV feed-in tariff schemes.

Time-of-use and real-time prices are often designed to reflect prices on the wholesale market and thus tend to follow the national demand profile. As a result, they incentivise consumers to shift demand away from the periods when the supply of electricity is most expensive, and typically has the highest marginal emissions factor [24].

Feed-in tariffs also provide consumers with a variable effective price of electricity, but as seen throughout the earlier sections of this paper, the profile created through this mechanism has no direct link to prices on the wholesale market. In some cases (in Germany, pre-January 2010), we can expect at least a general alignment; in other cases, the profiles will have a considerable mismatch.

For example, the occupants of dwellings with PV and feed-in tariffs in the UK have electricity prices that are highest at night. This is the reverse of the situation for consumers on the Economy-7 tariff, where prices are lowest at night. From a grid-balancing perspective, all consumers, including those with PV, should have lower electricity prices during the night (like with Economy-7), because this is when electricity is principally supplied by the generators with the lowest running costs. Feed-in tariffs can therefore produce price signals that encourage behaviour that is opposite to that needed for the purposes of efficient grid balancing. Note also that the price differentials shown in Fig. 3 are of similar magnitude to the differential provided by Economy-7 prices, which are approximately 16 p/kWh during the day, and 6 p/kWh at night [12].

The German feed-in tariff system (pre-2010) has a better alignment with wholesale prices, and occupants with this tariff are at least incentivised to export power during the day. That the German government changed this tariff to reverse the effective price signal, and incentivise PV owners not to export, is perhaps indicative of a greater issue concerning conflicting priorities within the power system at local and national levels. From a national power system balancing perspective, it is better for PV owners to export the power they produce, so that others can use it. From a local distribution network perspective, however, the situation might be different because high penetrations of PV can cause problematic voltage rises on the low-voltage network [25]. Distribution network operators might therefore prefer for PV owners not to export power, and indeed it seems this is one of the reasons that the German feed-in tariff was changed [21, 26].

As a general observation therefore, feed-in tariff designers should be aware that a high export price is useful from a grid-balancing perspective, but might exacerbate problems on the low-voltage network. A high generation price (and low export price), in contrast, might help to limit the impact of micro-generation on low-voltage networks, but might encourage consumption during the middle of the day. It should be noted that the carbon impact of such shifts is unclear as this depends on the times when the shift occurs, and the marginal emissions factor of grid electricity at those times.

Finally, in order to appreciate the impact of demand response in PV dwellings, it is also important to consider whether time-shifting of demand is also accompanied by an overall increase or decrease in demand. The prospect of very cheap electricity, for example, might encourage wasteful use of electricity. Likewise, when facing high day-time prices, occupants might forgo appliance-use altogether, resulting in a conservation effect. These additional effects obviously increase the difficulty of making precise estimates of the carbon impact of time-shifting in dwellings with PV.

6 Conclusions and future research

A variety of metering and tariff configurations have been set out and clarified, and this paper has systematically considered how the effective price can be calculated for typical configurations in the UK and Germany.

It was found that dwellings with PV systems on 'feed-in' tariffs can experience a variable effective price of electricity. Where export prices are greater than import prices, then there will be a high-price period during the middle of the day, when the PV is generating. When the reverse is true, and export prices are lower than import prices, then, in contrast, there will be a low-price period during the middle of the day.

The results illustrate that variants of schemes that are all called 'feed-in' tariffs can be very different in terms of the consumer behaviour they encourage. The former incentivises consumers to time-shift their use of appliances to the day-time (when the sun is shining), whereas the latter incentivises shifting away from this time-period. One group of consumers is incentivised to minimise day-time consumption, whereas the other is incentivised to maximise it.

Feed-in tariff designers should be aware therefore that a low export price might encourage consumption during periods of the day when wholesale prices and carbon intensities of grid-electricity might be relatively high. High export prices, in contrast, mitigate this issue, but can potentially exacerbate distribution network constraints. The UK and German (pre-2010) are examples of feed-in tariffs that have similar names, but in fact produce opposite price signals.

For occupants on feed-in tariffs in the UK, the advice that they should run appliances during the middle of the day when their PV is generating is broadly true, even during the winter. Occupants should, however, always aim to keep demand below generation, and avoid spikes in the demand. In practice, this might be achieved by using appliances consecutively during the day, not all at once. This paper also finds that effective electricity prices are broadly correlated with the outside irradiance. As a rule of thumb, the occupants can determine effective electricity prices by considering how sunny it is outside. Given the data considered here, this can be said to be valid for typical domestic PV systems sized 2 kW_{peak} and above. In-plane irradiance is a slightly better proxy for price than horizontal irradiance; so, ideally, solar direction should also be accounted for.

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Although this paper has discussed in detail how electricity prices vary in time for owners of PV systems, there are important questions remaining regarding what the consumers themselves think, and do, about them. This paper has shown that the prices these consumers experience are quite unusual compared to traditional flat-rate import tariffs. What therefore is the level of understanding among consumers with PV?

For example, it was shown that, in general, the marginal and average prices are not equal for consumers with PV. Should a rational consumer be attentive to the effective (weighted average) price signal or to the marginal price signal? These questions have been left open for future research.

More generally, this paper has shown that studying how the occupants respond to the variable effective price they experience can offer a window of insight into how consumers might respond in a future low-carbon power system where electricity prices are less predictable or regular. Further research is also recommended in this area.

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