Household behavioural responses to photovoltaic-system monitoring devices

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Abstract

The UK government is encouraging households to adopt solar photovoltaic (PV) systems as part of its climate change strategy. Helped by a £6 million grant programme, over 600 households have purchased PV systems and many of these systems include a performance-monitoring display device. On its own, PV can reduce the carbon emissions of the domestic sector by offsetting traditional sources of electricity; however the total savings achieved by the programme must also consider the household's behavioural response to the system and in particular the monitoring device. Evidence from other countries has suggested that behavioural changes after the installation of PV can either increase or decrease overall consumption from previous levels, depending on context. This paper explores these responses to PV with special attention to the monitoring devices and how they impact household energy consumption behaviour; parallels are drawn with existing work on feedback and energy consumption. Findings of new research are presented in an attempt to determine the likely behavioural impact of PV monitors in the UK context. These results are then used to suggest how government and industry might maximise the behavioural response to PV systems and associated monitoring devices.

Introduction

Driven by the imperatives of climate change, renewable energy has enjoyed significant growth in the United Kingdom and elsewhere. While renewables in the UK are currently dominated by hydro and biofuels, other renewables such as wind and solar are gaining in popularity with the support of government policy and a strong natural resource. However wind energy has faced significant obstacles from planning policy and local communities and solar photovoltaics (PV) is limited by its high cost.

Fortunately the UK government has allocated £6 million to domestic photovoltaics via the Major PV Demonstration Programme. This grant scheme provides up to 50% of the installation cost and since its inception in March 2002, over 600 households have purchased PV systems. This growth in domestic renewable generation capacity benefits climate change not only through the displacement of fossil fuel generation but because of its location in the home, there is the potential for PV to increase awareness of energy issues and stimulate conserving behavioural responses.

Domestic photovoltaics have not been studied extensively for their impact on household energy consumption behaviour. However a few key studies have suggested that PV may indeed change energy consumption in the home, both with regards to patterns of use and overall quantity (Erge *et al.* 2001; Haas *et al.* 1999; Schweizer-Reis *et al.* 2000). Research on domestic energy consumption and behaviour provides some insight into why this additional conservation effect may occur and information feedback seems to play a key role. Since PV systems are commonly installed with monitoring devices, which display various metrics on the PV system's performance, it is hypothesised that these monitors raise awareness and shape consumption for PV households in much the same as has been seen in feedback literature.

Therefore the aim of this paper is to examine PV monitoring devices in the UK domestic sector so that the potential behavioural responses to this growing generation technology can be understood. The paper will first review some notable findings from feedback and energy conservation literature, before presenting the findings of original research on UK PV households. The conclusions will focus on the future steps that industry and government might take to encourage conservation behavioural responses in PV households.

Direct feedback and domestic energy consumption

The motivations of energy conserving behaviour are complex and varied. Some individuals respond best to financial incentives, while others may enjoy leading a conserving lifestyle for its own sake (DeYoung 1996). In the case of PV, personal responsibility and symbolic values may be particularly relevant (e.g. Kaiser and Shimoda 1999; Monnier 1983). However the main focus is the potential for PV to raise household awareness of electricity generation and consumption. While many consumers understand the link between energy use and its associated environmental impact generally, this relationship is often poorly understood in the context of one's own consumption; hence the benefit of energy labelling standards (Winward *et al.* 1998). Awareness of energy consumption can be raised by feedback, or knowledge of one's energy consuming performance; that is, if the results of a behaviour do not match with the anticipated outcome, a cognitive dissonance can lead to shift in either behaviour or perspective (Seligman and Darley 1977). A review of feedback studies has identified a potential saving of about 10% through direct, indirect, and other forms of feedback (Darby 2000).

Direct feedback, e.g. from electronic monitoring devices, is the one of the most promising forms of feedback (Wood and Newborough 2003) and a key area of focus for domestic PV systems. However while most direct feedback studies focus on the monitoring of *consumption* behaviour, PV is a generation technology. Therefore benefits from PV feedback are likely to emphasise the generation of electricity, and thus providing a context for consumption in the home. In turn the behavioural responses to PV one might expect could include load shifting so as to better match generation with consumption (e.g. Kasulis *et al.* 1981).

PV Monitoring Devices

Monitoring devices are a key feature of PV installations and come in a variety of forms. However two primary categories might be noted for the purpose of domestic feedback and energy awareness: inverter-based and remote units. Inverter-based units are often small displays included with the inverter (e.g. a simple kWh counter) but can include more complex instruments that facilitate data download and computer interfacing. These monitors are primarily focused on technical information such as detailed system performance (e.g. voltages, currents, inverter efficiency, or faults). The nature of these data suggests that its primary use is for expert evaluation of system performance, providing an analysis tool for "data junkies" (SMA America 2004).

Remote units, which can be used in conjunction with inverter-based devices, provide more accessible information directly to the home-owner. These devices consists of a sensor attached to the PV wiring, which measures the system's generation and then transmits this information by a low-power radio signal to a receiving display unit located anywhere within the home. A common example of this display unit is shown in Figure 1 and this particular unit can display instantaneous kilowatts, cumulative kilowatt-hours (since the last reset), and kilograms of carbon dioxide saved by PV generation. Notably, this final metric provides the household with a direct reminder of the environmental benefits of their PV system and raises the possibility of designing monitors with a variety of accessible and meaningful metrics (e.g. £ saved per month and so on).

Figure 1 The Leiderdorp LI-12 PV monitoring device

It should be noted however that for the most part, these units do not measure consumption. This may be a function of design; that is, the monitor designers were concerned with measuring PV system performance (i.e. generation) and therefore consumption was not of interest. Monitors for measuring consumption do exist and they often work on an appliance-by-appliance basis, of the piggy-back type; i.e. the monitor plugs into the mains socket and the appliance plugs into the monitor (as used by Mansouri-Azar *et al.* 1996). Ideally the PV monitor could combine both generation and consumption monitoring for easy viewing.

Methodology and Results

The methodology and results discussed below are excerpts from the author's ongoing doctoral research. This project aims to understand the wider aspects of behavioural responses to PV in the domestic sector, including the roles of households, technology and industry, and government policy. Work began in the autumn of 2004, when a questionnaire was designed and distributed to PV households in the UK. Distributing the survey was made difficult by the low numbers of PV households in the UK but fortunately Solar Century, the UK's leading installer of domestic PV systems, was willing to assist by sending the questionnaires to its domestic customers. Therefore this sample is not random but does cover a large portion of the known UK PV population (~1/6). The questionnaire touched on many issues related to PV but for this paper, the goal is to examine the role of monitoring devices within these households.

Respondents were asked to indicate if a monitoring device was included with their PV system and a sample image, as shown in Figure 1, was included to eliminate any confusion between traditional electricity meters. Open-ended questions were asked to determine which models are popular and where the devices are located. Closed-format questions were used to determine the frequency of monitor viewing as well as the metrics featured on the monitor. All respondents, regardless of whether they owned a monitor currently, were asked what metrics they would like to have displayed on an ideal monitoring device. Choices included measures of instantaneous performance, cumulative performance, tangible measures (i.e. financial savings, generation vs. consumption, or carbon-dioxide savings) as well as a blank space for other responses.

The surveys were distributed to 118 domestic PV households in November 2004 and as of early January 2005, 88 questionnaires were received. This notable response rate (75%) is due in part to the offer of a prize incentive and the provision of self-addressed stamped envelopes. Anecdotal evidence also suggests that PV households are keen to share their experience with others. The results were coded and then analysed using R (R Development Core Team 2004).

General monitoring trends

It was found that 88% of respondents (n = 88) had monitoring devices installed with their photovoltaic systems and the key features of these monitors are shown in Table 1. Since the responses represent the customers of only one installation firm, further research is required to confirm the applicability of these results to other installation firms.

Table 1 A profile of PV monitoring devices in the UK

Monitor feature	Most common response	%	N
Model	Leiderdorp LI-12 (remote type)	65	66
Location	Kitchen or living room	61	76
Most frequently viewed metric	Instantaneous kW	63	71
Viewing frequency	At least once a day	51	73

Patterns of monitor use

It is promising that monitors are located in primarily high-traffic areas, though approximately one-third are located in cellars and storage areas. Table 2 indicates that, as one might expect, monitors located in high-visibility areas are viewed more frequently.

Table 2 Monitor location and viewing frequency

	Viewing Frequency	
Monitor location	**At least once a week**	**At most once a month**
Living room, Kitchen	37	7
Cupboard, Storage area	13	11
Other	3	2

$\chi^2 = 7.4196$, df = 2, p = 0.02448, n = 73

The type of metric viewed by respondents also varies according to viewing patterns and Table 3 shows that this effect is significant, with short-term measures (instantaneous kW or cumulative daily and weekly kWh) more common among frequent viewers. If these monitors were being used to assess generation over time, one would expect cumulative measures to be more popular. Therefore the overall popularity of instantaneous measures suggests that this metric is used primarily as a verification that the system is operating correctly.

Table 3 Most frequently viewed metric and viewing frequency

	Viewing Frequency	
Most frequently viewed metric	**At least once a week**	**Once a month or less**
Long-term cumulative measures (i.e. monthly, yearly or since installation, kWh)	7	9
Short-term cumulative measures (i.e. weekly or daily, kWh)	6	0
Instantaneous production (kW)	36	9
Other (e.g. flashing light or kg CO_2 saved)	4	2

$\chi^2 = 10.3047$, df = 3, p = 0.01615, n = 73

There was no significant difference in monitor ownership by the age of the PV system, indicating that monitors have been a long-standing feature of PV systems ($\chi^2 = 6.5652$, df = 3, p-value = 0.08712). However Table 4 demonstrates that monitoring devices are used differently depending upon the age of the PV system. Further research will be required to determine if monitors suitable for high-traffic areas were not available when early PV systems were installed or if there has been a change in the practice of installation firms.

Table 4 Differences in monitoring use by age of PV system

	Age of PV System	
Monitor feature	**New (< 2 years)**	**Old (> 2 years)**
Viewing frequency***	Daily	Once a month
Location**	Kitchen, Living room	Cupboard, storage
Most popular metric*	Instantaneous kW	Instantaneous kW and cumulative measures

Significant differences at *10%, ** 5 %, *** 1%, n = 73

Finally, 64% of respondents (including those who did not own monitors) indicated that their ideal monitoring device would display the generation of their PV system relative to the electricity consumption of their household.

Monitor use and electricity savings

Respondents were asked to indicate whether they believed their household's total electricity consumption had changed since the installation of photovoltaics. No significant difference in monitor ownership was found when respondents were grouped by those who reported saving and those who reported no saving or an increase ($\chi^2 = 0.0084$, df = 1, p-value = 0.9269 with Yates' continuity correction). Furthermore, no significant differences were found between the saving and no saving groups by:

- Monitor location ($\chi^2 = 2.2321$, df = 4, p-value = 0.6931)
- Viewing frequency ($\chi^2 = 10$, df = 9, p-value = 0.3505)
- Most frequently viewed metric ($\chi^2 = 12.0733$, df = 11, p-value = 0.3582)
- Monitor model ($\chi^2 = 9.1008$, df = 10, p-value = 0.5226)
- Length of PV ownership ($\chi^2 = 3.9866$, df = 3, p-value = 0.2629)

Discussion and Conclusion

Darby (2000) indicates that for feedback to be effective, it must be immediate, clear and specific. The results presented here indicate that monitoring devices in PV systems meet the requirements for immediate and clear information but are lacking in specificity.

First PV monitors are largely immediate and accessible. There is a high level of ownership and this demonstrates that installers are a viable means of introducing the monitoring technology into PV households. This makes sense as it minimises hassle for the household, who might otherwise have to seek an after-market monitor and perhaps even a professional installer. Accessibility of monitors is also demonstrated by their location in high-traffic household areas and corresponding frequent viewing.

The design of the monitors themselves is quite clear. The Leiderdorp model, common in the surveyed households, displays three simple pieces of information at the touch of a button. As well, the installation of these devices in high-traffic areas of the household is a testament to their aesthetic design and suitability as an interactive household appliance.

However it appears that the information provided by monitors lacks specificity. Measures of system performance are typically presented in electrical units and the popularity of instantaneous metrics suggests that the monitors may be used primarily to verify the continued functioning of the system. Presenting generation information in terms of kilograms of carbon-dioxide saved is a first-step in providing more tangible measures of performance but the user still requires a level of expertise to understand what this information means relative to daily behaviour. The lack of consumption information on monitors adds to this problem, as interested PV households can only compare generation and consumption when monthly or quarterly bills from their electricity supplier are delivered.

These findings, combined with the lack of difference between monitor use in saving and non-saving households, suggests that PV monitoring devices are used less as a tool for assessing energy use, and more as a novelty. Verifying this hypothesis, and investigating the detailed ways in which households use this information, is a focus for follow-up interviews. In particular, it will be very interesting to gather the stories of dedicated individuals who use this limited information in extremely novel ways (e.g. Kempton and Layne 1994)

Encouraging further conservation

The potential for further conservation savings in PV households, due to behavioural responses to monitoring devices and awareness of generation, may be limited since PV households have likely taken a number of conservation measures already (Haas *et al.* 1999). Nonetheless, government and industry should consider how these products might influence household energy consumption particularly as PV becomes more widely adopted and spreads to households with more diverse behavioural motivations. For example, a household adopting PV as a novel architectural material might be made aware of the benefits of conservation; an awareness that early environmentally-concerned PV adopters are likely to have had before the purchase of a PV system.

If government wishes to encourage positive behavioural responses to PV, and potentially other domestic generation technologies, they must ensure that monitoring devices are integrated with these installations; promisingly, the current grant programme does make provision for such devices. However additional motivations for conservation behaviour, such as financial savings from the export of green electricity and awareness of consumption, may require improvements in metering and electricity arrangements so that displaying this information on a PV monitor is both feasible and likely to influence behaviour. That is, displaying a financial metric is likely to be much more effective in Austria where there is a €0.70/kWh solar feed-in tariff (compared to €0.07/kWh in the UK).

While this research has not yet explored the role of industry in detail, it seems that the PV monitoring device is steadily maturing as a technology. The remote sensing and wireless display unit technologies in particular have overcome a major hurdle, with households accepting the devices into visible areas of their homes. However collecting technical data appears to be the primary goal of monitor design and therefore future designs should focus on presenting metrics which are more accessible to the household; for example, comparing generation and consumption on a daily basis. This survey has indicated an interest in such metrics and it follows that those who have invested significant amounts of money in PV would want to know exactly what benefits the system is providing.

Conclusion

This paper has briefly described the use of monitoring devices in the UK PV households. It has found that these devices are very common, visible in the household and used frequently. However the use seems to be more about curiosity than gaining detailed information about electricity use in the household. This is partly a function of monitor design, since most monitors do not support consumption monitoring, and partly government policy, which could do more to provide the institutional structures needed for sensible metrics such as financial rewards. Monitoring devices provide an opportunity for encouraging further energy savings in PV households, especially as PV technology becomes more widely accepted. The challenge for government and industry is to encourage these behavioural responses by providing the conditions and equipment necessary to supply households with timely relevant feedback.

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