Photovoltaics in the UK domestic sector: a double-dividend?

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Abstract

Solar photovoltaics (PV) can reduce the greenhouse gas emissions of the domestic sector by offsetting traditional sources of electricity; however the total savings achieved by these PV installations must also consider the household's behavioural response to the system and its associated monitoring device. Evidence from other countries has shown that these post-PV behavioural changes can either increase or decrease overall consumption from previous levels depending on local context. The UK government has recently supported domestic PV with a £6 million (8.5 million Euro) grant programme and over 600 households have purchased PV systems. The aim of this paper is therefore to determine whether PV households in the UK are likely to increase or decrease their domestic energy consumption, drawing upon the results of a recent survey. Three potential mechanisms for this behavioural change are discussed: personal responsibility for energy consumption, the symbolism of PV, and feedback and the role of monitoring equipment. The results suggest that, at present, further savings from behavioural responses will be limited primarily to use and maintenance behaviours, resulting from a commitment to responsible energy use. In future, the green symbolism of PV may encourage larger savings as the technology spreads to more diverse households. Suggestions are provided to maximize the benefit from behavioural responses to domestic PV.

Introduction

With the recent ratification of the Kyoto Protocol, climate change has been confirmed as a major concern of modern energy policy. Correspondingly most western nations have devoted increased attention to the potential ways of reducing greenhouse gas emissions. In the UK, policy makers have placed particular emphasis on renewable energy and a target has been set for 10% of electricity from renewable sources by 2010 (DTI 2003b). While 96% of the UK's renewable electricity currently comes from biofuel and hydro sources (DTI 2003a), other sources of renewable electricity are being strongly promoted with mechanisms such as the renewable energy obligation and capital grant schemes.

Solar photovoltaics (PV) are one of the most intriguing renewable technologies and there is a huge resource potential even in a northern country such as the UK (Jardine and Lane 2003). Most notably PV can be located in installations of only one or two kilowatts on the roof of someone's home, i.e. at the source of consumption. This raises several questions regarding distributed generation, metering and utility regulations; however when considering climate change and the benefit of such small-scale domestic generation technologies, the larger concern is the total emissions savings that such technology can deliver. The total benefit of domestic photovoltaics comes not just from displacing fossil-fuel generation, but because of its location within the home, there is a potential influence on energy consumption behaviour (e.g. load shifting, conservation, and changing purchase behaviour). Thus a positive behavioural response, leading to further energy conservation, could provide a 'double-dividend' for climate change.

There have been few studies on domestic photovoltaics and its impact on domestic energy consumption. Existing literature has examined off-grid systems and household consumption (Schweizer-Reis *et al.* 2000) and provided a mixed picture of consumption increasing, decreasing and remaining constant after the introduction of PV (EC 1997; Erge *et al.* 2001; Haas *et al.* 1999). For the most part, these behavioural assessments have been secondary observations, added to technical or policy evaluations, and as such the details of these responses remain uncertain. There is potential however to draw parallels with literature on energy conservation programmes and technological diffusion to help explain who purchases PV and how they might be predisposed towards further conservation behaviours.

This paper describes some early findings of research on behavioural responses to PV currently underway at the University of Oxford. This research is timely in light of the UK's current £6 million (8.5 million Euro) Major PV Demonstration grant programme, whose upcoming evaluation will determine the form of future domestic energy programmes. Therefore the final section of the paper will discuss the implications of these findings for PV support programmes and how the potential climate change benefit of domestic PV might be maximised through a double-dividend: combining clean technology with positive behavioural responses.

Domestic energy consumption and PV

Photovoltaics are one part of a larger domestic energy consumption system. This system, which incorporates technical, economic, psychological, and social factors, must be understood if relevant influences on PV response behaviours are to be identified. For example, the high cost of PV may restrict its ownership to a certain socio-economic group thus determining the physical and social environment of energy consumption and thus the potential size and nature of a behavioural response. This section will explore these links by first reviewing some of the most important elements of the domestic energy system. Existing studies of PV and behaviour will then be reviewed to provide a few starting hypotheses. Finally parallels from energy conservation literature will be examined to flesh out these ideas and set the stage for the research.

DRIVERS OF DOMESTIC ENERGY CONSUMPTION

Domestic energy consumption is determined by many factors. The physical environment is a starting point, with the dwelling's location determining temperature, hours of daylight and so on, thus altering the need for energy services such as heating, lighting, and appliances (e.g. Hart and de Dear 2004). Equipment within the house then determines how this demand will be met, as the actual energy consumption is a function of the efficiency and design of the appliances, lighting and so on (see Boardman *et al.* 1995; Palmer and Boardman 1998 for examinations of UK domestic energy technologies). These physical and technical factors are clearly applicable to photovoltaics, determining both how much solar resource is available (depending on the home's latitude, roof orientation, shading and so on) and how efficiently it is collected (the specifications of the solar modules and inverters).

Economics affect domestic energy consumption as energy services and equipment have a cost and therefore the demand for these goods and services is tempered by the finances of the household. A household following an economic rationale also might respond differently to the tariff structures that reward PV generation: depending on the metering and institutional arrangement, these feed-in tariffs can range from 5 p (0.07 Euro) in the UK to as much as 0.70 Euro per kWh in Austria (IEA 2004). As well, the high cost of domestic PV – £7 400 (10 000 Euro) per kilowatt peak in the UK (EST 2003) – suggests that even with a 50% grant, PV will be more popular with high-income households. This is an important contextual consideration when assessing the potential for behavioural responses, as energy costs for the highest earning third of households are only 2.6% of weekly income (Craggs 2003) and therefore financial incentives aimed at running costs may be less enticing to these households.

Energy consuming actions are often not determined by an economic rationality but by other internal motivations. The theory of social action suggests that in addition to rational behaviour, action can be motivated by beliefs and values, emotions, and habit (Weber *et al.* 1968) and these seem likely determinants of PV response behaviours. In particular, the purchase of photovoltaics is arguably a demonstration of a commitment to environmental values and energy conservation, and it follows that consumption behaviour might continue in a consistent manner to reduce cognitive dissonance. The importance of commitment to conservation has been seen in other studies (Heberlein and Warriner 1983; Katzev and Johnson 1983). Research has also suggested that "a lifestyle focused on restraining consumption of resources can be highly satisfying" (DeYoung 1996: 359); this 'intrinsic satisfaction' may be rewarded by PV. Psychological factors are clearly one of the most elusive parts of the domestic energy system and a key question for this research will be to understand the psychological profile and motivations of PV households.

Finally domestic energy consumption is a social phenomenon and must be considered in its cultural context. This includes, for example, the availability of energy-saving appliances as limited by market offerings and the symbolic values that societies associate with particular items and behaviours. This has been demonstrated in existing studies of energy use and housework (Cowen 1983), the evolution of domestic appliances (Hardyment 1988), and more recently our changing perceptions of comfort and cleanliness (Shove 2003). For PV, the primary social element may be the symbolism of the panels – visibly installed on one's roof – and associated social norms exerted upon the purchaser.

EXISTING STUDIES OF PV AND BEHAVIOUR

Domestic energy consumption is therefore a complex network, containing technical, economic, psychological and social elements. Photovoltaics touch upon nearly all of these determinants but unfortunately there is very little literature exploring these connections. Indeed most articles on domestic photovoltaics focus on technical matters or broader policy and industry evaluations (e.g. Kurokawa and Ikki 2001). There are however a few key articles that have discussed the topic of behaviour and solar energy systems.

Two recent studies of PV have alluded to the behavioural aspects of the technology in the context of a larger programme assessment. The first study examined 68 PV households in Germany and found that there was no significant difference between the consumption of PV households and non-PV households, although this finding was only briefly mentioned (Erge *et al.* 2001). Notably this research was conducted as Germany's premium feed-in tariffs were being established and therefore an updated review might reveal the impact that this significant economic incentive has had on household behaviour. Secondly, a review of photovoltaics throughout the EU makes a brief mention that PV has reduced the energy consumption of households in France (EC 1997). This is not elaborated upon but it does lend anecdotal evidence to the claim that PV can reduce household consumption.

A more detailed study of Austrian PV systems suggests that PV can indeed reduce the consumption of a household, though there is a consumption threshold of about 3 500 kWh/year below which consumption increases and above which it decreases – as the authors put it, "one may suspect that PV is an 'energy conservation tool for the rich'"; i.e. households with high pre-PV consumption (Haas *et al.* 1999: 189). The paper also suggests that PV is purchased as the final stage of conservation chain. That is, these households have undertaken a series of household improvements and efficiency measures, the culmination of which has been the addition of a PV system, a premium product which confirms their interest in using domestic energy efficiently and responsibly.

The reasons for purchasing PV are likely to be an important factor in this research, as the factors that influenced the purchase decision may predispose the owners toward a particular behavioural response. An early study of solar thermal systems revealed that the individuals who adopted these systems were young, well-educated, well-paid professionals at an early stage in the family life cycle (Labay and Kinnear 1981). The significant differences found here between adopters and non-adopters suggest that despite the high-cost, these individuals felt that the technology exhibited acceptable levels of relative advantage, financial risk, social risk, complexity, and matched their personal values. These traits fit very well with the theoretical definitions of early technology adopters (Rogers 2003) and therefore diffusion of innovation research might help explain how such individuals respond to the technology once purchased.

Finally a review of off-grid solar photovoltaic systems sheds some much needed light on why further conservation behaviours might happen. The off-grid situation is different from most UK installations, as the household must stay within the energy provided by their solar system (and any other generation sources) if reliable service is to be maintained; however the willingness of residents to accept these restrictions suggest that responsibility may be a possible explanation for a positive response to PV: "We are happy with this limitation: it makes us feel *responsible* for our energy consumption." German User, 1999 (Schweizer-Reis *et al.* 2000: 8, italics added). This research also demonstrated how the technology of PV, especially the performance monitors which are installed with the panels, might affect patterns of consumption: "Before watching TV the children look at the charge gauge. We respect the rules: Turn off light, no stand-by of appliances, make use of daylight." Spanish User, 1999 (Schweizer-Reis *et al.* 2000: 8). Reacting to a display monitor rather than a charge gauge, it is not hard to imagine that a grid-connected household might respond in a similar manner perhaps maximising their daylight exports of PV to take advantage of a premium feed-in tariff.

POSSIBLE MECHANISMS FOR PV-TRIGGERED CONSERVATION BEHAVIOURS

These studies of PV and behaviour are promising but provide little detail on the mechanisms of PV-triggered conservation behaviours. To address this problem, we turn to the extensive literature on domestic energy consumption and conservation which began following the oil crises of the 1970s. Some of the findings from this work may provide useful parallels when considering behavioural responses to photovoltaics. Three possible motivations, hinted at above, are examined: symbolic consumption, personal responsibility for energy use, and the impact of monitoring (or feedback).

Consumption has long been recognised as a symbolic action, providing indications of who we are and what we believe (e.g. 'conspicuous consumption' as identified by Veblen (1899)). Energy use, and the ownership of PV system, is no exception and displaying PV on one's roof might be interpreted as a visible demonstration of one's environmental beliefs. However symbols can mean different things to different people at different times; for example, automobiles are viewed by some as a tool for escaping the city and by others as a symbol of drudgery of urban commuting (Sachs 1983). The importance of symbolism in energy consumption has been identified by other authors, as an influence on consumption behaviour (Wilhite and Lutzenhiser 1999), and associated with lifestyles and their modes of consumption (Clancy and O'Loughlin 2002; Lutzenhiser 1992). From this perspective, PV can be seen not as a single symbolic purchase but as part of a larger suite of behaviours. This is consistent with the view of Haas *et al.* that PV is a culmination of a series of conservation lifestyle decisions. Symbolism is a potential tool for encouraging behavioural responses to PV but it is important to identify which reference groups PV homeowners are concerned with.

Managing the demand side of domestic energy consumption increasingly requires an element of personal responsibility from householders (Fuchs and Arentsen 2002). Energy consumption has impacts beyond the location of the consumption and therefore taking responsibility for how one's energy use affects, for example, the environment may lead to changes in energy using behaviour. Early conservation studies have demonstrated the role of personal responsibility as a predictor of ecologically sensitive behaviour and conservation lifestyles (Leonard-Barton 1981). This responsibility works in two ways: first and foremost as a moral incentive, e.g. guilt; and secondly as a conventional incentive, i.e. socially normative (Kaiser and Shimoda 1999). Under this analysis, photovoltaics can be interpreted as a proactive step taken by a household in recognition of their impact on the environment, more for their own intrinsic satisfaction rather than the approval of others.

Awareness is another factor which might trigger behavioural changes in energy use. Feedback studies have demonstrated a potential savings of 10% by raising awareness of energy consumption in the home (see Darby 2000 for a review). The most effective form of feedback is "direct feedback" and photovoltaics can be considered part of this group as most systems are fitted with a display monitor that shows the system's generation. However many of these monitors do not show consumption information directly and so any consumption feedback would be indirect through reduced bills. Drawing upon knowledge of practice theory, effective feedback must be timely and useable (Ammons 1956) and therefore if one hopes to raise awareness of generation in comparison to consumption, the monitors should show these two figures in a compatible manner. The format and design of these monitors is therefore an important consideration and has been flagged for further consideration (Wood and Newborough 2003).

In summary, little has been written directly about domestic PV and how it shapes domestic energy consumption. While a few studies suggest that there is the potential for savings from behavioural responses to PV, the difficulty is to identify the mechanisms by which these savings might occur and determine how they can be encouraged by technologies and institutions. Fortunately literature on energy consumption and behaviour suggests at least three possible mechanisms – personal responsibility, symbolism, and feedback – by which PV might lead to further energy savings in the domestic sector.

Methodology and Results

The methodology and results discussed below are part of the author's ongoing doctoral research. This larger project aims to understand behavioural responses to domestic PV in a wider context, including the roles of technology, industry, government and households. Work began in autumn 2004, when a questionnaire was designed and distributed to PV households in the UK. This questionnaire touched on many issues related to PV but for this paper, focus will be placed on those questions which might indicate the causes of behavioural savings.

SURVEY DESIGN AND IMPLEMENTATION

The questionnaire was designed with five sections covering demographics, energy-related psychological constructs, energy use in the home, details of the PV system and its monitoring devices, and overall opinions. Owing to the low numbers of PV households in the UK (approximately 800) and difficulty accessing relevant contact lists, a pilot study with the target group was not possible and therefore expert opinion was used to refine the questions through three drafts. The survey was quite long and took approximately 15 minutes to complete; closed-format questions were therefore used to encourage participation.

While a full discussion of the survey's design is not possible here, it is worth examining how the psychological constructs at the centre of this paper were measured. Four established measurement instruments were used, covering knowledge levels, self-identity, worldview, and values; all of which have been identified as potential psychological influences in energy-using behaviour (Banks 1998; van Raaij and Verhallen 1983). Direct measures of attitude, subjective norms, and control factors were not possible as a specific behaviour was not being assessed (Ajzen 1991). To assess knowledge levels, four questions were asked regarding climate change and photovoltaics and these were drawn from existing sources (ECI 2004; Park *et al.* 2001). Pro-environmental worldview was then assessed using the New Ecological Paradigm (NEP) (Dunlap *et al.* 2000). The original NEP instrument is fifteen questions long, which was too long for the purpose of this survey. Instead three elements were selected for their relevance to the PV question at hand. Self-identity was measured according to Callero's methodology (1992); here respondents indicate their own opinion and as well as how they believe a "home energy-saver" would answer. Values were measured using a modified version of the Rokeach value survey (1973). The original methodology was again too long for this survey and so an abbreviated list of five value clusters was selected. This approach is supported by previous research, which found these five distinct factors among energy-concerned households (Banks 1999). Appendix A details the exact wording of the questions as well as how summary indices were calculated.

Distributing the survey was made difficult by the low numbers of PV households in the UK. Fortunately Solar Century, the UK's leading installer of domestic PV systems, was willing to assist by distributing the questionnaires. This sample is therefore not random but does cover a large amount of the known population of approximately 800 PV households. To ensure a good response rate, a prize incentive was offered and self-addressed stamped envelopes were used.

RESULTS

The surveys were distributed to 118 domestic PV households in November 2004 and as of early January 2005, 88 questionnaires were returned. This notable response rate (75%) may be explained by the involvement of the households, with their excitement in the technology making them more willing to discuss their experience with others. The results were coded and entered into R for analysis (R Development Core Team 2004). The analysis began by calculating a single index for each psychological construct (knowledge, self-identity, worldview, and values) as described in Appendix A.

The mindset of PV households

The first of these indices reflected the respondent's awareness or knowledge levels. As shown in Figure 1, PV households exhibit a high level of overall knowledge about climate change and PV technology itself. This is not unexpected as diffusion of innovation theory suggests that these early-adopting individuals should be better informed about the technology, its risks and benefits (Rogers 2003). This result also indicates awareness about the connection between energy use and climate change. This suggests that alerting these households to their relative consumption of renewable or non-renewable energy sources may lead to a shift away from polluting sources where possible.

The high level of awareness suggests strong environmental concern among PV households. To confirm this, an index was created reflecting the respondent's agreement with the pro-environmental perspectives of the New Ecological Paradigm (NEP). Plotted in Figure 2, one can see high levels of agreement with NEP values. No significant difference was found between the different elements of this index ($\chi^2 = 11.7757$, df = 8, p = 0.1615) confirming that respondents believe modern science will not solve environmental problems without lifestyle changes, the climate threat is not exaggerated, and one should do what is right for the environment even if it costs more money or time. These findings are promising and provide evidence that personal responsibility may indeed be a powerful motivation for positive behavioural responses to PV.

Next respondents were asked to indicate whether or not they saw themselves as a "home energy saver". The index plotted in Figure 3 reflects each respondent's agreement with their view of this target identity; aggregate analysis shows that a "home energy saver" is much more likely to pay attention to their energy bills and enjoy do-it-yourself (DIY) home renovations. These results suggest that PV households would be receptive to feedback on their energy consumption and are not averse to taking home improvement measures, though further analysis shows that 42% of respondents are either neutral or do not enjoy DIY, suggesting that such improvements may require professional assistance.

Finally the values of respondents were measured. Owing to the abbreviated scale employed, these results are an approximation and not a definitive measure of PV household values. However Figure 4 shows that equality and environmental values are extremely important. More interestingly social recognition is less important, suggesting that any symbolic value of PV may be rewarded through an internal process (e.g. intrinsic satisfaction) as respondents may be less concerned with the plaudits of their neighbours and instead enjoy the feeling that they are "doing their bit" to help the environment. The equality element, which notably includes family security, suggests that these environmental concerns are tightly linked to concerns about the well-being of loved ones.

A significant change in these core beliefs was not expected following the installation of PV (especially in the case of values, see Rokeach 1973). In any event, the questionnaire could not make a direct measure of this point as households were not surveyed before and after the installation. However respondents were asked whether their total electricity consumption had changed since the installation of PV and this poses an equally interesting question: is there a difference between these core beliefs for saving and non-saving households? After dividing the respondents into saving and non-saving groups, chi-square tests revealed that there were no significant differences for any of the four constructs: knowledge (p = 0.2306), world-view (p = 0.3071), self-identity (p = 0.1297), and most important value (p = 0.4699). Therefore these findings provide an important perspective on the drivers for *future* savings behaviour but do not explain the self-reported savings of this questionnaire.

Post-PV changes in energy awareness

Respondents were asked to indicate if their change in energy use was due to any of four listed reasons, measured on a seven-point Likert scale. Again, respondents were grouped into those who indicated total electricity savings or no savings for comparison and the results are indicated in Table 1.

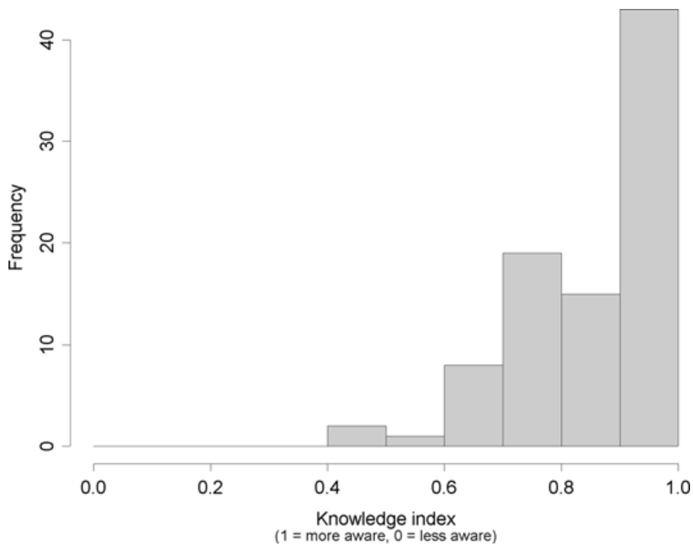

Figure 1. *Knowledge of climate change and PV issues among PV households.*

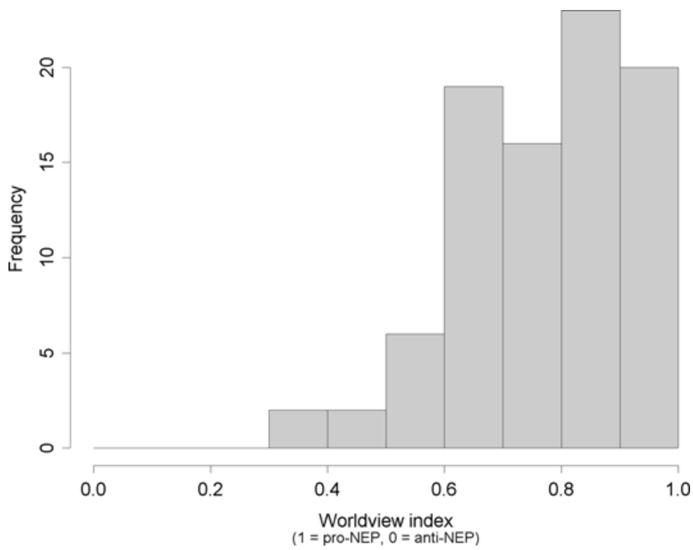

Figure 2. *PV household agreement with the New Ecological Paradigm.*

These results show that PV households who believe they have saved electricity are significantly more aware of both electricity generation and consumption. There are also significant differences between whether households are trying to live within their limits or are now 'green' households; however in both of these cases the median responses are still on the negative or neutral side of the scale. Both saving and non-saving groups neither believe that they have changed consumption to stay within the limits of their system (as many indicated this is extremely difficult to achieve), nor that they are *now* a 'green' household. Indeed comments confirm that most households were 'green' before getting PV; as one respondent indicated, the "impact [of PV on consumption] has been less than might be expected because I

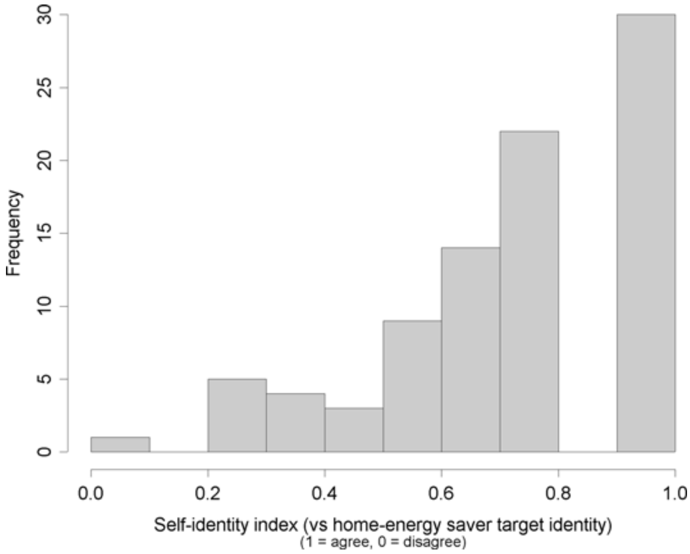

Figure 3. *Are PV households "home energy savers"?*

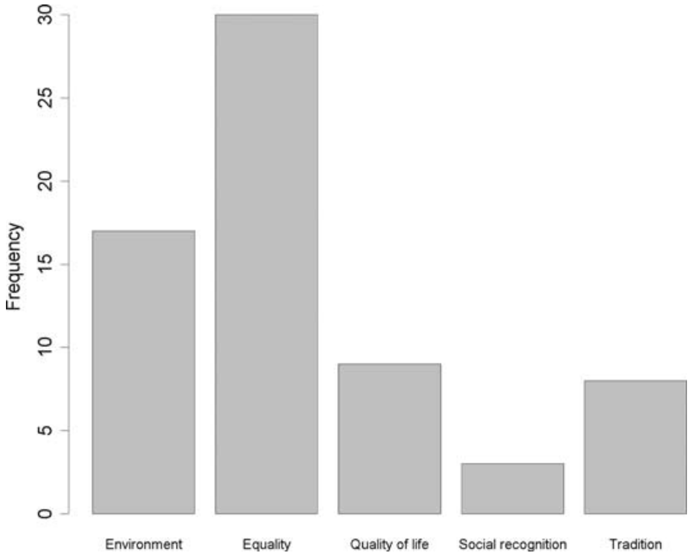

Figure 4. *The most important values of PV households.*

have always been energy and water use aware, so [I] have done a lot of things already." (Male, Age 45-65).

Respondents were also asked if their system was installed with a PV monitoring device. It is through the information displayed on this device that feedback mechanisms are hypothesised to act. The survey revealed that 88% of respondents' systems have monitoring devices, although these results only represent the customers of one installation firm. The most common monitor, the Leiderdorp LI-12 (65%), displays the system's instantaneous output (kW), cumulative generation (kWh) and the equivalent carbon-dioxide savings but has no measure of consumption. The CO_2 metric is quite interesting and suggests that there is potential for such monitoring devices to convert technical electrical measures into something more tangible and accessible for the household.

As a final check, the saving and non-saving groups were investigated for differences on socio-economic factors. Chi-square tests revealed no significant differences in gender, education, income, or property ownership. However there were differences in age, number of occupants, and length of residency as noted in Table 2. This suggests that the saving group is comprised of more younger, larger households, i.e. families with children as opposed to empty-nest retirees.

To summarize, these findings reveal that PV households are as we might expect. They are concerned about the environment and are well-informed about climate change and the role of energy. Most see themselves as home-energy savers and it appears that this is for personal reasons, rather than to gain social recognition. A link between electricity savings and increased awareness of generation and consumption has been found and this may be encouraged by the high levels of monitoring device ownership. However further research is necessary to determine why this awareness has raised and how that in turn has resulted in reduced consumption. One final caveat: these results apply to households that have purchased PV themselves and therefore one might expect non-purchasing PV household, e.g. social housing, to have different responses.

Table 1 PV has changed our consumption because...

Reason	**Saving Group** (median response, 1 = Strongly agree, 7 = Strongly disagree, n = 37)	**No Saving Group** (median response, 1 = Strongly agree, 7 = Strongly disagree, n = 41)	**Results of Mann-Whitney U Test**
We are more aware of *how electricity is generated*	3	6	U = 324, p = 0.000134
We are more aware of *how much electricity we consume*	2	5	U = 270, p « 0.001
We *try to live within the amount of electricity produced* by our PV system	6	7	U = 444, p = 0.0101
We are now a *'green' household*	4	6	U = 473, p = 0.0300

Table 2 Differences between saving groups by socio-economic factor.

Socio-economic factor	Saving Group (estimated mean, n = 37)	No Saving Group (estimated mean, n = 41)	Results of Chi-square Test
Age (years)	59	62	χ^2 = 7.4717, df = 2, p = 0.02385
Number of household occupants	2.81	2.29	χ^2 = 12.218, df = 5, p = 0.03192
Length of residency (years)	13	19	χ^2 = 10.481, df = 4, p = 0.03306

Discussion

The results presented here are a starting point for assessing the potential of photovoltaics as a catalyst for further domestic energy savings. The extent of this additional saving will be determined by the options open to homeowners, in key areas such as purchase, use, and maintenance behaviours (van Raaij and Verhallen 1983). Therefore consideration must be given to the likely ways in which the mechanisms identified above can be leveraged to pursue specific conservation behaviours.

CONSERVATION MECHANISMS

Three possible mechanisms have been identified for encouraging positive behavioural responses to PV: personal responsibility, which is tied with environmental values; symbolic consumption; and feedback. Of these, the impact of PV symbolism is likely to vary most over time. Current PV households are likely to view their systems as a reminder of their commitment to environmental protection and energy conservation since social recognition was not a very important value. This internal symbolism might encourage these households to 'stay the course', though as this course has likely included a number of conservation actions already (primarily purchase behaviours such as efficient lighting and appliances, Haas *et al.* 1999), the potential for further savings is limited. However as PV moves through the diffusion cycle, its symbolism may change from internal to external (Rogers 2003). Adopters in later stages of diffusion may view PV as a status symbol initially and decide to purchase a system, despite the lack of existing efficiency measures in the home. In this case, once the technology is installed further savings may occur as steps are taken to reduce the cognitive dissonance between high levels of consumption and the green imagery of the PV. Thus the potential for savings in these households may be larger. Whether or not these stages are reached depends on the size of potential market but it is safe to assume that at current prices, adoption will remain limited and therefore the symbolic value of PV will be limited for the moment to internal reminders of a household's commitment to energy conservation.

Personal responsibility was identified as a potential factor for motivating energy conservation in PV households. The results of this survey confirm this and suggest that this responsibility is rooted in environmental and egalitarian values. Financial benefits may be less attractive as indicated by the socio-economic status of PV households and their willingness to do what is best for the environment even if it is more costly. Of course there are limits to this munificence and campaigns encouraging these individuals to take further measures might backfire. PV households have spent a lot of money installing these systems, were committed green households before PV, and it would be hard to justify pushing them to make further conservation steps in their lifestyle when others in society are not doing their share. Consequently it might be best to provide positive feedback reinforcing to these households that what they have done is making a difference and thereby subtly encouraging continued commitment to conservation. Basic usage and maintenance behaviours, such as switching off lighting and keeping the PV system in good condition, are likely to be impacted by this mechanism.

If feedback is to be a mechanism for further conservation, then the presence of monitoring devices in most PV households is promising. Furthermore the high levels of knowledge in these individuals suggest that they may be able to make use of the information to assess their system's performance. Curiously however respondents who indicated energy savings after PV said they became more aware of both energy generation and consumption. Since PV monitors only display generation information, more research is required to determine how they became more aware of consumption.

Behavioural changes from monitoring could impact both purchase and use behaviours. First monitors may help build energy literacy so that when individuals go shopping for new appliances they can select a device which uses less energy. Promisingly, there is evidence to suggest that individuals with positive environmental attitudes, as demonstrated by the surveyed PV households, are more likely to respond well to feedback (Brandon and Lewis 1999). Secondly monitors would ideally compare both generation and consumption on an instantaneous timescale. This would allow homeowners to not only see the impact of particularly inefficient appliances (the high tech equivalent of watching a rotary meter spin faster when the electric oven is on), but also to see how much is being consumed at any one moment versus generation. While respondents did indicate that living within the means of their PV system was not feasible, such information may encourage load shifting so that heavy demand uses are timed to coincide with peak generation periods. Conversely if financial feed-in incentives were improved, this effect might lead to households maximising their exports to the grid and therefore using high-demand appliances in times of low solar generation. In any event, monitoring of both generation and consumption would provide PV households with the information they need to determine how further savings can be achieved.

Research has shown that resident behaviour accounts for approximately 30% of domestic energy consumption (Seligman and Darley 1977; Wood and Newborough 2003), though this assumes a fixed stock of appliances; i.e. use and maintenance behaviours only. While it has been shown that behavioural responses to PV might include replacement of appliance and physical improvements to the dwelling, it is clear though that there is a limit to how much saving could reasonably be achieved, allowing for at least a minimal 'social base load' of consumption (Wilhite and Lutzenhiser 1999). This acceptable minimum will vary from household to household but clearly future research needs to identify how much saving might reasonably be achieved through behavioural responses to photovoltaics.

IMPLICATIONS FOR GOVERNMENT AND INDUSTRY

It seems then that in the short-term, the most promising form of behavioural response to PV will arise from the personal commitment of these households to energy conservation. Further benefits there might be seen through gentle reinforcement of the symbolism of PV panels and assisted by energy savings advice on use and maintenance behaviours. Purchase behaviours are less likely as most steps have likely already been taken and the purchase of more efficient appliances and compact fluorescent lightbulbs is likely only as existing equipment fails.

On a longer time scale, there is room for government and industry to encourage greater savings from behavioural responses to PV. Continued government support for PV will help its diffusion and hopefully the market will expand until different types of adopters enter the ranks of PV households. This could open up a range of possible mechanisms to encourage conservation, notably different symbolic responses which might encourage less-green households to invest in energy efficiency. Providing a premium feed-in tariff might be particularly appealing to later adopters for whom economic motivations may be more important than environmental values. Industry has a key role to play, in particular in the design and installation of monitors which allow real-time comparison of generation and consumption. With this information at hand, households could then assess their own energy use and determine the next steps to take.

Conclusion

A double-dividend from PV seems possible in the UK, combining green electricity with conservation behavioural responses. Current PV households have favourable knowledge, values, worldviews, and self-identities; they also have the monitoring devices required to display feedback information. The question is how they will act in response to these technologies. These results suggest that the PV system may represent a symbolic reinforcement of a personal dedication to responsible energy use and environmental values. However these households have already made significant investments in energy conservation and therefore support programmes should emphasise use and maintenance behaviours.

While the current potential for a behavioural response appears limited to small improvements in energy-efficiency, the importance of symbolic values in PV suggest that as the technology is diffused to more diverse households, PV might build upon its green symbolism and convert moderately conserving households into larger savers. Thus support for emerging PV markets should be continued. Monitoring technology must also improve to allow households to compare consumption and generation at the same time, thus facilitating informed conservation decisions.

This research is part of a larger project on behavioural responses to PV and further work will focus on the details of household responses, such as how monitoring information is incorporated into daily life and what specific conservation behaviours have resulted from the installation of PV. An examination of the potential market for PV should be conducted to see how likely certain symbolic values might be, as well as an assessment of how much domestic energy consumption could be reasonably further reduced. Finally, it would be beneficial to study the impact of PV on households which did not purchase the technology (e.g. social housing); work on this theme is currently underway in five European countries (RESURGENCE 2004).

While behavioural responses to domestic photovoltaics are not completely understood, this paper has indicated that it is fertile ground for further research. The potential implications of the research will be important not only for photovoltaics but also for other domestic technologies that change the way we think about energy, such as micro-wind, micro-CHP (combined heat and power), and even hybrid-electric cars. A 'double-dividend' of renewable generation and efficient consumption would be a significant tool in the fight against climate change.

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Appendix A

The following questions were used to assess the psychological constructs presented in this paper.

Knowledge

Each question here (drawn from ECI 2004; Park *et al.* 2001) was measured on a seven-point Likert scale, with the exception of "photovoltaics uses the energy of the sun to" which had a list of options: heat water, generate electricity, and don't know. Responses for each question were given scores between 0 (incorrect) and 1 (correct). The four scores were then averaged to give the overall knowledge index.

- Climate change is caused by a hole in the Earth's atmosphere (FALSE)
- Every time we use coal, oil or gas, we contribute to climate change (TRUE)
- Solar photovoltaics use the energy of the sun to: (Generate electricity)
- Solar photovoltaics don't work in the UK because it's not sunny enough. (FALSE)

World-view

Each question was measured on a seven-point Likert scale in accordance with the NEP methodology (Dunlap *et al.* 2000). The numbers in brackets below indicate the author's perception of the most pro-environmental response and responses were graded against this ideal, giving scores between 0 (no agreement) and 1 (complete agreement). The three scores were then averaged to give the overall world-view index.

- Modern science will solve our environmental problems with little change to our way of life (1 – Strongly disagree)
- Many of the claims about environmental threats are exaggerated. (1 – Strongly disagree)
- I do what is right for the environment, even when it costs more money or takes more time. (7 – Strongly agree)

Self-identity

These questions, based on Callero's methodology (1992), were assessed on a seven-point Likert scale. The score was calculated by determining the agreement between each question pair; i.e. the maximum agreement for each pair is 6 (7-1), the minimum 0 (*n-n*; n 0 [1,7]). The average of the two scores was calculated and reduced to a value between 0 and 1. Therefore a self-identity score of 1 indicates strong agreement with the perceived home-energy saver identity, regardless of what the respondent perceives that identity to be.

- Compared to people in general, a home energy saver is more likely to pay attention to energy bills:
- Compared to people in general, I am more likely to pay attention to energy bills:
- Compared to people in general, a home energy saver is more likely to enjoy DIY (do-it-yourself renovations):
- Compared to people in general, I am more likely to enjoy DIY:

Values

These were measured using the following set of values, reduced from Rokeach's list (1973) by Banks (1999). Respondents ranked the five items in accordance with Rokeach's methodology, from 1 = most important to 5 = least important. The abbreviated value name used in the paper is given in brackets below but was not part of the original questionnaire. The most important value was used in the analysis.

- Clean, polite, independent, helpful, responsible, obedient (traditional)
- Protecting the environment, unity with nature, respecting nature (environmental)
- Existing and varied life, curiosity, comfortable and prosperous life (quality of life)
- Social recognition, ambitious, lasting contribution (social recognition)
- Sense of belonging, equality, family security (equality)