Behaviour, practice – whatever? A theory-agnostic framework for describing and informing demand-side response

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Abstract

Different theoretical perspectives present diverse interpretations for why and how people may (or may not) be able to vary their electricity consumption patterns, and often propose different approaches to facilitating demand-side response (DSR). The framework set out here is suggested as a way of matching and marrying these various approaches with the goal of exploring how to achieve the maximum possible demand response which people are happy and able to provide.

The framework is based around 'electricity-relevant dimensions', or factors which may be considered to be associated in some way with a person or people's electricity use – activities engaged in, location, room temperature, and so on. Within each dimension, at any instant in time, certain states (such as 'walking' or 'watching TV' for activity) are more or less possible/acceptable than others for a variety of reasons. Effective DSR is understood as involving influencing adoption of those states with lower (or higher, as necessary) electricity outcomes at certain times, from a 'phase space' of possible options.

This paper describes how the framework can be used to consider the role of DSR interventions with their roots in different theoretical positions, such as changes in material conditions or competencies (associated with social practice theory), or in the framing of messages to activate loss-aversion (behavioural economics). It is intended to prompt consideration of how such approaches (and their proponents) could work together to optimize the potential of DSR programmes and policies, and is illustrated throughout with real and hypothetical examples.

Introduction

Demand-side response (DSR, or 'change in electricity consumption patterns in response to a signal' (Element Energy, 2012: 9)) has a range of potential benefits for electricity systems, including local congestion management, supporting integration of variable renewables, and others. Alongside other flexibility options such as storage, many European countries are supporting its development as a way of optimizing system cost and stability (Bertoldi, Zancanella and Boza-Kiss, 2016). In the UK, for example, electrification of heat would likely add very significantly to winter peak load, with associated high costs in reinforcing the grid (Eyre and Baruah, 2015). The more that low-cost flexibility options can be deployed, including DSR, the more cost can be avoided and the more electrification can be viably supported.

A wide range of theoretical perspectives have been brought to bear in the study of DSR and how it might most effectively be obtained. In investigating whether or not a household changes their electricity use in response to a DSR event, for example, a classical economics approach may focus on price elasticities (e.g. Wolak, 2007), a social practice theory approach on the meaning attached to the event (e.g. Strengers, 2010), and a psychology or behavioural economics approach on risk aversion (e.g. Shen, Narayanaswamy and Sundaram, 2015). The research methods employed are often different, as are the kinds of DSR interventions that may be tested or proposed. Any study must be judged on its own merit, but it is our belief that, when applied appropriately and in the context of rigorously designed study, all these (and other) perspectives can contribute much that is useful to our understanding of DSR. However, ontological, epistemological and methodological differences can lead to findings that seem incommensurable.

This paper proposes a simple framework which we believe can help sidestep this incommensurability and make it easier to talk about and integrate findings from research based on different theoretical foundations. We also hope it can be used to prompt consideration of how knowledge gleaned from these different research domains can be matched and married to as to maximize the amount of DSR that is attainable (and acceptable to people). However, we emphasize that this work is in its early stages and we share it here in the hope of generating discussion and garnering feedback for future development. The next section describes how the framework is composed. We then expand on why we consider it to be useful and briefly situate it in the context of related work. Further sections provide some illustrations of use cases and concluding thoughts with initial suggestions for next steps.

The Dimension-Set Framework

ELECTRICITY-RELEVANT DIMENSIONS AND ELECTRICITY OUTCOMES

At any instant in time, a certain rate of electricity use (ranging from 0 kW upwards) may be attributed to any individual, group or other unit of interest. They may be directly employing electricity-using technology for various ends, or benefitting from the services provided by electricity used outside of their direct responsibility (such as for air conditioning in a library). Questions such as how exactly this attribution is made, collective/individual responsibility/drivers for electricity use, etc. are important and considered later in this paper, but for the time being this is the working proposition for subsequent arguments. The remainder of this explanation is set out with reference to an individual for the sake of clarity. The electricity attributed to an individual may be thought of as being affected by any number of factors. These include, for example, the activity they are engaged in, the temperature of the (electrically-heated) space they are in, or the number of people benefitting from a certain electricity service – and any other way in which people may believe attributed electricity use to vary. In this paper these factors are referred to as *Electricity-Relevant Dimensions* (ERDs).

A *set* is a collection of related objects of any kind (see Halmos, 2013). For example, a set of integers may be {1, 2, 3}, a set of items of furniture may be {bed, chair, table} and a set of emotions may be {happiness, sadness, anger}. When considering ERDs, a set of activities may be {cooking, jogging, TV-watching} and a set of room temperatures may be {18 °C, 19 °C, 20 °C}. Every ERD that can be imagined can be described by such a set of states. For each set of states within an ERD, there is an accompanying set of *electricity outcomes*. These are the instantaneous power values associated with each state within the ERD. For example, each degree Celsius of room temperature may be associated with a different electricity outcome value measured in kW (or kWh per unit time). The ratio between ERD state and electricity outcome is the electrical efficiency of meeting that state (subsequently referred to as *ERD efficiency*).

Electricity outcomes are not constant for states but may change over time, being affected by (and sometimes affecting) states in other ERDs – but with a level of predictability. For example, and electric heater may come on and off to maintain a specified temperature (but will come on more to maintain a higher temperature), and using a kettle will almost always have a higher instantaneous electricity outcome than using a microwave.

TYPES OF SETS AND SUBSETS

For any individual, for each ERD, there is a set of all the states which could conceivably exist at the instant in question. For example, the room temperature set could include all temperatures ranging from absolute zero to infinity degrees[1], making this the *conceivable set* of states of room temperature.

We may consider there to be four *subsets* of states of ERDs with associated electricity outcomes. The first is the *possible subset*. Imagine a hypothetical room whose temperature we are interested in contains one electricity-using appliance – an electric heater. It has a thermostat which can be set to hold the room temperature at discrete temperatures ranging from 5 °C to 30 °C (and is always on, with no other source of energy available to affect room temperature). Temperatures below 5 °C and above 30 °C, while in the conceivable set, are impossible, and therefore outside of the possible subset of states for an ERD which (for the purposes of this example) is described by room temperature. The associated subset of electricity outcomes cannot be below 0W or above the maximum rated output of the heater. So possible states are any that exist within the bounds of what is conceivable but not impossible. The room temperature can exist in any state between 5 °C and 30 °C (inclusive), each with a different electricity outcome – these states constitute the possible subset both for 'room temperature' ERD and electricity outcome.

Within the possible subset, three further subsets containing zero or more states may exist for all ERDs – the *neutral*, *attractor* and *repeller* subsets:

- The attractor subset contains states which an individual will tend to attempt to attain at a given instant, depending on the costs associated with doing so (with 'cost' being interpreted in the broadest sense).
- The repeller subset contains states which an individual will tend to attempt to avoid at a given instant, depending on the costs associated with doing so.
- The neutral subset contains states within which an individual is driven neither to specifically attain nor avoid but are acceptable, depending on the relative costs of moving towards attractor or repeller states. The thinking behind this subset originates in the concept of the 'thermoneutral zone', or 'the range of ambient temperatures without regulatory changes in metabolic heat production or evaporative heat loss' for human physiology (Kingma, Frijns and van Marken, 2011, p 1975). However, it is here understood much more broadly.

Considering room temperature, for example, an individual may be most comfortable between 18–21 °C (the attractor subset), but make no endeavour to change the temperature if it strays to

1. There may be physically determined limits of temperatures (or energy levels) which can exist, in which case this would be the upper bound of the set.

17 °C because the effort (cost) involved in doing would outweigh the perceived benefits, making this temperature fall within the neutral subset[2]. If the temperature falls to 14 °C the individual may then be moved to take action, making this temperature fall in the repeller subset. Similarly, for the activities ERD, at 7 pm there may be no states in the attractor subset, cooking and reading in the neutral subset and gardening in the repeller subset. It is not simply a matter of what the individual in this case desires to do, but the results of many drivers explored by various social theories which result in an activity falling into a given subset – this is discussed in more detail in a later section. Subset boundaries do not have to be rigidly defined in this case, but as will be shown later, it is helpful to do so where practical.

It is worth observing again here that while these sets have been framed in terms of individuals, what makes states attractive or repellent is likely to be highly dependent on social factors. The important role of these is picked in a later section on 'collectives'. It is also important to clarify that the terms 'attractor' and 'repeller' do not necessarily refer to an individual's assessment of how much they 'like' a certain state, although it may do. Rather, it describes the result of any factors that may have a tendency to move an individual towards or away from a given state (including wants, needs, habits, expectations, responsibilities, etc.).

Subsets do not have to be rigidly defined in technical or physical terms (while acknowledging that actual electricity use is always the result of the action of electricity-using technologies). While this may make different ERDs incommensurable (for example in modelling terms[3]), it makes for a flexible framework because every dimension which may have a bearing upon electricity use at a point in time can be described in terms of the above sets and subsets, as and when it is considered useful to do so. Internal structure within the subsets is not necessary (although it is possible), but the relationship of the subsets to each other is consistent across ERDs.

A final key point about sets is that the states within them must be viewed as mutually exclusive. For example, in the case of the room temperature, the setting can be 18 °C or 21 °C, but not both 18 ° and 21 °C simultaneously. In the case of activities this means that every compound of activities, such as watching TV while washing up, is considered an activity in its own right. It would not, therefore, be simultaneously possible to 'watch TV' while 'watching TV and washing up'. This consideration is important for the next section.

COLLAPSE

Sets of states exist for ERDs, each with an associated set of electricity outcomes. While sets of states exist over time, at any given instant only one of those states can be held in each ERD, with a certain electricity outcome.

Imagine a point in time – say next Tuesday at noon. There exist a range of states for different dimensions that might apply to a person:

- Where are they – home, office, shopping, in the park?
- What are they doing – working on computer, cooking, walking?
- What is the (electrically controlled) temperature where they are – 18, 20, 23 °C (or not applicable)?
- How many people are present at the metered location?

While next Tuesday at noon remains in the future, each ERD exhibits a set of states with some possible/attractive/neutral/repellent status, and the eventual state may be described with a level of probability depending on the person's ability to affect the outcome and external factors. However, at the precise moment of noon on Tuesday, the states within each dimension converge and finally 'collapse' into a real single state within the possible set with an electricity outcome for that instant. Total electricity use is the product of collapsed states over a series of present instants.

What can be said about where collapse occurs? Logically it must be within the possible set of every dimension. Pressures may act to increase the likelihood that it falls at least outside of the repeller subset and, where reasonably practicable, within the attractor subset. Pressures will not systematically act to move anticipated collapse *within* a subset. To summarize, collapse:

- *could only occur* within conceivable sets
- *always occurs* within possible sets
- will be subject to pressures to move it away from the repeller subset towards the attractor subset
- will not be subject to systematic pressures to move it within a subset.

The present represents a continuous series of collapses. The point of collapse within a set of ERD states in the future may be said to occur within a kind of *phase space*[4] described by the above rules – and, as such, so can the associated collapse into an electricity outcome.

RESEARCHING AND EFFECTING DSR

Based on this framework, it is possible to question or influence where electricity outcome collapse occurs through consideration of (a) what states lie within each ERD set and subset, (b) the electrical efficiency with which ERD states are obtained, and (c) where collapse occurs within the subsets.

a. **Understanding/influencing the bounds of ERD subsets.** It is possible to question why the bounds of possibility/attraction/repulsion/neutrality in ERDs fall where they do, and to try to influence them. For example, by giving someone warm clothing, the lower bound of neutral room temperature may be decreased from 16 to 12 °C and lower bound of attractor temperature may be decreased from 18 to 15 °C. The bounds of a possible set of activities may be altered by purchasing a table tennis table for an office.

2. NB This concept differs from that of the classic 'thermoneutral zone' in that it takes in all factors, physical and psychological, which may affect satisfaction, rather than only physiological reactions.

3. This can be avoided by conceptualizing sets in commensurable terms, such as by predefining a group of energy services containing sets of states which can be ranked or ordered.

4. The term is loosely adapted from the concept as applied in physics to mean 'the space of all possible states of a physical system' (Tao, no date: 1).

b. **Understanding/influencing the efficiency of ERD delivery.** ERD efficiency refers to the amount of electricity required to obtain a given state. It is possible to question/influence the amount of electricity required to reach each state. For example, by insulating the walls of the room in the example above, the heater would use less electricity than before to meet each temperature point. The ERD subsets would remain unchanged, but the associated electricity outcome set of obtaining each state would be of lower magnitude.

c. **Understanding/influencing the collapse point within subset bounds.** It is possible to question why the collapse point appears where it does in an ERD subset, and endeavour to influence it so that it appears at the point within these bounds with the lowest electricity outcome. For example, the heater could automatically reduce the thermostat set-point until such time as an individual adjusts it back up. Within the attractor or neutral subsets there would be no benefit to the individual to react and increase the set-point when it dropped, so in such a situation the collapse point would always be lower than might be expected on average. Within the repeller set it may still be possible to reduce the temperature, but only where the costs of doing so where perceived as outweighed by the benefits (for example if the individual received an incentive to let the thermostat drop at certain times).

More simply still, DSR interventions may be characterized as being based upon ideas of *difference* or *indifference*, with *different* interventions being those which attempt to influence the position of states within sets/subsets, and *indifferent* interventions altering either the electrical efficiency of delivering a state or influencing the point of collapse within a subset (both of which are interventions to which an individual is – in theory – indifferent). It is important to be clear that no assumption should be made about what individuals or groups may be *indifferent* to – this is a question for empirical research. The key distinction of this framework that it assumes the existence of a range of states to which the individual is indifferent, and thus raises important questions about what determined the breadth of this range of states and what this means for DSM interventions.

All DSR questions (and efforts to exert influence) can be conceptualized within this framework. Any demand response/management goal can be described in reference to it. For example:

- Influence position of state within sets/subsets (different):
  - Giving someone a lesson in how to make great salads expands their 'food preparation' ERD possible subset with an additional low energy option, making it at least possible (and maybe even attractive) that, at times, their electricity outcome will collapse in this state.
  - Introducing a time of use tariff to make high electricity-consuming activities repellent at certain times.
- Change electrical efficiency of delivering a certain state (indifferent):
  - Energy efficiency retrofit measures for a person's house aims to increase the efficiency with which certain ERD states (such as room temperature) are provided to them and their fellow occupants, reducing their electricity outcomes when at home and therefore total electricity use (in a sustained way).
  - Install a hybrid gas/electricity water heating system allowing fuel source (and therefore electricity use) to be varied for the activity of washing.
- Influence collapse at alternative state within subset with lower electricity outcome (indifferent):
  - Automatically running a person's dishwasher next Tuesday at noon rather than at 1 pm may make no difference to an individual (i.e. this activity is in the neutral subset for these times), but it causes collapse at a lower electricity outcome of their 'activities' ERD at 1 pm (while increasing it at noon)[5].
  - Cycling off a fridge-freezer at a moment in time, altering the 'fridge functioning' ERD and reducing the electricity outcome of 'food preservation'.

The framework is shown diagrammatically in Figure 1.

Why this framework?

There is more to say about how the framework might be used, but at this point it is worth considering some of the possible benefits as it stands. The framework has two key strengths: aiding in describing and informing DSR strategies, and accommodating different social theoretical stances. In explaining this, it is first useful to explore what a maximally effective DSR programme (potentially encompassing many individual interventions) might look like. Firstly, it would recognize and attempt to act within as many ERD dimensions as (cost-effectively) possible, as it is the sum of their energy outcomes that leads to total electricity use. In each ERD it would attempt to exert influence within the 'different' channel to make high/low electricity outcomes states impossible/possible or attractive/repellent as appropriate. On the 'indifferent' side, it would attempt to probe the boundaries of indifference to ensure that the state with the lowest electricity outcome was collapsed at, and that the least electricity was being used to obtain that state (increases in electricity use may also be the aim, but usually with the associated goal of depressing it at some other time). This approach could be referred to as 'total DSR'.

Any other DSM intervention may be assessed and described relative to the maximally effective 'total DSR' example described above. Consider, for example, the British Gas *Home Energy Free Time* tariff, which provides free electricity between 9 am and 5 pm on a weekend day and has been claimed to shift some electricity demand away from peak times[6]. For points of

5. NB An intervention that allows a dishwasher to be run at a time when it previously couldn't would be classified as changing the position of a state within subsets, since this activity becomes possible at a time when it was previously impossible.

6. See oral evidence by Pam Conway of British Gas to the House of Commons Science and Technology Select Committee inquiry on 'Evidence Check: Smart metering of electricity and gas': http://data.parliament.uk/writtenevidence/committeeevidence.svc/evidencedocument/science-and-technology-committee/smart-meters/oral/33099.html.

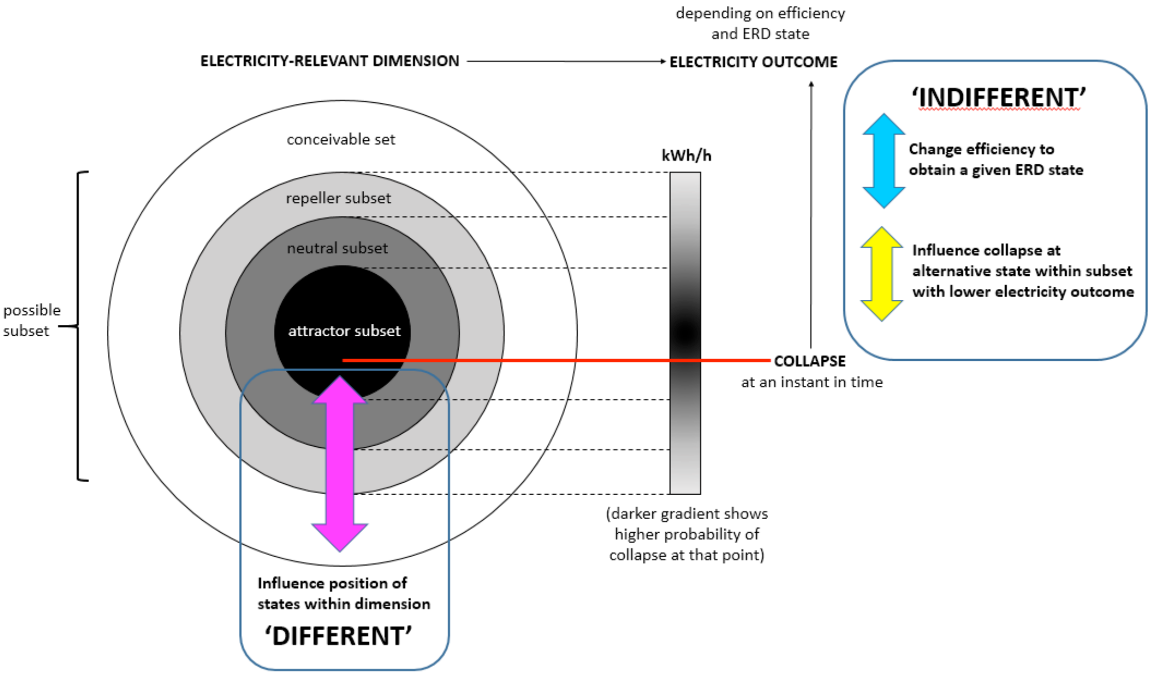

Figure 1. Diagram of the DSM Dimension-Set Framework.

time between 9 am and 5 pm on Saturdays, it attempts to shift activities which require more electricity into the attractor subset – a 'different' intervention. Activities are not shifted towards the repeller subset during the week, since unit prices on this tariff in the week are not punitive. As the weekend approaches, there may be a small effect as activities that could conceivably be delayed until the weekend and performed for free become relatively slightly 'repellent'. However, the intervention itself (the tariff) provides no information about what activities have lower or higher electricity outcomes, therefore relying on people's own knowledge and beliefs about this. It does not explicitly address any ERD. No explicit action is taken on the 'indifferent' side, except that as electricity is free on Saturdays, people will be indifferent to the electricity use of activities at these times – and therefore also their electrical efficiency and whether they collapse at higher or lower electricity-consuming activities when they have no overt preference.

By thus describing and classifying those areas of the framework where DSR interventions set out to act, it is easier to determine possible areas for augmentation and improvement. In the above case, for example, email or SMS reminders could be sent to people on the day before the free period starts reminding them of some electricity-intensive activities and suggesting that they are carried out in the free period – increasing their attractiveness through increasing their salience, and hopefully increasing the chance of shifting them from peak periods during the week. Such notifications would not necessarily need to come from British Gas, but any party who wished to provide such a service.

It is also useful in focusing inquiry on what people might be 'indifferent' to. For example, it is often stated that automation is the best way of doing DSR because it does not need people to remember to change their behaviour. However, thinking carefully about the ways in which people have to accept behavioural change in order to accommodate automation, and whether they care – i.e. in questioning whether it is a 'different' or 'indifferent' intervention – can be helpful.

Another strength of this framework its theory-agnosticism – it can accommodate and make it easier to think and talk about different theoretical approaches to the same problems. Consider the example of some unspecified time of use tariff. The price signal is classical economics – as a rational occupant, an individual should maximize their utility and change their activity in response. However, they can only do so within the possible activity set, and are only likely to do so if the increase in cost makes other activities comparatively sufficiently attractive. However, it may be that at that precise moment, their activity set is constrained by factors best interpreted through another theoretical lens, such as social practice theory. It may be that they perform an aspect of a given practice (such as using an electric shower) at that time because other aspects of their routine demand that they do so, and material constraints prevent them from using other technological options to perform that function. For their electricity outcome to collapse at a lower point at that time, additional interventions (such as flexible working hours or installation of a gas hybrid system) may need to be in place in combination with the price increase, broadening the activity set, potentially reducing the electricity outcome of the activity ERD and increasing the likelihood of achieving demand-side response.

There is longstanding recognition that there is value on drawing on different world views to address societal challenges. Timmerman (1986), for example, highlights the plurality of social perspectives on nature[7] and considers how these dictate our expectations of how nature will respond to perturbations. We can-

7. As in 'the natural world'.

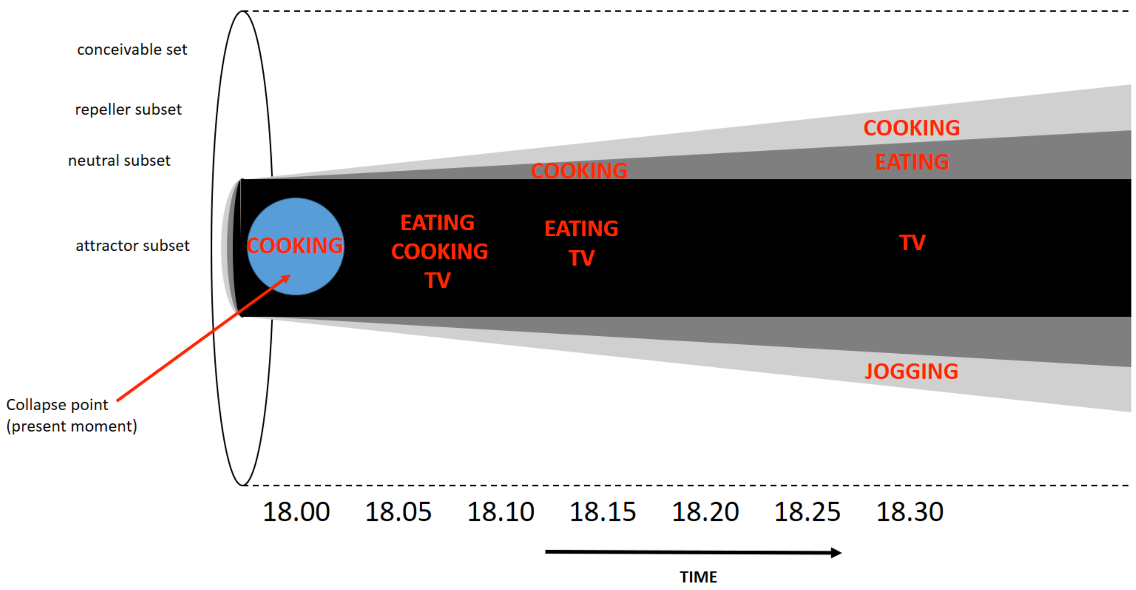

Figure 2. The 'activities' phase space.

not expect to do away with these divisions, but we can recognize their 'essential pluralism' (p 454, from editorial commentary by M Thompson) and 'husband them and make the most of them'. More recently, Wilson and Dowlatabadi (2007) give an overview of many models (in this case of decision making) that have been applied during decades of research on energy use, ranging through economics (conventional and behavioural) through psychology to sociology. They include an appeal 'to entrench the social and behavioral determinants of energy use as a wholly integrated part of energy efficiency research.' (p 193).

One possible response to this challenge is to draw together elements of more than one model in an attempt to increase its inclusiveness and explanatory power. This results in 'integrated models' along the lines of the Technology Acceptance Model 3, which includes 16 explanatory variables (Venkatesh and Bala, 2008). This approach can usefully bridge boundaries between models, but may be less convincing across disciplinary bounds due to inherent ontological differences. Another approach is to develop an 'integrated framework' more along the lines of the Energy Cultures framework (Stephenson *et al.*, 2010) or the Behaviour Change Wheel (BCW) (Michie, van Stralen and West, 2011). These frameworks do not have explanatory power in themselves, but seek to help guide characterization of interventions or consideration of the factors which may structure action. The Energy Cultures framework in particular aims explicitly to bridge the divides of disciplinarity, and both this and the BCW have been widely adopted. The framework discussed here has more in common with the latter category but is formulated to deal with a more specific subject – that of demand-side response for electricity (and more specifically still, the determinants of electricity consumption at any given instant). Its usefulness is that it can be overlaid on such existing frameworks to prompt questioning of how ERD states can be moved between sets, or the point of collapse otherwise influence, to effect demand-side response.

Briefly, then, we have seen how using the framework allows useful description of DSR measures and suggests ways of increasing their effect drawing on a range of theoretical approaches. However, the framework can also be used in more specific contexts to help understand the opportunities for DSR at given times in the future and for groups of individuals. This is based on the idea of the ERD 'phase space'.

Use illustrations and the phase space

The concept of the phase space of possible states has already been introduced. Briefly, it refers to the space of possible ERD states over future time within which collapse must occur, and which can be described with an estimated probability. Figure 2 is a visual representation of the activities phase space for a period of time stretching from the present to half an hour later.

At the present moment there can only be the single collapsed state, which is cooking. Going forward, other options are introduced, enlarging the set of possible states and with progression of states between subsets. Any period of time can be conceptualized in this way – for example, Figure 3 shows an illustrative activities phase space overnight. Note how different activities become more/less attractive/possible at different times. By mapping out the position of different activities at different points in time, it is then possible to understand where and what actions may or may not be taken to affect them for DSR reasons (such as those described in above sections). For example, consider the hypothetical phase spaces shown in Figure 4.

In this case it shows the way in which the activities ERD phase space may change when a local park is opened (for someone without any outside space at their home)[8]. It is conceivable that factors such as this which shape the options available to people could be influenced by the requirements of electricity management – or at least their salience and attractiveness increased (for example by notifying people that the park has just opened). In another example, an individual may be indifferent as to how they cook at 6 pm on a given evening (Figure 5) – i.e. different ways of cooking are in their neutral subset.

8. This is relevant to discussions of the impact on energy of 'non-energy' policy (see Cox, Royston and Selby [2016]).

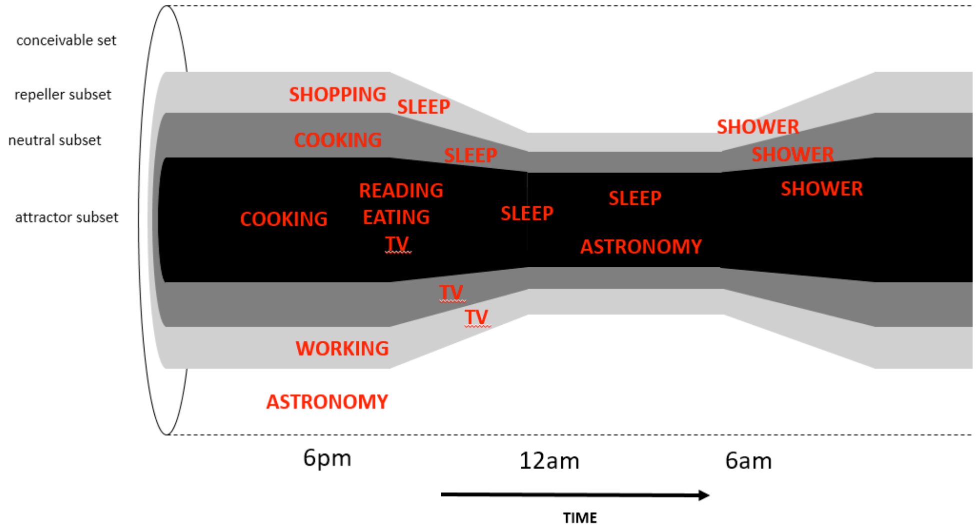

Figure 3. Activities phase space overnight.

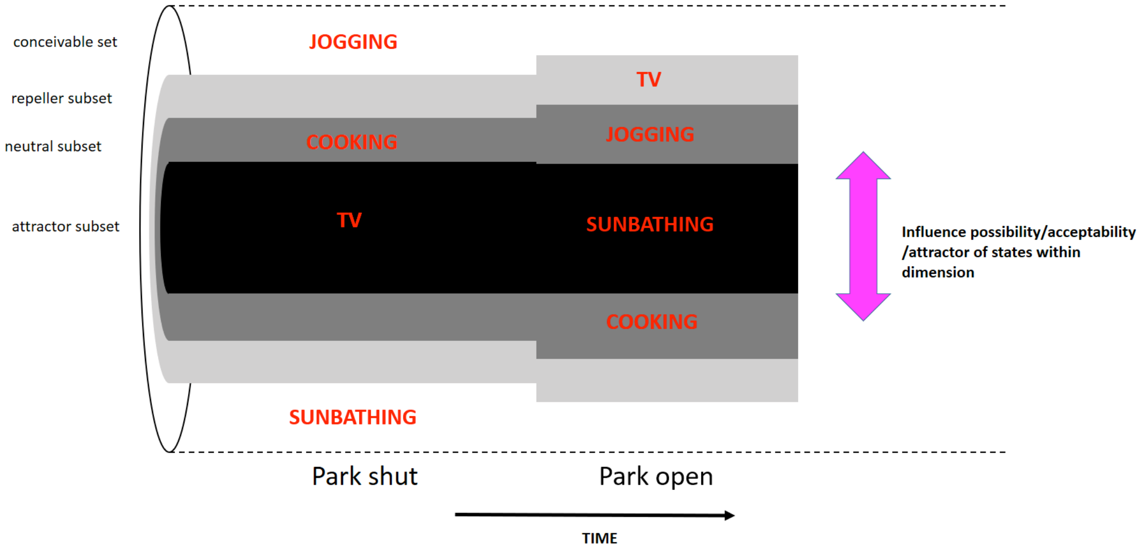

Figure 4. Activities ERD phase space depending on whether a local park is closed or open.

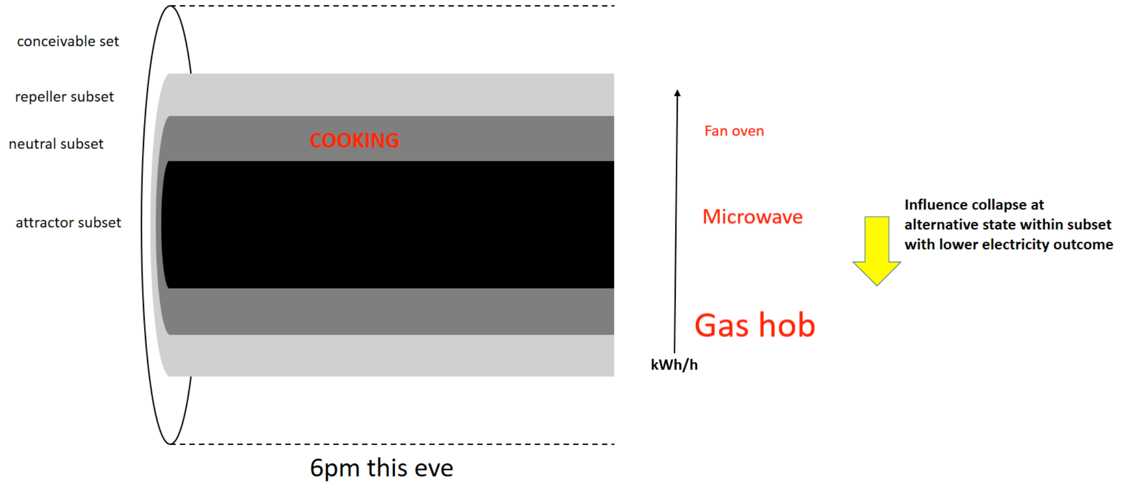

Figure 5. Influencing the mode of 'cooking' can affect point of collapse.

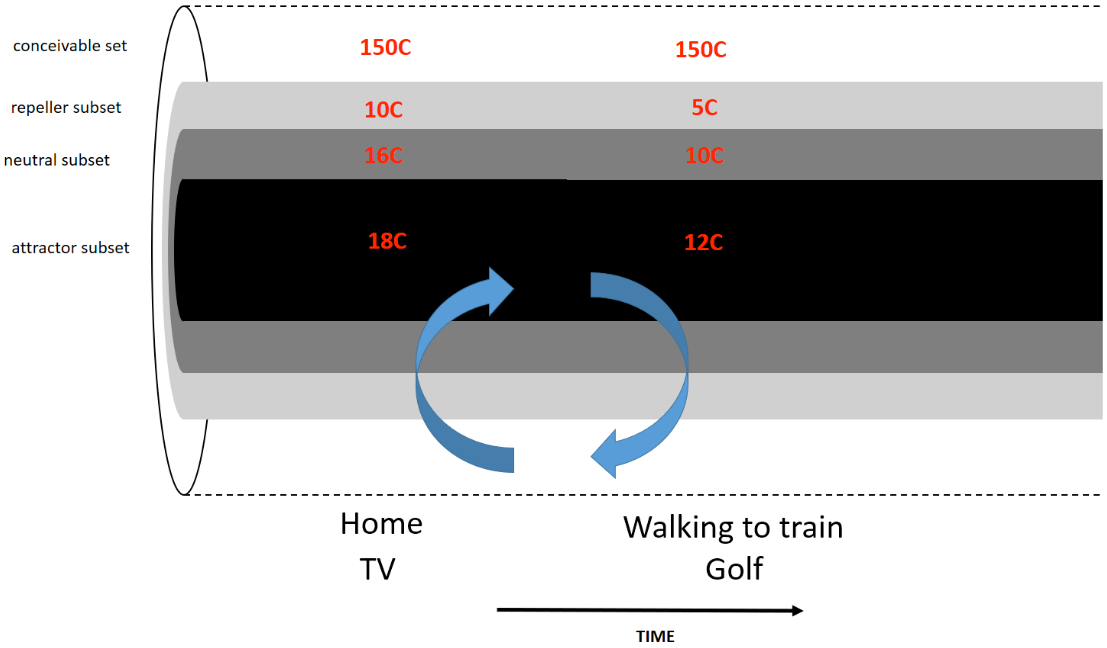

Figure 6. Interaction of temperature and activity/location.

In this case a DSR intervention may be used to increase the likelihood that they collapse at a lower-electricity option – for example some combination of a time of use tariff and recipe suggestion email. It may be useful to think of this as a kind of phase space architecture (borrowing from the concept of choice architecture introduced by Thaler and Sunstein [2008]).

While ERDs may be considered separately to each other for the purposes of the framework, in fact they are likely to interact. For example, consider the interplay of temperature and activity or location (see Figure 6).

On the left of the figure are indicated a range of temperatures and where they reside within the sets while an individual is at home, or watching TV. To the right are the appropriate temperatures when the individual is walking to catch a train or playing golf. Lower temperatures in themselves may provoke a transition to the states on the right hand (i.e. walking or playing golf), and vice versa. From the point of view of DSR, this interaction is useful to note because it is possible that different measures may be used to act on different ERDs to increase the cumulative effect of the DSR. In the case above, an automated reduction in room temperature could be permissible if coincided with prompts or incentives to go and play golf, for example by offering a significant discount. The connections between different elements of practice and their progression over time are a subject of current enquiry, both in developing theory and modelling (e.g. see Higginson *et al.*, 2015; McKenna, Krawczynski and Thomson, 2015). It will be useful to explore how the current framework maps onto that research.

Collectives

As has been repeatedly pointed out throughout this paper, while the examples given of use of framework have been based around individuals as the smallest sensible unit to which to attribute electricity use, it is equally applicable to groups (e.g. households, departments at work, etc.). However, it is also interesting to consider the questions the framework poses from an individual perspective in a group context. Consider the room temperature ERD. If there are two people in a room, both have attractor/repeller/neutral temperatures that will inform their actions and partly determine how the room temperature gets set. For example, if the neutral zone of one extends down to 14 °C but for the other only to 17 °C, the second person will (depending on the 'costs') act to maintain the temperature at the higher bound – which, so long as 17 °C is also in the first person's neutral zone, they will be happy with. Indeed, the knowledge that the second person would not be comfortable at 14 °C is likely to make it a repeller for the first person too. Of course, other considerations such as the cost associated with maintaining a certain temperature may also act to influence the final agreement, although this can be factored into specification of the bounds of the neutral zone (for example, cost might dictate the upper bound).

In another example, think about a four-person household with a single bathroom. Everyone may want to shower in the morning, but only one at a time can do so (the shower is 'rivalrous' in economic parlance). Each person's activity phase space extends before them, with the possibility of showering influenced by the activities and perceived needs of others. The person who needs to leave first may shower first, and during this time the other occupants' phase spaces reflect the 'negative space' where the first person's showering activity resides (by positioning showering outside the possible set). For communal (potentially non-rivalrous) activities such as TV watching, there may instead be overlap between phase spaces (depending, perhaps, on the programme being watched). In this way the presence/absence of other people, and their real or perceived wants and needs, becomes 'just' another factor which can act on the possibility/acceptability of states and can be used to inform phase space architecture. This principle of collectives can apply to any collection of people, whether it be a household, a workplace, or (usually temporarily) in a more public space such as a cinema.

Whether certain states exclude or include the states of other individuals is important for DSR. Because sharing an energy service often reduces the amount of electricity attributable to each individual compared to if they had been using that service individually, this suggests possibilities for reducing the electricity collapse-point for individuals by promoting sharing at certain times. The question of how electricity use can be usefully attributed to individuals in collectives in discussed in a separate paper under preparation.

Conclusions and ways forward

This paper has described the Dimension-Set Framework for DSR. The framework consists of Electricity-Relevant Dimensions of any kind made up of sets of states which are more or less possible or attractive. States have associated electricity outcomes. ERD states exist as phase spaces in the future described by the probability of them being the state into which 'collapse' occurs at the present moment, crystallizing an electricity use at that time. DSR activity ultimately aims to affect where collapse occurs, and this can be done by altering the possibility/attractiveness of states ('different' approaches) or by affecting the point of collapse within states, or the electrical efficiency of attaining states (indifferent' approaches, as people are indifferent to them).

Any DSR activity can be described in the framework, and insights from various social theories applied to understand why changes might or might not be possible. By describing DSR approaches in the framework and thereby making them explicit, it is possible to think about how they might be changed or augmented to make them more effective. For example, a time of use tariff makes electricity-requiring activities more/less attractive at certain times, but have nothing immediately to say about which activities should be affected relatively more or less – this relies on individuals' knowledge and experience.

One potentially fruitful next step would be to review and classify a sample of real DSR interventions according to the framework, making explicit the dimensions which they attempt to work in. Going the other way, an ERD (such as location) could be considered, proposing a wide range of possible ways in which position of states within sets could be influenced, as a way of generating novel DSR approaches. Another would be to explore whether similarities between sets for different individuals may be used to aid profiling or in suggesting the sort of approaches that might work best for different groups in architecting phase spaces around times of anticipated peak demand, and affecting electricity outcomes. Finally, it would be useful to explore in greater detail how different social theories may be applied within the framework to explain, inform or predict demand responsiveness.

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