Enhancing energy efficiency through smart control: paths and policies for deployment

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Abstract

Smart devices and controllers are often proposed as an effective way to both minimise and optimise the timing of energy consumption in order to minimise the peaks in demand. A key component of the Smart Grid vision is the widespread use of such devices, advanced as a way to mitigate the intermittency of renewable energy generation which in turn is crucial to the decarbonisation of electricity supply.

In this paper, we focus on the use of smart controllers and the adoption of distributed renewable generation at household level as part of the transition from a conventional electricity grid to a Smart Grid. We utilise an Agent Based Model to investigate the effectiveness of both smart controllers and distributed generation in reducing household energy consumption, alone and in combination. We also investigate the possible paths to adoption of such devices and the interdependence of the case to adopt one on the other. Electricity consumption patterns for households in the model are heterogeneous and generated in accordance with data for the UK and initial adoption rates for distributed generation are calibrated from UK National data.

We illustrate the potential for smart controllers to alter demand patterns over time both with and without distributed generation. We show the effect of order of adoption of devices at the householder level on the energy consumption of their building, but also on consumption at a larger scale and highlight issues for policy makers designing policies intended to incentivise a transition towards smart control of energy demand.

Introduction

Many EU countries have explicit policies to meet sometimes ambitious targets for CO_2 emissions reduction in the medium to long term (for instance by the years 2020 and 2050). In some, for instance the UK, these policies have been made legally binding via legislation (UK Parliament 2008).

From those targets, national, regional and local governments have developed strategies which often describe paths to move from today's routine emissions to a low carbon future. In the UK, the national strategy for decarbonisation in set out in a suite of policy documents and legislation (UK Parliament 2008; DECC 2009; DECC 2010; Ofgem 2008; DTI 2003). What these documents in combination provide is an approach which focuses on a transition to the use of electricity as the primary fuel for space and water heating (from the current situation of mostly natural gas fired boilers) and transportation (from the current reliance on petrol and diesel). For this to provide de-carbonisation, a concomitant transition in electricity generation from the currently fossil fuel dominated situation to a vastly less carbon intensive supply mix is necessary. In summary, the strategy is to move from fossil fuelled transport and heating toward electric vehicles and heating with de-carbonisation being delivered by a concurrent de-carbonisation of the generation of electricity.

Such a strategy immediately presents two challenges:

1. Phasing of transitions – if the shift of demand from direct use of fossil fuels to electricity for heating and transport happens before de-carbonisation of electricity generation, there is a large potential for those activities to actually *increase* their carbon intensity.

2. Capacity of the electricity network – use of electricity for heating and transport will place a significant extra load on the electricity transmission and distribution networks. The currently installed infrastructure may not have the capacity to cope with that extra load.

At the national level, decisions regarding incentivisation for various potential solutions are made, for instance whether to encourage nuclear powered electricity generation, large scale investment in bio-fuel development, large scale renewable schemes such as wind farms, medium scale schemes (such as community owned PV or anaerobic digesters) or micro distributed solutions such as the adoption of per-household PV.

Both the challenges noted above exist at several scales across both time and space. One often cited way to meet the second challenge is the introduction of smart grids in order to intelligently shape demand such that peak loads are minimised – by moving loads which are not time specific to more favourable times of the day and intelligently switching off unnecessary load. As the capacity of the infrastructure is largely determined by peak load such an approach will limit the infrastructural capacity increases required by the additional use of electricity. This paper represents a step toward analysing the effects of phasing on energy efficiency both in terms of physical efficiency and CO_2 intensity in a single building and, crucially, in a group of building such as might exist on a local distribution network. The implication of this for required capacity on the network and policy is analysed.

The next section analyses in more detail the effects of the national policies and strategies at local level in the UK and the implications of phasing at that scale. This analysis motivates a simulation of adoption behaviour to explore the effects of the phasing of technology of adoption for two technologies (photovoltaic generators and smart electricity controllers for domestic buildings). The following section describes a simulation model, including a subsection describing the potential behaviour of electricity consumers. The model described is constructed using an innovative methodology, incorporating the behavioural factors described. The model is an agent based model, with agent behaviour and interactions defined but with system behaviour allowed to evolve within environmental constraints. The model is run for several local scenarios. The results of the model simulations are presented and analysed, with observations made as to the implication of the findings on building electricity consumption, larger scale demand, overall efficiency and de-carbonisation. Finally, the implications of these observations are drawn together as conclusions which are relevant to policy makers.

The local component of challenges

Each of the components of the national and regional level strategy set out in the introduction has a related local component. For instance, one component of the national strategy to decarbonise electricity generation is to encourage the adoption and use of small scale distributed renewable generation, such as household or community scale photovoltaic installations, micro-CHP and other mini and micro scale renewable generators. At the local level, this means that electricity network users are deciding whether and when to adopt renewable generation.

Another component of the national strategy which has local implications is the move toward electrification of transport and heating. For such a move in the domestic sector to have an appreciable impact on national energy consumption patterns and carbon intensity requires large scale adoption of (potentially hybrid) electric vehicles and electrical heaters (most likely heat pumps) respectively. Again, at the local level, this implies that electricity network users are deciding upon adoption of these technologies.

Taking into account these impacts, the envisaged move towards electrification of heating and transportation will increase load on the electricity network dramatically – a 2.5 times increase in household demand is commonly accepted (e.g. Winser 2010, slide 12; Gan et al. 2011). This effectively increases risk at the local level – such an increase would potentially overload local circuits leading to blackouts. The 'Business as Usual' strategy to overcome such risk is large scale investment on the local level (as well as at higher scales) in order to reinforce distribution networks to cope with the increased load. The scale of such investment for the UK has been estimated at up to ~€12 bn[i] (e.g. Gan et al. 2011; Pudjianto et al. 2013). This provides a hefty incentive for owners of local distribution networks to find innovative solutions to limiting the scale of the increased load on the network thereby limiting (or indeed eliminating) the required investment.

It should be noted at this point that the adoption of local distributed generation ***in combination*** with adoption of electrical heating and/or electric vehicles will tend to complement each other allowing greater use of electricity for those energy intensive activities without increasing load on the grid as much as might be feared as the electricity is both generated and stored locally. Furthermore, if these two adoption paths are considered ***along with*** smart control and/or energy storage and/or energy efficiency through works to buildings then the load on the grid will be even further reduced as the problem of very fine grained phasing between generation of electricity and its consumption will be ameliorated.

The combination of events required by the paragraph above gives some indication of the complexity of the system transition that is required if the UK is to make its strategy for decarbonisation workable. We require large scale adoption of multiple technologies, some of which require considerable financial means at the local level as shown in Table 1[i].

Simulation model for adoption decisions and their impact

In our simulation, we concentrate on two of the main technologies which must be adopted at local level in order to deliver the government strategy for de-carbonisation and smart grids. We concentrate on the domestic level, although the same principle might be expanded to include community level technologies. The technologies we select are photovoltaic generators and smart controllers. The former have become familiar in recent years, the latter may still require some explanation. The functionality of the smart controller in these simulations is to 'flatten' the demand of the household in which it is installed as far as possible, within the constraints of the desired usage pattern of that household and the available technology. In order

Table 1. Costs of technology modeled.

Technology	**Cost (€)**
Household photovoltaic generator	7,200 (based on EUR ~2.4/Wp and 2.5 kW system, see e.g. Cherrington et al. 2013, fig. 2)
Smart Controller	900 (estimate based on trade evaluation price from http://www.enistic.com/trade-evaluation-kit and price for a rather simpler product from http://www.rudgerenewables.co.uk/intelligent-power-management/the-immersun)

to perform this function, the controller receives a signal from the household's electricity supplier which gives it information necessary to schedule the household demands that it has been allowed to control. This signal is often conceived as being a real-time price for electricity, but it need not be tightly coupled to price. In our simulation, the signal is an engineering one designed by the supplier to flatten the aggregate load of its consumers based on a profile of consumer response to incentives which it learns over time. The detailed algorithmic implementation of this is beyond the scope of this paper, but is described fully in (Boait et al. Under review).

The simulation is initialised with 1,000 agents representing households which are all physically suitable for the installation of PV panels and/or smart controllers[ii]. These households are given physical heat loss properties drawn from a distribution in order to match national statistics. They are assigned occupancy again drawn from a distribution to match national statistics. The households are then assigned appliances taking account of occupancy and in order that the overall appliance ownership of the sample population matches national statistics.

Baseline demand profiles are then generated on a per-household basis, using the techniques described by Stokes (2005) for generation of appliance, lighting and cooking loads alongside a single node model to calculate the building heating loads for space and water heating. All households are assumed to use a heat pump for space and water heating, with a resistive immersion heater available to supplement water heating load if required. The heating model runs actively in the simulation, calculating loads based on external temperature and desired set point at each time step.

BEHAVIOUR OF DOMESTIC CONSUMERS

As well as the physical characteristics described above, the agents are also assigned segmented attitudes to pro-environmental behaviour, drawn from a distribution to match the distribution of such attitudes as defined and measured by the UK Government's Department for the Environment, Farming and Rural Affairs (DEFRA 2008). This report highlights that the particular behaviour considered in this paper (installing microgeneration) is characterised by a low willingness and ability across the population of the study (Figure 1). The willingness and ability were determined from a combination of DEFRA's own survey work (DEFRA & BMRB 2007) and a commissioned report "Public Understanding of Sustainable Energy Use in the Home" (Brook Lyndhurst 2007). The combined sources indicated that 30 % of the population were willing to, and 7 % of the overall population had the ability to, install microgeneration. This is based on those respondents stating that they either already had microgeneration or were seriously considering fitting solar panels, solar heating or wind turbine. The combined low willingness and ability is likely to be influenced by the relatively high capital cost of microgeneration to some degree – with one of the reports stating that "initial cost and payback period was seen as the main obstacle" (Brook Lyndhurst 2007, p. 35). Other factors influencing willingness were perception of aesthetic disbenefits, lack of awareness of different options and a perception that microgeneration is for the countryside, not towns and cities.[iii]

It also shows that within the population, there is variation in willingness and ability to take various environmental actions. Although the report contains no specific numbers defining relative willingness and ability between groups, a qualitative indication of these are given in the DEFRA report and reproduced in Figure 2.

Taking these two graphs into consideration, households are assigned an economic ability and propensity to install technologies as follows in Table 2. Each household makes an adoption decision based upon the propensities given above in combination with a number of factors detailed in Table 3.

These factors are combined in an agent by assigning the homeowners with decision making processes based on the Social Cognitive Theory of Bandura (1986). The decision process works as follows – each agent initially draws a time to think about adopting technology from a Poisson distribution with a mean of 30 days. When that time occurs in the simulation, the agent decides whether to adopt a technology based on a combination of the factors described above. The agent also draws a time period to the next time it will think about adoption again from a Poisson distribution with mean of 30 days. In this way, adoptions are likely to be staggered over time as might be expected in a realistic situation.

A strong component in the decision to adopt a technology is the economic case for adoption. This is a complex factor to model in itself as the case depends on technology capital, each householders' desired payback period, householders perception of economic benefits and the tariff for electricity consumed, generated and/or exported to the grid. For example, the economic incentive to install a smart controller is rather small if the only ongoing 'payback' is avoided consumption – typically each kWh of consumption avoided will avoid €0.12 and the amount of *total consumption* that can be avoided simply by energy efficiency appears to be rather small. Typically, avoided consumption is of the order 2–5 % of total consumption – see for example, the results from use of the oPower system reported by Allcott (2011), or the results of the UK Energy Demand Reduction Pilot, EDRP (AECOM 2011). However, if a variable tariff which charges different amounts for consumption at different times of the day is available, the benefits of demand shift-

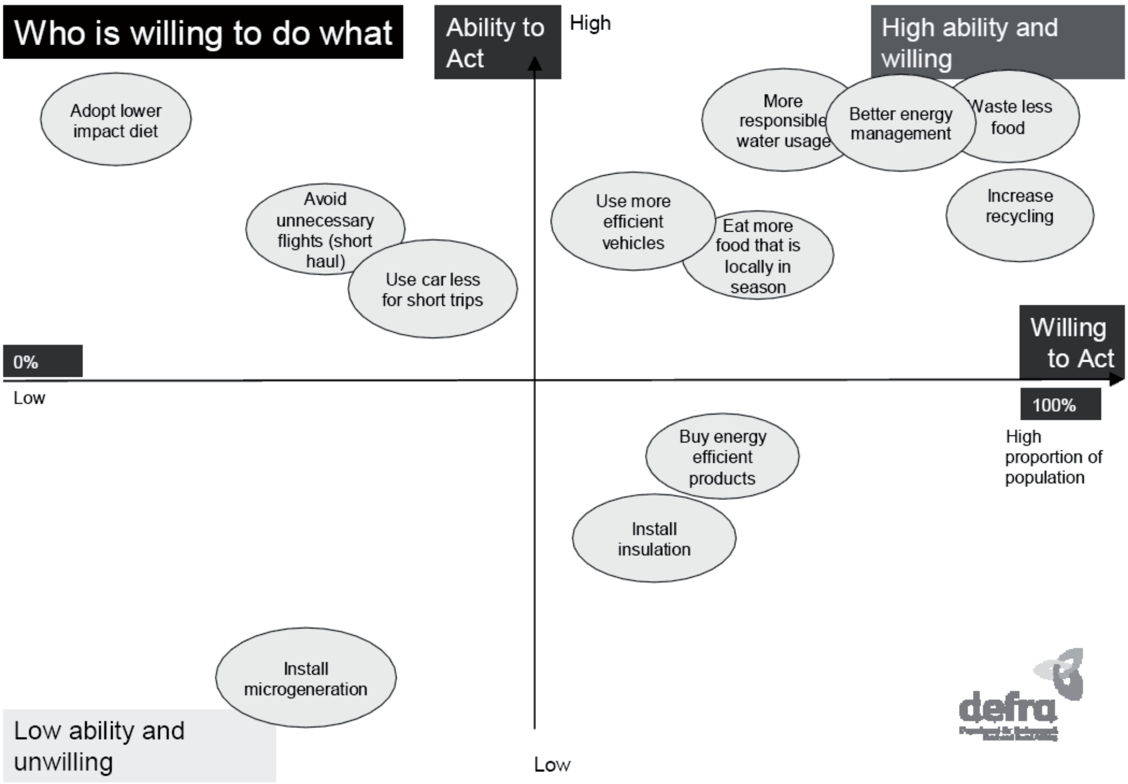
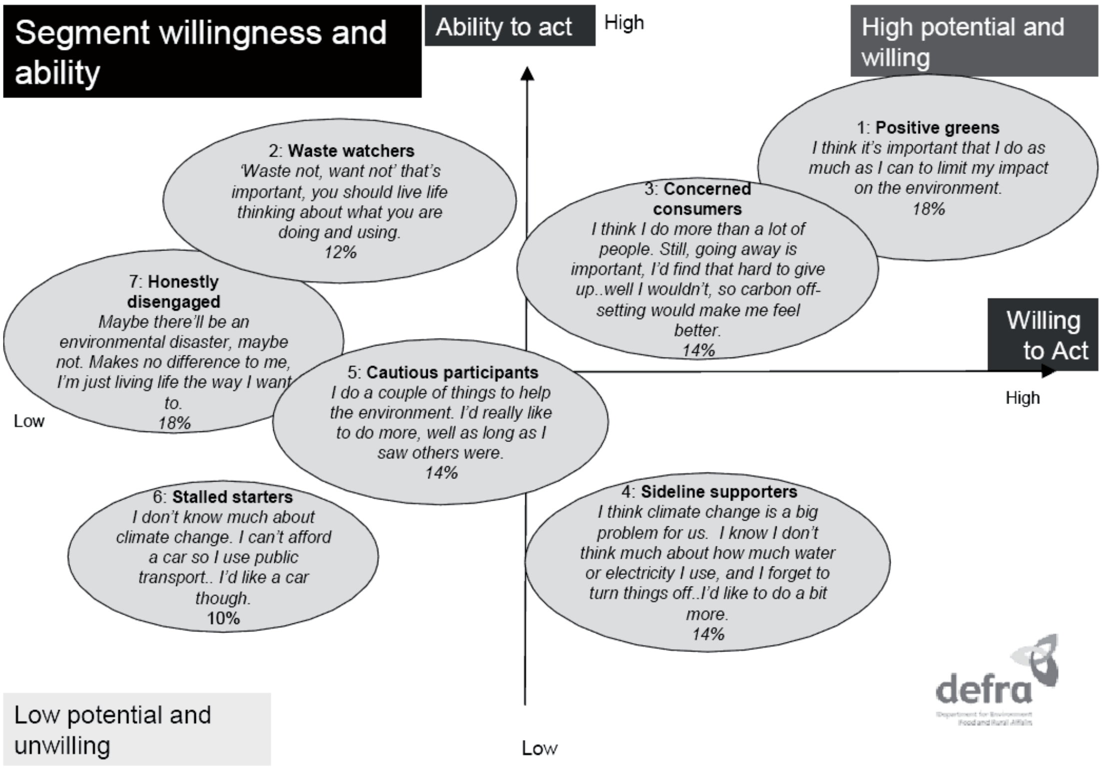


Figure 1. Relative willingness and ability to install microgeneration (DEFRA 2008, p. 7).



1: **Positive greens** *I think it's important that I do as much as I can to limit my impact on the environment.* 18%

2: **Waste watchers** *'Waste not, want not' that's important, you should live life thinking about what you are doing and using.* 12%

3: **Concerned consumers** *I think I do more than a lot of people. Still, going away is important, I'd find that hard to give up..well I wouldn't, so carbon off-setting would make me feel better.* 14%

4: **Sideline supporters** *I think climate change is a big problem for us. I know I don't think much about how much water or electricity I use, and I forget to turn things off..I'd like to do a bit more.* 14%

5: **Cautious participants** *I do a couple of things to help the environment. I'd really like to do more, well as long as I saw others were.* 14%

6: **Stalled starters** *I don't know much about climate change. I can't afford a car so I use public transport.. I'd like a car though.* 10%

7: **Honestly disengaged** *Maybe there'll be an environmental disaster, maybe not. Makes no difference to me, I'm just living life the way I want to.* 18%

Figure 2. Distribution of seven segments of UK population by attitude to pro-environmental behaviour (DEFRA 2008, p. 8).

Table 2. Household categorisation and installation propensities.

DEFRA pro-environmental behaviour category	Economic ability to install	Propensity to install microgeneration	Propensity to install smart energy controller
1 : Positive Greens	1	0.001	0.5
2 : Waste watchers	0.75	0.0005	0.5
3 : Concerned consumers	0.75	0.0005	0.2
4 : Sideline supporters	0.2	0.0002	0.05
5 : Cautious participants	0.5	0.00025	0.2
6 : Stalled starters	0.2	0.000025	0.05
7 : Honestly disengaged	0.2*	0.0000025	0.05

** It should be noted that in Figure 2, households in segment 7 have an intermediate ability to act. However, in the more detailed segment profiles in the report (e.g. pp. 84 & 106–109) it is indicated that segment seven have the lowest income bracket and are therefore, in this simulation, taken as having the lowest economic ability to act.*

Table 3. Factors influencing adoption decisions.

Factor	Value (a range is given where the value changes between agents)	How determined in simulation
Perceived social normality of having PV	0–1	Observation of number of neighbours with PV installed
Perceived social normality of having smart controller	0–1	Number of neighbours with a smart controller – random draw to determine whether they talk about it p=0.05 Positivity weighted by actual savings
Perceived economic benefit of PV ownership	€650/year	Estimated average economic benefit of a 3kWp system €650/year (EST 2012)[i]
Perceived economic benefit of smart controller	0–5% of household electricity bill	Based on current situation. This would be significantly affected by different tariff structures.
Cost of PV	€7200	Based on €2.4/Watt see refs in previous section
Cost of smart controller	€900	Based on prices of currently available comparable devices see refs in previous section
Economic sensitivity of household	0–1	Random selection from uniform distribution on initialisation

ing become far greater – with perhaps €0.36/kWh being saved by shifting demand from one time to another as well as the potential for far greater numbers of kWh to be moved. Examples of potential tariffs and their likely effects on consumption can be found in excellent meta studies by Faruqui and colleagues (Faruqui & Sergici 2010; Faruqui et al. 2010; Faruqui & George 2005). Similarly, adoption of distributed renewable generation is affected by the tariff received for kWh generated. These can range from simply cost avoidance as above (for instance if a household uses electricity generated by its own generation it avoids the cost of consuming that electricity from the grid), through avoided cost supplemented by a payment for exported electricity through to a tariff where all generation receives a payment regardless of whether it is consumed locally or exported, in addition to avoided cost of consumption and payment for export.

For generation tariff, we use the current UK Feed in Tariff (FiT) structure, limited to photovoltaic installations. This consists of a payment per kWh generated (dependent on the size of installation) and a payment for exported electricity of 4.5 p/kWh. This is obviously in addition to avoided cost of consumption – which is calculated from the cost of consumption if the renewable generation were not present and is dependent on the consumption tariff as described in the preceding paragraph. Finally, the household's economic case for adoption is combined with its economic sensitivity as described in Table 3 and forms a factor in the decision to adopt.

The smart controller is modelled as a device which responds to a signal sent to the Household agents from an energy supplier. The objective of the smart controller is to move any energy consumption over which it has control from periods where the signal is high to periods where the signal is low. It does this in a probabilistic fashion, in order to avoid problems of co-ordination where all smart controllers move demand into a low signal timeslot, thus creating a demand 'spike'. The controller is constrained to:

1. maintain temperature within 0.5 °C of the household's set point in order to maintain thermal comfort
2. move water heating only forward in time (so that the hot water is available to the household when needed)
3. switch off cold appliances for only one half hour slot per day, maintaining their temperature within acceptable limits
4. move wet appliance loads (washing machine, dishwasher etc) only within two hours of the originally desired use time.

The signal received by the controller is sent from the electricity supplier and is optimised to achieve the supplier's objective of flattening its net demand. The full mechanism by which this is achieved is described in (Boait et al. 2013).

In this simulation, we evaluate cost to the households, both individually and collectively, and the CO_2 intensity of the overall energy used in the simulated community. The generation due to adopted PV is simulated using a basic constant efficiency approximation to translate insolation from CIBSE Test Reference Year (TRY) weather file for Birmingham into electrical output at the household. In order to minimise complexity in presenting results, all houses (if they adopt PV) adopt the same size (3 kWp) installation and external temperature (from which baseline heating load is calculated) is maintained constant. Both the electrical model for PV generation and refinement of the sizing of installation to reflect property characteristics are possible within the simulation framework, but are not presented here.

In order to calculate the CO_2 savings, we take a representative profile of CO_2 intensity for grid electricity – in the UK this typically varies from hour to hour, day to day and seasonally. However, there are consistent patterns such as lower CO_2 intensity in periods of low demand. The pattern we use in analysing simulation results is shown in Figure 3.

It is appropriate to note here that the CO_2 intensity thus calculated is a pessimistic estimate of the benefits gained by installation of smart controllers and/or distributed renewable generation. Convincing arguments have been made that in fact the CO_2 saving ought to be made using the marginal CO_2 intensity, which has been found to be higher by a factor of around 1.5 (Cooper 2011; Hawkes 2010).

Finally, we measure the aggregated variables presented in Table 4 at the end of the one year simulation run, as well as recording pathways of adoption for households. Results are presented in the following section.

Results

Table 5[i, iv] presents results for 6 scenarios for which simulations have been run using the model described above. All simulation runs presented in this section were run for a period equivalent to one year. As each time step in the model represents half an hour, this requires a run of 17,520 time steps. In addition, the smart controllers and the supplier's model of its consumers' behaviour require 55 days' worth of simulation (2,640 time steps) to initialise. Thus, measurements are taken between time steps 2,640 and 20,160. All simulation runs were performed with the same random seed to ensure comparable initial conditions.

As these are preliminary results from a stochastic simulation, caution should be exercised in interpreting the absolute values in the tables and graphs before. Whilst these should be representative, they are not calibrated to the extent that they could be used in a quantitatively predictive fashion. Rather, they should be used to inform analysis of the relative merits and effects of different scenarios.

Scenario 1 represents the baseline case – all households run for a year with no photovoltaic generation or smart control.

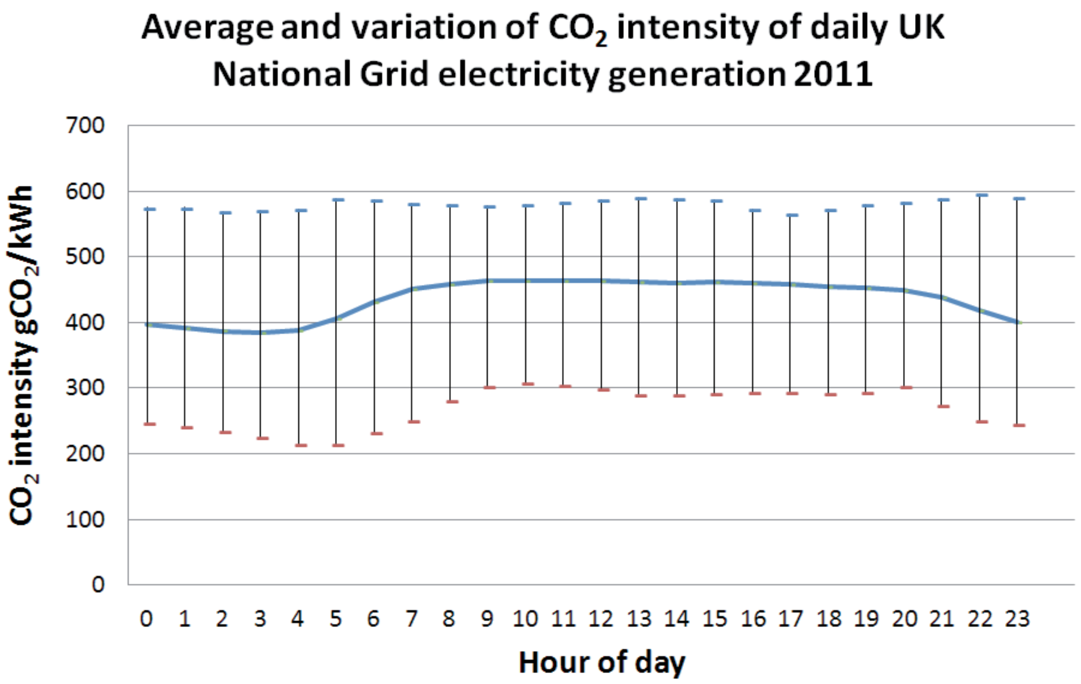


Figure 3. Average CO_2 intensity in each hour of the day, UK National Grid electricity Generation 2011. Source data: (EarthOrg.co.uk 2011).

Table 4. Measured output variables.

Variable	Measured over
Actual savings	Aggregate over households
Demand reduction	Aggregate over households
CO_2 reduction	Aggregate over households
Peak load	Max at aggregator

Table 5. Scenario measures.

		Aggregate over 1000 households				Per household
Scen No.	Scenario	CO_2 saving (tonnes/ year)	Range of half hour demands (kWh)	Maximum demand in a single half hour timeslot (kWh)	Standard deviation of HH demands (kWh)	Average saving with flat tariff (€/year)
1	Baseline: No smart controller, no PV	0	590	1116	154.8	0
2	Max renewable: All houses have PV at start, no smart controllers	1060	1710	1060	296.4	300
3	Smart control: All houses have smart controller at start, no PV	-80	383	1016	75.5	-16.8
4	All houses have smart controller and PV at start	950	1668	1051	276.7	182
5	Current situation with added smart ~1% of houses have PV, all have smart controllers	-67.5	378	1016	72.8	-18
6	All houses have smart controller, choose whether to adopt PV (1% initially have PV)	-54	703	1043	79.6	-14.4

This demonstrates the composite variability of the demand profiles over the 1,000 households.

Scenario 2 presents a (rather extreme) scenario where all households adopt PV. Unsurprisingly, this yields the greatest CO_2 savings and the greatest monetary savings to the household (albeit at a rather large capital cost). However, there is a large increase in the variability of demand and a very small reduction in peak demand due to coincidence of PV generating in the timeslot which happened to have the largest demand.

Scenario 3[v] in Table 5 shows that, in a relatively static situation, the smart controller alone best achieves the objective of reducing peak demand and "flattening" the demand profile (i.e. maintaining as close as possible to a constant demand). The mechanism by which this is achieved is described in more detail in (Boait et al. 2013).[v]

In scenarios 3, 5[v] & 6[v], the average loss to the households of around €14–18/year is equivalent to roughly €0.04/day or €0.06/kWh consumed. This indicates that the reduced tariff needed to induce customers to consent to smart control from a purely economic point of view would be around €0.06/kWh. If the capital cost of the controller (~€900) is to be amortised over, for instance, five years, the householder would need a further €0.60/day benefit to make the investment pay in the longer run. This could be generated from a reduced tariff or, like the FiT for PV, policy based subsidy. In addition to this economic case for smart controller adoption, it is likely that a greater reduction than this may be needed if the other psychological barriers present in adoption behaviour are to be overcome. A sophisticated economic analysis of the potential for reduction in price of controllers is beyond the scope of this paper.

Scenario 4 shows an interesting result – the adoption of smart controllers along with PV in all households produces a small reduction in peak demand seen on the network as well as in variability. However, it produces a marked negative effect on the savings made by the household in the year both in terms of money and CO_2. This scenario remains the subject of investigation at the time of writing, however it is believed that this may be due to the water heating required in the morning across the simulation being constrained to move forward in time, rather than being deferred to the middle of the day where the PV generation could offset the load.

Scenario 5 is one which translates roughly to installing smart controllers in all UK homes now. Currently ~1 % of UK households have PV installed. In this scenario, we show the effect of installing smart controllers in all homes at the present levels of PV adoption.

What the above results demonstrate is that there is a trade-off between objectives of reducing CO_2 emissions and flattening demand. The scenarios which have full smart control but little or no photovoltaic adoption (3 & 6) succeed in reducing both the maximum demand of the 1,000 houses under simulation and the variability of demands presented. However, they show a slightly negative CO_2 saving.

A useful facet of the simulations is the ability to track adoption patterns. This facility can be used to give insight into the interplay between the adoption of both devices. In the relatively simple examples described, the adoption of a photovoltaic generator has a significant effect on case for adoption of a smart controller and this in turn has a significant effect on the peaks and variation in demand seen by the supplier of the simulated households.

The case to adopt the smart controller is, of course, largely dependent on the tariff available to those consumers using it. In Table 5 we showed that with a flat tariff, the consumer is likely to lose money slightly by adopting a smart controller. However, the flattening effect of the controllers produces benefit for both energy suppliers (who can bid with more confidence for flat demand in the wholesale market) and energy infrastructure owners (who need to do less infrastructure reinforcement in the face of vastly increasing overall demands). This benefit can, in part, be passed to the consumer to incentivize their adoption of the smart controller and one would expect that in a competitive market this would occur.

Discussion of pathway implications

The graphs above indicate that with smart control alone, there is potential for both saving to households and demand flattening. The exact implementation of smart control is the subject of separate research, with many possible arrangements for a service provider to influence demand in a smart fashion (e.g. Roscoe & Ault 2010; Vytelingum et al. 2010; Boait et al. Under review). However, with the scheme implemented to specifically reduce variation in demand across the prosumer base (i.e. 'flatten' demand), the results show good performance, reducing the range and standard deviations of aggregate demand.

With photovoltaic adoption alone, whilst the overall quantity of electricity required by the prosumer base is obviously reduced, the consumption pattern without any form of smart control is actually made far more variable over time. This is in line with expectations of intermittency from renewable generation. The standard response to this is to add some form of storage, often direct electricity storage such as batteries but increasingly energy storage in the form of heat. This is highlighted by the emergence of a niche industry allowing owners of photovoltaic cells to use "excess" electricity to heat water via an immersion heater – in effect storing the excess electricity generation in the form of heat. A more smart solution, however, can give better results still, by not only heating water (when the requirement for hot water may or may not be present), but also using the thermal mass of a building whose set point temperature is known to store energy.

What this research highlights is the interplay between microgeneration adoption (in this case photovoltaics) and adoption of smart control in households. When the expected savings from each technology and their cost is examined before a household has either technology, we see that the adoption of PV (which already benefits from generous incentives via Feed in Tariffs) has a fairly strong economic case for adoption. This has empirically observed to have increased adoption in the UK and we see this reflected in the simulation which in turn increases each agent's perception of the social normality of PV adoption. In the case of the smart controller, though, no such incentives are currently available and we see the trade off between demand flattening via load shifting with the slight increase of overall consumption from the heat losses incurred by such shifting, making the economic case for adoption weak.

If the photovoltaic generators is adopted first, the economic analysis for the smart controller means that the projected benefits are rather less as the net electricity demand after the PV generation and hence the electricity bill is reduced. This would lead to the conclusion that the adoption of smart controllers would be less likely after a household had adopted photovoltaic generators. Of course, this is critically dependent upon consumption tariff. With the smart controller design presented, the tariff would have to take account of the probabilistic nature of demand shifting for the individual household. Such a probabilistic demand shifting regime is beneficial to suppliers and network operators as has been shown above, but if a tariff which heavily penalised consumption at certain times were employed a householder could lose out significantly if the probabilistic algorithm happened to assign consumption to these expensive times. Hence, a scheme which offered a rebated tariff in return for household adoption would be most likely to incentivise adoption of smart controllers. On the other hand, for households which already have smart controllers, the economic analysis for the purchase of photovoltaics barely alters.

The most economically advantageous thing to do with the present policy landscape is adopt PV only. However, evidence shows that there are other factors in play. Empirically, it can be seen that people are keen to use excess PV generation themselves rather than export to the grid – hence the emergence of controllers that switch on an immersion heater to heat water rather than export generated electricity to the grid (Rudge Renewables 2012). This can make economic sense – a generated kWh that is used to avoid consumption yields around €0.12, whereas the same exported to the grid yields €0.054. However, such a case only holds if the 'avoided' consumption would have happened in any case and if the heat losses incurred by such storage are less than the benefit gained.

In addition to the current lack of an incentive scheme or subsidised tariffs to encourage adoption of smart controllers, it is likely that social pressure to adopt smart control devices is much weaker – for simple reasons such as the fact that they are not easily observable (tending to be placed in an unobtrusive location and always within the home so observable only to those invited into the house) and less likely to be talked about between social contacts.

The simulation methodology described offers a means of exploring the effect and relative importance of these factors. It would be interesting to extend the simulation to encompass a greater range of technologies. Boait (2008; 2007) has previously shown that the adoption of micro-CHP *in conjunction* with photovoltaic panels and a smart controller could give significant co-benefits. The model described in this paper can be used to explore the pathways and likelihoods of reaching a scenario where such an arrangement is commonplace.

Conclusion and further work

This paper represents a report of preliminary results for a work in progress. It contributes toward an understanding of the interdependence of adoption patterns for smart controllers and distributed renewable generation (in the case described, domestic photovoltaic installations). Further work to be performed includes the addition of further technologies for adoption (such as micro-CHP as mentioned in the previous section), sensitivity analysis for all parameters, refinement of the decision making model in the household agents and increased repetition of scenarios with further random seeds to generate a larger ensemble of results. The methodology outlined is suitable to accommodate this further work.

We have also moved toward an analysis which takes account of interplay between scales. We see the effect of individual households' decisions on a larger scale as the technology adopted changes the demand profile which in turn changes the electricity supplier's model of its consumer base. We also see scale effects in the opposite direction where there is a (perhaps more obvious) effect of national and regional policies on individual household decisions. Finally, we see the effect of decisions made on a relatively long timescale (technology adoption) on the short term characteristics (half hourly demand) on the grid. Crucially – the results presented indicate that as adoption of technologies takes off, the incentives for further adoption change even without change of national policy. This can lead to widely varying patterns of adoption as scenarios evolve.

Our findings suggest that it is likely that, in the presence of electrical space and water heating, the adoption of photovoltaic generators weakens the economic case to install a smart controller in the same building. However, there is empirical evidence that householders that have taken advantage of the Feed in Tariff have some appetite for a controller which can avoid excess generated energy being exported to the grid. This observation has important implications for the UK at present; whilst the current strategy emphasises the importance of smart grids and adaptable demand, the present policy regime is encouraging mass photovoltaic adoption without smart controllers. This implies a conflict between two strategies with apparently the same goal – to contribute toward meeting the legislative emissions targets of the UK. The present and future economic case for the installation of smart controllers may be weakened by the present strategy of highly incentivised photovoltaic adoption.

The implication of our findings for policy makers is that policies which apply blanket incentives to large numbers of small scale agents (households) can have rather unpredictable consequences when considered in light of multiple policy goals requiring adoption of multiple technologies over time. The Feed in Tariff is a mechanism that demonstrably increases the number of domestic renewable generators; however, this may adversely other policy goals, such as the adoption of smart controllers for a smart grid. Thus, the incentives for a single building to install microgeneration and save both energy and money may in fact hinder system wide initiatives to decarbonise. The implications for system wide energy and carbon efficiency must be carefully considered; this paper describes a novel methodology for investigation of the interplay between such policies. Initial results suggest that if the adoption of smart controllers is to play a significant role in future UK electricity networks, subsidy of some kind will be necessary to incentivise widespread adoption – particularly as such adoption will follow some years of distributed renewable generator adoption in response to policy incentives.

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Endnotes

[i] All monetary values converted by the author from GBP to EUR at a rate of 1 GBP = 1.2 EUR.

[ii] In this simulation, all houses are considered suitable for installation of 3 kWp PV systems. Adding houses without the possibility of PV installation is possible, but is not considered for the purposes of this paper.

[iii] The Feed in Tariff, introduced since this research and accounted for later in this paper, will have had some effect on these figures, but they represent the best estimate of predisposition to install microgeneration available at this time.

[iv] Note in this table that with large penetrations of PV, there are some periods of net export hence the range of demands can exceed the maximum.

[v] Note the slightly greater overall consumption caused by the smart controller shifting heating loads to more appropriate times of the day. This incurs some heat losses, which *prima facie* creates greater CO_2 emissions due to the consumption at the household level. It should be acknowledge, however, that the ability to plan more constant (baseload) central generation rather than using peaking plant may offset the losses so incurred. This is supported by (Cooper 2011) who finds that the marginal CO_2 intensity of peaking plant is far greater than the average figure used in our calculations.

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