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Exploring Implications of Capacity-Based Electricity Pricing for Peak Demand Reduction

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***Abstract*—In the face of climate change, the UK has set concrete goals to decarbonise energy systems. Associated strategies include increasing electrification of residential heating and transport and the substitution of fossil fuel energy sources with renewables. These entail expensive infrastructure reinforcements to support increased peak loads. Energy demand management can help mitigate this anticipated load increase. Capacity-based pricing is a mechanism to incentivise energy demand management by charging for a maximum power draw as opposed to the volume of consumed energy. In this text we use a persona technique to study how user needs drive the typical energy services that compose the aggregate power draw in a family home. We use this to reflect on user feedback (obtained through a demand shifting workshop with 10 participants) to discuss the factors that would allow excessive power demand to be shifted away from peak demand times, thus reducing the maximum draw. Subsequently, the role of ICT as an enabler of energy demand flexibility is discussed which provides the basis for a quantitative evaluation of demand flexibility scenarios.We find that household power draw is dominated by a few services that require significant changes to increase flexibility.**

I. Introduction

Global energy demand has grown steadily at around 2.4%/year (± 0.08%) since 1850. In 2017, it grew by 2.1% after 5 years of 0.9% average growth, with over 70% derived from fossil fuels. Energy-related carbon dioxide emissions increased concurrently by 1.4% [1]. Scenarios by the UKs National Grid suggest that annual electricity demand will increase from 297TWh in 2017 to 373-441TWh in 2050. Peak demand is expected to increase accordingly from 59GW in 2017 to 79-87GW in 2050 [2]. In the face of climate change, the UK, like many other countries, has set targets to decarbonise the energy system [3]. These plans require the substitutions of fossil-fuel-based heating and transport systems with renewable electricity-based systems.

One of the challenges associated with the growing need for (clean) electricity is the need for significant reinforcement of the electricity grid to accommodate this projected increase in unregulated demand, particularly peak demand at times of heavy usage (typically between 5-9pm) [4]–[6]. To avoid costly additional capacity, alternative approaches such as increasing flexibility, defined as "modifying generation and/or consumption patterns in reaction to an external signal (such as a change in price) to provide a service within the energy system", are being considered [5], [7].

In the context of UK electricity networks, large electricity consumers have been charged by capacity for some time [8]. Residential households, on the other hand, are typically charged via a model that combines standing charges (measured per day) and volume-based charges in proportion to consumption (measured per kWh). Capacity-based pricing has the potential to incentivise consumers to be more flexible in their service consumption and reduce or defer consumption at peak times. In this text, we study for the first time the implications of such a capacity-based alternative charging model for residential households from the ICT4S perspective.

In this paper we explore the following **questions**:

1) What energy services constitute peak time electricity demand for residential households?
2) What energy services currently offer flexibility to accommodate capacity constraints?
3) How can ICT augment energy services to increase flexibility or substitution potential?

In order to investigate the implications of a capacity-based pricing approach and identify new strategies that help defer peak time electricity consumption, we have drawn on the notion of personas [9]. In our context this involved the creation of a representative UK household undertaking its activities during a normal peak-demand time. We use this personification to identify energy consuming activities and services, and model the energy use profile of our representative household and explore implications of demand shifting on its power profile. We then integrate the feedback from an energy demand shifting workshop carried out with 10 participants to discuss how energy consumption at peak demand time can be deferred and reduced. Following from this we discuss current barriers to greater flexibility and identify strategies to overcome these barriers based on ICT innovations and policy interventions, and consider the social implications.

II. Background

Increasing penetration of variable renewable energy sources places increasing strain on energy systems. Aside from the total levelized cost of electricity, their integration into energy systems also imposes integration costs upon specific market participants. These costs depend on the extent to which demand-side and supply-side flexibility can counteract variable and uncertain renewable energy generation. The most cost-efficient approaches to flexibility are technologies (and behaviours) that provide flexibility as a by-product [10].

Capacity peaks can be reduced through positive flexibility (ramping up generation and/or releasing stored energy) while excess generation by variable renewable energy sources require negative flexibility (ramping down generation and/or storing energy). Although the increasing penetration of variable renewable energy sources increases market opportunities for both 'positive' and 'negative' flexibility assets, market uncertainty in the UK limits the viability both of storage and additional generation capacity. At the same time, increasing specialization and diversification in the UK's flexibility market is actually decreasing margins. This constellation lends itself to the exploration of alternative pricing models for energy demand.

A. Volume and Capacity-based Pricing

Infrastructure system services - of which the energy system is one - can be charged for in a variety of ways. Usage-based charges provide an important mechanism to incentivise the consumption of services in certain ways. Usage-based charge models include volume and/or capacity-based models and combinations of both. In principle, volume based charges increase by the cost per consumed unit of a finite resource. For example, residential water services are frequently charged by volume of consumed water.

Capacity-based pricing is motivated by the cost of providing infrastructure via a "big enough pipe" to satisfy demand. To use another example, wired internet access networks (DSL, Cable, etc) are typically priced based on maximum speed (i.e. data transfer capacity) they can provide. Here, the cost for the service use does not increase in proportion with the amount of data consumed per month. On the other hand, in the same domain of internet access networks, charges for cellular mobile network data are typically based on transferred volume of data. Consumers have adapted to those alternative pricing approaches through a variety of strategies, depending, among others, on the price elasticity of broadband [11]. Such strategies to substitute use of mobile broadband include proactively downloading media content onto the phone before leaving home, or deferring consumption of content [12].

With domestic energy demand expected to grow as a result of increasing electrification of heating and transport, capacity-based pricing charges might play a role in energy demand reduction. Compared to increases in generation and storage capacities, domestic demand side response (DSR) is cheap, quick and easy to implement. DSR can also enhance the reliability of electricity systems through pricing and direct load control (DLC) of appliances by third parties [13], [14]. Research suggest that households switching their use of white good appliances such as washing machines, tumble dryers and dishwashers from evening peak to non-peak periods can transfer at least 8% of peak demand (on average 57W per household) [15].

Such DSR depends on the nature of the signal used to influence consumption patterns, including price signals (e.g. cost-effective or dynamic pricing), volume signals (e.g., load capping) and direct signals (e.g., DLC of appliances) [13], [16]. Cost-reflective or dynamic pricing includes time-based pricing [17] critical pricing [18] and real time pricing [19]. Dutta and Mitra [20] differentiate between between the following electricity pricing policies:

- Flat tariffs
- Block rate tariffs
- Seasonal tariffs
- Time-of-use (TOU) tariffs
- Superpeak TOU
- Critical peak pricing (CPP)
- Variable peak pricing (VPP)
- Real-time pricing (RTP)
- Peak time rebates (PTR)

Innovative approaches to incentivise DSR combine pricing signals with volume signals through abovementioned capacity-based electricity pricing [21].

Capacity-based pricing is expected to flatten load curves by encouraging both optimised load scheduling (i.e. shifting consumption) as well as total energy demand reduction [16], [22].

Electricity pricing is based on complex models that aim to balance the need to fund the cost of the network effectively, guarantee supply, and encourage sustainability while keeping the cost for consumers low [23]. For example, the charge model for extra high voltage (EHV) customers combines standing charges (per day), capacity charges (per kVA per day), exceeded capacity charge (per kVA per day) and volume based peak time penalty charges (per kWh) for the consumption as well as generation of electricity. Notably, the charge model for EHV customers does not include a charge that is proportional to the amount of electricity consumed outside of peak times [8].

Generally, capacity-based pricing is based on demand (measured in kilowatt (kW) to represent power) instead of consumption (measured kilowatt hours (kWh) to represent energy). It requires households to pay for the maximum amount of electric power they draw from the electricity grid at any moment, as opposed to how much electric power they use over the billing period. Capacity-based pricing involves the allocation of a particular load ceiling (load capping) on which the monthly charge is based. If the household exceeds the ceiling, it will be moved to a higher band of service at an increased charge [16], [21].

To date, most studies on innovative pricing models have analysed differential pricing such as time-of-use or Economy 7 [13], while studies on automated DSR have focused on dynamic scheduling algorithms, such as the scheduling of distributed energy resources [24], price-volume signals to affect consumption patterns by integrating personal preferences and technical information and constraints [25], and predicting household behaviour to optimise appliance control schedules (Moratori et al., 2013). More recent studies combine customer preferences with automated demand scheduling (Rahseed et al., 2016) and algorithms to optimise scheduling of demand-side appliance management [22].

Few studies, however, focus specifically on capacity-based pricing and user comfort. Similar to Agnetis et al. [25], we hypothesise a household energy consumption optimisation problem derived from a prototypical consumer scenario. Our focus, however, is on specific load caps and specific remote demand-side interventions [13], [16].

B. Understanding energy behaviours, social practices and socio-technical systems

In order to explore capacity-based pricing and its implications for consumers, it is necessary to understand energy usage and behaviours. A number of studies have attempted to categorise energy consumption behaviours and contexts to assess importance and flexibility. There are two different areas to explore here, one is overall consumption and the other load profiles - the more relevant area for our study.

For example, Boomsma et al. [26] categorise consumption by contexts: morning, evening, regular, important, most energy consuming, summer or winter. Jones et al. [27], in an extensive literature review, identified 62 factors that affect energy consumption of households. These factors were related to three key areas: socio-economic (e.g., number of occupants, presence of teenagers, higher disposable income), building-related (e.g., number of rooms, floor area, electric space and water heating, air conditioning) and appliance-related (e.g., number of appliances, rate of use of appliances, desktop PC, electric cooking, tumble dryer). Kavousian et al. in their US-based study [28] came up with similar areas with the addition of external conditions (weather / location).

Whilst the factors above are important, energy use is not an end in itself but rather the result of 'a complex series of interlinked and interacting *socio-economic, dwelling and appliance* related factors.' [27]. Shove and Walker [29] suggest that 'energy supply and demand are realized through artefacts and infrastructures that constitute and that are in turn woven into bundles and complexes of social practice' and thus a part of the ongoing transformation of society. It is important that we approach our study with an understanding of this range of practices and factors affecting energy usage.

C. Socio-economic implications of variable pricing

A substantial study of over 2400 households in 2012 (Demski et al. [30] and Spence et al. [31]) revealed variations in the acceptability of different demand-management scenarios: for example switching appliances off standby after a certain time was acceptable to 78% of respondents but a fridge-freezer being turned off for short periods was only acceptable to 30%. They also observed that those who were most concerned about energy prices were least keen on DSM technologies whilst they were still willing to think about and reduce energy use themselves. The study suggests that this might reflect concerns over sharing data and feelings of powerlessness and vulnerabile to exploitation.

Burchell et. al. [32] contrast the 2 approaches to changing behaviours - described as *literacy* and *know-how* and characterised respectively by factual knowledge and reasoning or by practical skills and experience. The former is more easily scaled up and tends to be used by policy makers but achieves less than a *know-how* approach which, whilst more resource intensive, recognises that personal and social contexts are important. The challenge lies in finding ways of combining these approaches. Variable capacity-based pricing relies on capacity caps to determine costs for individual households, and the extent to which consumers can respond to these caps will determine overall costs. It might be argued that consumers for whom overall cost is a less significant driver are less likely to respond whilst those at lower income levels will be forced to change their consumption patterns in order to maintain or reduce overall costs, thus placing the burden of response unfairly on lower income households. The issue of *justice* in the context of energy is an emerging and significant area for exploration [33] and needs to be aligned alongside the fast-changing application of technological approaches to addressing energy demand saving and shifting.

III. METHODOLOGY AND STUDY DESIGN

A. Methodology Overview

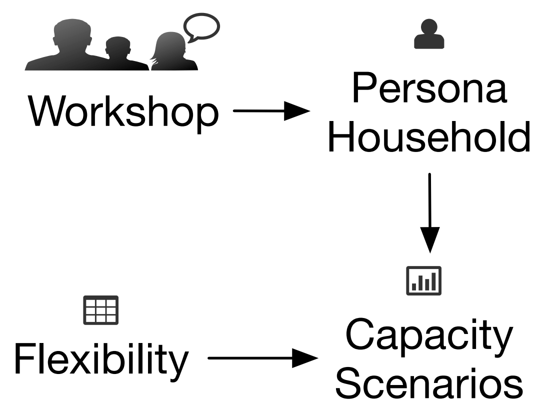

Fig. 1. Overview of Study Methodology

In Fig. 1 we present the four elements of the overall methodology used in this explorative study. This study started with a user co-design workshop where 10 user-researchers got together in a workshop to discuss demand response and identify what issues they consider relevant for energy demand shifting away from peak time. The workshop started with the participants reflecting on their individual behaviours while using various appliances, and noting factors that encourage (or prevent) demand reduction or shifting to other times. The individual reflections were then shared and discussed with the group and compiled in a list of behaviours and their change-encouraging/preventing factors. The workshop re-convened a week later to discuss the household-persona construction for analysis of consumption and demand shifting behaviours.

Personas are archetypal users that exemplify the characteristics of actual users in an understandable and amiable form [9]. First developed as a tool to aid software development [34], personas have become a commonly used method for product and system design. They can be used to consider the needs and goals of the users that the system is being designed for [9]. Thus, personas enable users to be a key component of the design process, a tool that is fundamental for the success of product or system design (e.g., Maness et al. [35]).

Personas are increasingly used to examine novel energy systems. For example, they have been used to explore behaviours, attitudes and motivations towards domestic energy retrofitting in owner-occupied homes [9]. Likewise, personas provided an understanding about how households make decisions about electricity pricing [36]. Similarly, Dodge et al. [37] used personas to examine how electricity consumption feedback affects consumption behaviour. Due to their ability to make designers' assumptions explicit, provide meaningful constraints to the problem space, and represent users in an engaging manner, personas are particularly relevant for building a shared understanding of the different user groups that might engage with a new system [9], [38], [39]. In the present case, we expect a persona-driven study to provide fruitful insights for understanding the implications of capacity-based pricing for peak-demand shaving in one household type.

Although personas are frequently based on qualitative research [40], they can also be assumption-based [41], [42]. Ad-hoc personas are particularly effective in the early stages of a project to formalise what developers know or infer about users [9]. Thus, they represent a resource-efficient method for exploring the needs of different users [42]. Moreover, while personas can be used as a distinct method to support design, they can also be used in combination with other (qualitative and quantitative) methods to amplify their effectiveness [43]. We used our persona in combination with data on power draw of some common household devices and average demographics of the UK households to outline scenarios and explore the feasibility of a capacity-based pricing model.

During the workshop the participants defined occupancy energy service profiles for their own personal households. The occupancy profile that was most substantially considered during the workshop was that of a family household with two working adults and two children. This profile was then selected for this current scenario analysis in which the persona-household undertakes various energy-demand activities on an average evening peak demand time. This scenario then provides a quantitative basis to explore the flexibility of a variety of energy services.

Having outlined the scenario, the participants then discussed changes that could be incorporated into the given scenario to reduce the power draw and retain it within a set capacity band. These changes were categorised as easy, moderate, and difficult. The scenario, changes, capacity bands and the related pricing and implications are discussed in the subsequent subsections.

The workshop participants fully acknowledge that behaviours and factors outlined in the resultant lists and the household-persona are biased towards the perceptions and experiences of the participants. Yet, as this is an explorative study, both the lists and the sample household-personal are considered to be adequate tools for the present exploration.

B. Scenario Design

The exploratory scenario is set between 5 and 7 pm GMT on a weekday in the UK.

> The persona-household, which consists of a mother, father, a teenage son and a younger daughter, have all just come home. They are not even aware that they left the light in the front garden on, as they used it when unlocking the door. The fridge is running, as normal, without anyone's interference, as is the router (they always have the router on).
>
> The father has started preparing dinner. He is in the kitchen, with lights on, listening to music on the stereo, while using an induction hob to cook some vegetables and the oven to prepare fish. He has also switched on the kitchen extractor fan to remove cooking smells and fumes. The mother comes into the kitchen and boils the kettle to make herself and her husband a cup of tea. She notices that all the cups, some cutlery and most dishes are used and have been placed in the dishwasher, and there will not be enough clean dishes for serving dinner. So she also switches dishwasher on a fast cycle. Before coming into the kitchen to make a cup of tea, the mother has been working on her laptop, and has left it switched on while charging because she will return to it with her tea, when ready.
>
> The teenage son has been playing football at school, and is now taking an electric shower to wash away the mud. As he switches on the shower, the towel rail starts to warm up, and the bathroom extractor fan turns on to remove the steam. He will need his sports kit again for school tomorrow, so his father has started the washing machine to get the sports kit washed and ready for the morning (he has two sets of sports kit, but the other one was used over the weekend and needed a wash too). Meanwhile, the daughter is playing a game on the games console hooked to an LED TV. She has also connected her smartphone to a quick charger, as she is going to have a long call with a friend later on, and the phone was running low.

C. Power Draw and Energy Consumption

For each device category providing some energy consuming service we sourced a representative maximum and average power draw during use at grid peak (5 to 7pm GMT). We also estimated how long a device would be in use during the peak time interval. We estimated the duration of use of the individual energy services based on the participant personal experience. We then calculate the total energy consumption per device category over the entire peak time duration. Our power consumption estimates are derived from real-time measurement, user guides and a wide range of both lab and consumers websites such as CSE [44] and British Gas [45]. The power consumption values for the device categories are supposed to be representative only. The power consumption by actual devices may vary from our values. The goal of the values is not to predict average household power consumption but to provide a quantitative view on the implications of capacity-based pricing that can help rank and sanity check conclusions.

For many device categories, power consumption varies throughout their use. For example, while a typical washing machine draws on average 440W while heating water, it draws significantly less energy at other times during the wash cycle with average power consumption of about 50W. Similarly, a fridge/freezer draws an average of 40W but it peaks when the freezer door is left open for too long at 400W. The oven shows a steady high power draw and the washing machine and dishwasher peak at the beginning and end of their usage cycle respectively. Other appliances have an continuous power draw such as light bulbs and chargers.

D. Capacity Bands

Variability can also be found in the peak demand for electricity from the grid; affected by several factors, including chiefly the weather and working/non-working days.

Additionally, statistical variability of demand in households aggregates to a increasingly less variable load on the grid branching points to combine to the observed aggregate levels of demand in the grid [46]. At the local transformer station that aggregates the connections of the individual households the instantaneous power draw of each household is relevant as they are installed with a given peak capacity (either single or three phase 100A with a maximum power of 24kW/41kW). In the result section we estimate this instantaneous power draw by a persona household. For comparison, we also calculate the effective household power consumption during the peak period (5-7pm) which is calculated from the total energy consumption during the peak period divided by the duration of the peak period. Assuming everything is equal any local reduction of demand will also result in a reduction of peak demand at the aggregate level. Deferral of local demand spikes to a time outside of the peak period will translate to a marginal reduction of aggregated peak demand at grid level. However, deferral of local demand spikes *within* the peak period do not generally affect the aggregated peak period demand at grid level.

According to the Household Energy Survey [47] the average peak demand for a household without electric heating was 7.5kW. Importantly, the mean (of the sampled population) average (typical for the household) peak power demand varies significantly within the population of survey households, with the most energy intense households routinely drawing more than 18kW (on average) while the least energy intense draw just over 2kW from the grid. According to the same survey, the mean average maximum power demand for households with primary electric heating was 9.3kW.

In the following section will analyse different interventions that can reduce the demand in the persona household. We ground this analysis in the responses from the previously mentioned demand shifting workshop which we describe next.

E. Demand Shifting Scenarios

As noted above, to explore the potential for shifting energy demand away from the peak time, ten researcher-users carried out reflection and analysis activities at a co-design workshop.

During the workshop participants brainstormed the set of energy services they typically used during peak time.

For each service, they considered the motivating factors that drove their use; these are here called "contexts". The workshop participants then thought of interventions that could be undertaken to defer or substitute the energy service for each context. These interventions were then rated according to their ease of shifting to result in a reduction of peak energy consumption. The workshop participants also identified enabling and constraining factors for each context specific intervention or change.

IV. Results and Implications

A. Peak Time Power Consumption

The individual energy services together with their power consumption values are listed in Table I. The overall energy consumption in the scenario is 12.7kWh which equates to an average peak power draw of about 6.4kW (when accounting for the estimated duration of the device use).

B. Workshop Results - Demand Shifting Potential

In this subsection we present the ease of shifting various household energy services as it had been identified during the workshop. The participants discussed shifting the peak time use by dishwashers, washing machines, power showers, hobs, ovens, microwaves and kettles. The participants produced a list of contexts under which the appliances were used. For each context they then judged the ease of shifting the appliance use as either having low, medium or high potential to provide effective shifting of energy consumption away from peak time. The summary of the appliance use contexts, as well as possible drivers and obstacles for shifting the appliance use time are summarised in Table II.

The most common intervention to enable deferral of energy consumption was found to be additional planning of appliance use to take place outside of the peak period. The greatest flexibility and thus most probable changes were identified to be those for which the time of the appliance use is inconsequential. Conversely, participants found that consumption is most difficult to shift in case when energy services are needed to *respond to the immediate context*. This usually refers to activities that take place once household members return

TABLE I
AVERAGE POWER DRAW BY ENERGY SERVICES IN THE PERSONA HOUSEHOLD.

Device category	Power Draw [W] max / (avg)	Use duration (h between 5-7pm)	Peak time energy [kWh]
Electric shower	10500 (10500)	0.25	2.625
Induction Hob (3 plates)	3500 (3500)	1	3.5
Kettle	3000 (3000)	0.3	0.9
Dish washer	1800 (1000)	2	2
Oven	2400 (2400)	1	2.4
Washing machine (avg 50W)	440 (50)	2	0.1
Fridge/Freezer (40W avg)	400 (40)	2	0.08
Towel rail	250 (250)	1	0.25
Games console	100 (100)	2	0.2
LED TV	80 (80)	2	0.16
Kitchen lighting (LED)	80 (80)	2	0.16
Kitchen extractor fan	50 (50)	1	0.05
Smart phone (quick charge)	35 (35)	1	0.035
Laptop	25 (25)	2	0.05
TV box	25 (25)	2	0.05
Extractor fan	24 (24)	2	0.048
Stereo	20 (20)	2	0.04
Garden lightning CFL	20 (20)	2	0.04
Internet router	12 (12)	2	0.024
Tablet (charge)	10 (10)	2	0.02
		total [kWh]	12.732
		eff. power [kW]	6.366

home. For example, in our scenario the son has to take a shower right after arriving at home as he needs to wash away the mud immediately after the football game, which was just completed; the family must have dinner after the work/school day. These activities are difficult to shift because even with planning and preparation the consumers would need to respond to the context that they find themselves in when they return home.

Medium levels of complexity to increase energy flexibility were attested by the workshop participants to cases where *planning and preparation* allow to move the consumption activities away from the peak time. For example, if the family in the above scenario had installed a pre-heating kettle, there would be no need to boil the water at the peak time. This change is relatively easy to make as it requires a "one-time" effort of new kettle installation. On the other hand, the participants agreed that energy consuming behaviour associated to established practices ("rituals") is much more difficult to change and thus has lower potential. For example, getting dishes washed right before when they are used (as the mother did in the scenario).

In contrast, the workshop participants found that *automation of activity* that is possible without any behavioural change are easiest to implement. For instance, should the garden lights in the above scenario be motion sensitive, they would turn on and off for the period where the family members enter or leave the house.

C. Factors supporting behaviour change

In all cases where the use displacement requires effort from the consumers and behaviour change, the workshop participants noted that such efforts would be fostered through motivational factors such as:

- *Direct and sufficient financial benefit*: should the income gained from the consumption time displacement be substantial, most of the consumers would likely be willing to carry out the required planning and preparation activities. Thus, capacity-based pricing with substantial differences in the prices per capacity band could be a promising solution.
- *Ownership of carbon savings*, where the households that reduce their consumption are able to monetise their reduced greenhouse gas emissions. Here, instead of relying on a utility provider to set capacity bands, the individual households can directly monetise energy demand below a capacity band and their "saved" emissions vis-a-vis their personal average.
- *Environmental benefits* are another powerful motivator: in contrast to personal monetary benefits, this motivation stems from the ethical/societal values and beliefs of the households who are concerned with climate change and wish to contribute to healthy living environments.
- *Visibility of power draw* allows users to see, and so remind themselves about their ongoing energy use (not unlike how the dripping tap reminds about the water loss).
- *Legacy (non-smart) devices* prevent the user from capacity shifting as they do not support preparation and planning (e.g., if the dishwasher does not allow start time delay and/or remote activation, its use cannot be shifted to late night or midday off-peak times, as somebody would have to be present to activate the device).
- Finally, *connecting with other users* to form a group to share capacity and spread the load could help even-out the variability in individual household daily activities, e.g., when the arrival of an unexpected guest requires extra cooking and/or washing activities.

D. The role of ICT to enable capacity reduction

The workshop participants identified ICT as an enabling technology that can support our household-persona in meeting capacity constraints, and therefore hopefully making it both easier and more acceptable to those involved. In this section, we consider the role of ICT in supporting our alternative capacity-constraint driven scenarios more generally. We categorise six ICT interventions:

1) Awareness: Eco-feedback and smart meter technology have long been advocated as a means of encouraging reduced energy usage. They have demonstrated modest but non-trivial results, leading to criticism from some quarters. However, such techniques are likely to be essential in supporting households

TABLE II
FLEXIBILITY FOR DEMAND SHIFTING PER ENERGY SERVICE.

Devices	Context	Potential (Ease of Shifting)	Shifting enablers	Constraints
Dishwasher	Need for clean dishes	Low	Planning	
			Audio / visual reminders of full machine / empty cupboard	
	Ritual of daily use even if not full	high	Understanding implications of particular uses	Resistance to change
			Automation to run at more suitable time	Noise if running at night
			Digi-reminder that its not full	
			Automation to run when full within user-set limits	
	Capacity of machine		Larger machine could reduce number of uses	Dried-on food necessitates more intensive wash
Washing machine	Need particular clothes	medium	Automation to have a 'complete by' setting	Need to be ready by a particular time
				Clothes not available to wash earlier eg work / sports kit
	Regular wash of accumulated washing	high	Awareness of implications of different use times	Availability of user to load / unload
			Differential pricing for different times	
			Delay / timer settings	User has to have loaded machine
				Not left too long in machine
				Need to hang up or move to dryer
				Noise of machine, rules in the building re use
Power shower	Wash person - evening	medium	Visual display of other power draws in the home	Small window for wash
	Morning wash	medium	Shorter shower - using timer	
Cooker - hob	dinner	Low	Display showing cost / capacity at time of use	hungry family, timing when people are home
		Medium - suggested by 20-30 mins		
Cooker - oven	dinner	medium	Automation to allow short duration switching off when other short duration devices are used pre-heating	
	baking	medium		
Microwave	Defrosting / heating	medium		
Kettle	Hot drink and forgetting use / reboiling	medium	Pre-heated water, +insulation of device, +interface automation	
			reminder that its just boiled	
	Cooking meal speed up availability of hot water	medium	Pre-heat water at more suitable time interface with other devices / automation	

asked to operate within a capacity constraint. Besides the traditional smart meter approach of providing an overall power consumption figure, this could be augmented with:

- Some visual warning of an approach to a capacity constraint (eg green/amber/red)
- Feedback at point of use. Eg a kettle displaying a warning that switching it on will exceed the constraint.

2) Decision support: ICT can provide information and prompts to enable behaviour change. This could be carried out both in-the-moment and proactively. In-the-moment decision support would make suggestions as to possible courses of action now. For example, if you want to boil the kettle, you will need to either wait 5 minutes for the oven to finish heating, or switch off the oven until it is boiled. Proactive decision support would spot patterns of appliance use, and/or have knowledge of the schedule of the household members via calendar integration. It would then make suggestions such as the most appropriate time to load the washing machine.

3) Buffering in response to anticipated demand at peak times, and/or spreading of power demand: Energy at off-peak times can be used to prepare systems to reduce energy use during peak periods. In our scenario, we can imagine an insulated kettle which automatically pre-boils when demand is lower (possibly in response to past historical data of likely use times) and then can be re-boiled using a lower power input at peak times. Similarly, a fridge/freezer can cool itself to a lower temperature in anticipation of peak periods, and so either avoid re-chilling or chill at a slower rate. One important area of buffering that ICT can support is the use of batteries to enable self-consumption of energy generated from solar PV cells at off-peak times. In particular in the UK, peak demand occurs outside of the time when solar PV cells are effective. Local battery storage that is instrumented to release energy at peak times can be an effective mechanism for some suitable households to reduce peak demand.

4) Time slicing, micro-delays and appliance coordination: With the necessary integration of appliances such as washing machines, dishwashers, ovens, hobs and fridge/freezers, ICT can multiplex available electricity among devices. These all draw a high power, but for short periods of time. By automatically coordinating them, and so delaying one while another is in operation, the overall peak demand can be reduced. For example, the washing machine and the dishwasher can adjust their operation to prevent concurrent heating cycles.

This may result in short delays in estimated completion time. In addition, ICT has a role in making this automation visible and appropriately controllable by the user. It is known that there is resistance to allowing energy companies to remotely make such micro-delays in customers. How can control and authority be placed in a customers hands and improve acceptability of a strategy such as this?

5) Macro-delay: Smart appliances, such as dishwashers and washing machines, already have the ability to delay activity to off peak times such as running overnight. Anecdotal evidence suggests these abilities have only modest uptake in usage currently. Can this functionality be combined with decision support to find acceptable changes in routine for a household, and coach them through it?

6) Efficiency: Finally, via sensing and control ICT can be used to provide energy services when they are needed and in exactly the right proportion. This can prevent waste. For example, an intelligent washing machine can reduce the amount of water heated for small loads or intelligent hobs and instrumented pots can use the right amount of heat for a specific recipe.

V. Discussion

We have identified the following limitations and further research questions, that need addressing in order to reduce significant uncertainty around the effectiveness of capacity-based pricing to encourage demand management.

With easy-medium changes in place, our representative household would reduce the power draw from 23kW peak to around 17.7kW peak and further to 12-12.6kW peak with hard changes in place, which are still not enough to stay below capacity band C.

Delaying the power shower would shave 10,500W, bringing the household down from 17.7kW down to 7.2kW. The shower has been identified as a hard change.

Our scenarios indicated that, apart from the electric shower, the most energy consuming activities (those related to cooking and boiling water) are the least flexible as they require significant behaviour changes. This should not be surprising as it is their lack of flexibility that results in these activities being common and co-occurring — they are principal to the national grid peak demand. On a national level it is the large-scale alignment of work patterns (which includes the alignment of the school day) that in turn causes the synchronisation of consumption of energy in households during the peak period. The ICT-enabled increase of home office jobs has somewhat increased the flexibility in timetables. In particular in the ICT sector there are a number of organisations of which the staff is globally distributed and working on loosely coupled timetables. The diurnal rhythm of the body however naturally limits the flexibility of meal and rest times.

Macro delay is one of the most important ways in which ICT can enable flexibility. One important intervention to avoid reinforcements, that is already been trialled, is the delay of charging electric vehicles to periods outside of the peak interval [48]. According the national grid, electric vehicles could add between 5 to 8 GW peak electricity demand to the electric grid. This is not surprising given that electric vehicle battery chargers can draw between 3 and 90kW.

Despite the potential that ICT has to create flexibility of demand, behavioural changes seems to be required for a significant reduction of peak electricity demand. One area of further work is to describe the factors that support behavioural changes through theoretical frameworks, for example from behavioural psychology.

Although framed in the context of grid reinforcement and the avoidance thereof, the characteristics of demand flexibility and the role of ICT as enabler are relevant in order to support the decarbonisation of the energy system.

Our scenarios are based on a persona household that is inspired by personal experience but statistically not significant. However, the actual power consumption level is relatively similar to the average power consumption by the households measured as part of the Household Energy Survey (7.5kW - no electrical heating) and thus are representative of real loads by residential households.

VI. Conclusion

Our workshop participants have identified a number of flexible energy services with high load on the electric grid. Given these services capacity-based pricing is an important lever for reducing peak demand. We have identified a categorisation of the ways in which ICT can avoid or support hard behavioural changes to support the shifting of energy service use.

Given the limitations of our research approach, these findings require significant empirical substantiation for generalisable conclusions to be drawn. Nevertheless, the results point towards the need to combine capacity-based pricing with a wide range of demand shifting facilitation. From a policy perspective, it is evident that capacity-based pricing gives the regulator greater leaverage to encourage demand reducing behaviour. Capacity-based pricing also lends itself to rising block tariffs where a certain capacity can be considered 'baseload' for each household persona (e.g., a family of four versus an couple) with step-wise increases for higher demand.

This allows more vulnerable customers to be granted with a certain 'baseload' at a reduced rate to address fuel poverty.

Volumetric pricing alters the price signal which might encourage energy saving behaviour and increase demand for energy efficiency services. Overall, this paper suggests that more research is required into the factors that are most likely to change energy demand and underlying practices through a combination of altruism, price signals, nudging and ICT automation.

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