Flexibility in supply and demand

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Abstract

Flexibility is emerging as an increasingly sought after property in electricity systems. After decades of fossil fuel based power generation, system operators are facing difficult times, if conventional plants are increasingly displaced by less controllable renewable sources of electricity.

Alongside calls for enhanced networks and storage, the demand side is expected to become flexible for the benefit of the system. The value of the technical potential is said to be as high as £5 billion per year.

This paper systematically reviews flexibility as a dynamic property on supply and demand side. In doing so it attempts to shift the perspective from 'what flexibility is for' to 'where flexibility comes from'.

Eight mechanisms of demand side flexibility are identified and illustrated with a range of examples highlighting the origins and costs associated with providing them. Parallels and differences with supply side flexibility are exposed and discussed.

This approach leads to the conclusion that even seemingly automated forms of demand response rely to a large degree on flexibility of energy users. Common currencies of flexibility include material, skill, time and space. To better understand the potential of demand side flexibility, this paper calls for more dynamic and larger scale studies, which not only capture observable load shifts, but also explore the underlying dynamics and broad range of factors which can inhibit flexibility.

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1 Introduction

The UK energy system is in the early stages of a fundamental transformation. The established order of easy to control, large scale, centralised power stations is rapidly being displaced by new, smaller, distributed and harder to control renewable generators.

Despite their reputation for being ‘expensive’, the operating costs of renewables are lower than fossil fuelled electricity. In wholesale markets renewables are out-competing conventional plants, displacing their energy and driving up their operating costs.

While the displacement of high carbon electricity with low carbon alternatives is desirable, the process has an unintended casualty: flexibility. Flexibility is a convenient by-product of conventional generators. This system property is being lost at the very time when variable sources of renewable energy require greater flexibility for their integration.

In this paper we will ask what flexibility is and what it is needed for in the electricity system. We will explore where flexibility comes from in the context of an energy system and how the demand side would provide it with mechanisms such as Demand Side Response (DSR).

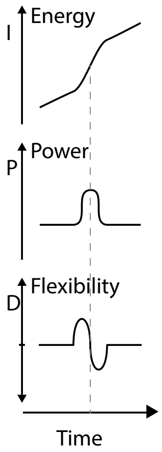
This paper is not concerned with assessing the potential or likely availability of flexibility. It is instead taking a more fundamental perspective of the origins and costs of ‘being flexible’, which is intended to sharpen our focus when evaluating current and potential future sources of flexibility. The study forms part of a wider effort to understand household electricity consumption and its flexibility. (Grünewald 2015, Grunewald15a)

DSR is commonly defined as ‘a change in electricity use in response to an incentive such as price’. (Darby and McKenna 2012, McKenna, Grünewald, and Thomson (2014) and Roscoe and Ault (2010))

For a deeper understanding of DSR it may be necessary to understand how the ‘change in electricity use’ is achieved at household level. What are the mechanisms that provide the flexibility to respond to incentives? What factors could inhibit flexibility and are price signals well placed to overcome them?

1.1 Energy, power and flexibilty

The relationship between energy, power and flexibility in physical terms is one of simple derivatives. The mathematical notation in Figure 1 is intended to underline the basic nature of the relationship. The rate at which energy is consumed over time is power. When the rate of energy consumption increases, as shown by the steeper slope in the middle section of Figure 1, more power is required to serve this need.



Relationships	Unit	Requirement	Example
$E(t) = \int P(t)\,\delta t$	W h	Resource	Fuel
$P(t) = \frac{\delta}{\delta t} E(t)$ $P(t) = \int R(t)\,\delta t$	W	Capacity	Plant size
$R(t) = \frac{\delta}{\delta t} P(t)$	$\frac{W}{h}$	Responsiveness	Load change

Figure 1: Energy, Power, Flexibility - a relationship of derivatives

The relationship between power and flexibility is analogous. When more power is required, generators have to ‘ramp up’, which requires them to be flexible. As the need for power reduces, flexibility is required again, this time to ‘ramp down’ power. The rate at which power changes in time is proportional to the scale of flexibility required.

This definition provides a clear and simple measure of flexibility from a supply side perspective. It may, however, not be appropriate when exploring demand side flexibility. This paper will therefore systematically go through the ways in which different sectors provide flexibility, explore what the origins of this flexibility are and where the cost of providing it may be located.

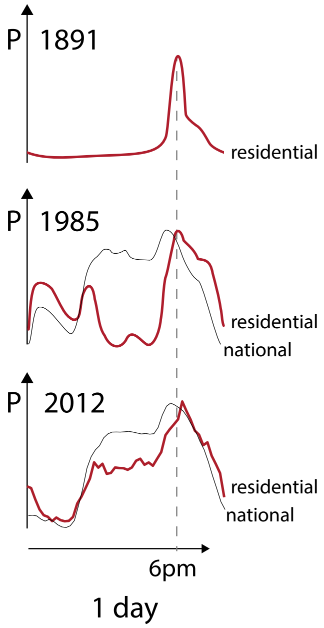
Based on this more nuanced understanding of different mechanisms of providing flexibility, we will explore to what extent flexibility in the residential sector could be observed, measured or even influenced.

1.2 Time and time scales

Time and flexibility are inextricably linked in several ways. Flexibility exhibits:

- **time specificity**: By its nature, flexibility cannot be shifted in time itself. Being flexible before or after an event that requires flexibility is of no value.
- **change in time**: Flexibility is a rate of change over time, expressed as power per unit time.
- **duration**: Flexibility is provided for a given period of time.
- **lead time**: Some flexibility is required on short notice, other flexibility can be forecast and prepared for.

The latter three of these can cover wide ranges. The rate of change can be a matter of seconds, or a change could take place over a generation where social practices gradually adapt to new forms of provision. The latter has been observed in the form of deliberate promotion of electrical goods in the 1950s, 60s and 70s, including night storage heaters to diversify the load profile to suit large scale baseload generation. The transition from lighting dominated load profiles in early networks towards the more diversified modern system is shown in Figure 2. Similar long term transitions could be envisaged to shape future load curves, drawing on flexibility in social practices.



	Mean	Peak (% of national)	Peak:Mean
1891	100 kW	600 kW (n/a)	600 %
1985	15 GW	22 GW (46%)	150 %
2012	21 GW	28 GW (53%)	130 %

Figure 2: Evolution of residential and national winter load profiles

The duration over which flexibility is required also follows broad ranges. Load profiles have diurnal and seasonal components. Some response needs can be instantaneous, such as a sudden failure of a generator or a surge in demand during the departure of an electrically powered train. The rate of change in net demand increases further with wind and solar generation. (Sinden 2007)

The notice period can have an important bearing on the availability of different kinds of flexibility. Some forms of flexibility can be available at all times and on short notice. Others can increase their flexibility by taking preparatory steps. For thermal generators it could take a several hours or even days to start up from a cold state. Grünewald and Torriti (2013) argue that demand side responses could be enhanced with longer notice periods. Activities could be rescheduled or chillers run in anticipation of a later response requirement. Forecasting, both on the supply and the demand side, can help to increase notice periods and could thus help to provide greater flexibility at lower costs.

2 Flexibility in electricity systems

Electricity systems have evolved with remarkable degrees of flexibility. This development was in part the result of fortunate properties of dominant forms of generation, rather than the particular focus of central planners or regulatory bodies. It is important to note that flexibility in electricity systems is by no means a new requirement. Load profiles have always fluctuated. In the early days, when the only energy service provided was lighting, the evening ramp up was greater than it is for the more diversified load profiles of today (see Figure 2), prompting widespread deployment of batteries in DC networks prior to 1910. (Schallenberg 1981)

Ever since the invention of the electricity meter in the 1890s, the value of this flexibility has largely gone unnoticed in an environment that was initially seeking to reward the provision of electricity measured as *energy*. More recently, concerns over peak capacity provision have prompted several European Governments to adopt Capacity Mechanisms, which reward *power*. Flexibility is the logical next derivative in the sequence of energy, power and flexibility.

In the UK and many other liberalised markets, flexibility is rewarded on the supply side through numerous markets classified as axillary services, balancing markets and other contracts for fast response. While such markets offer revenue for existing flexible assets, they have as yet not succeeded in delivering significant new forms of flexibility (Torriti and Grunewald 2014).

2.1 Supply side flexibilty

The flexibility of current power systems is said to rest on four mechanisms (Strbac et al. 2012):

1. Flexible Generation
2. Networks and interconnects
3. Storage and
4. Demand response

Each of them will be briefly discussed here. Flexible generation will be broken up into active provision (load following) and a more passive feature drawing on grid frequency.

1a. Load following thermal plant. Overcapacity is the first necessary condition for this form of flexibility. Power station are able to respond to upward changes in demand so long as they are not already running at capacity. Load factors (the ratio of what could have been generated with a given capacity and its actual output) for most power stations is somewhere between 55 and 85%. This leaves some headroom at most times. For short periods of time, rated capacity can even be exceeded, at the expense of maintenance costs or plant life. In order for a power station to provide a downward flexibility it has to be running in part load.

Thermal power stations, as their name suggests, rely on a thermal gradient to generate power. This is typically achieved by heating water by burning fossil fuels or nuclear reaction. The rate at which this change in heat can be achieved depends on the plant design and the willingness of its operator to suffer thermal stresses, which can increase maintenance cost or shorten the lifetime of the plant. Power stations that are not already running will take longer to ramp up from a 'cold' state. As with the need to part-load a plant for downward response, enhanced flexibility can require keeping a plant 'spinning', even if it is not the most economical asset to dispatch.[2]

1b. Grid frequency. The rotating mass of thermal generators spins at a synchronised rate of 3000 rotations per minute (hence the grid frequency of 50 Hz). Sudden changes in demand can be 'ironed out' by drawing on the inertia of this rotating mass, in essence using it like a flywheel storage device. Allowing the grid frequency to drop from 50 Hz to 49.5 Hz is equivalent to nearly 1 GW of generation being avoided. The service provided by the lower frequency is reduced - AC motors run a little slower and clocks fall slightly behind the time. For this reason the system operator will endeavour to compensate with higher frequencies later in the day to balance this effect. It is the customers who provide flexibility by tolerating these fluctuations.

2. Networks and interconnects. If we consider networks to consist of wires and transformers, then it is immediately apparent that, apart from negligible capacitance effects, no flexibility is provided by networks themselves. Electricity networks differ in this regard from gas networks, which offer considerable storage in their 'line pack'. The reason 'smart grids' are often cited as sources of greater flexibility is that these either comprise elements of storage or because they facilitate access to flexibility in other parts of the network. Akin to the presence of overcapacity being a necessary condition for load following on the generation side, so is the presence of sufficient network connectivity a condition to access these forms of flexibility.

The same applies for interconnectors. The UK has a combined interconnector capacity of 4 GW used for bi-directional flows between the UK, the Netherlands, France and Ireland. Responses on different time-scales can be facilitated, provided the national system on either side has the flexibility to absorb this change. Interconnects are thus merely a pathway to 'other countries flexibility'.

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[2] flexible plant tend to be less efficient and thus more polluting than assets which seek to run at higher load factors

The benefit from a macro-economic perspective is that different regions may have different characteristics, which offers opportunities for trading flexibility. However, if the connected systems have consistently different levels of need, the interconnector capacity will be used to provide power rather than flexibility (when operating at either end of its transmission-capacity the room for flexibility is restricted in much the same way as observed for power stations).

3. Storage. The installed electrical storage capacity in the UK is small (less than 30 GWh compared to over 100,000GWh in gas and coal). However, this capacity is highly flexible. Dinorwig pumped hydro storage can provide up to 1.8 GW in as little as 16 seconds from a spinning start. This can be used for upward or downward changes. Such fast responses are only required for short periods, such that the storage capacity of up to five hours does not tend to provide a limiting factor.

4. Demand response. Large users, such as aluminium smelters, benefit from lower electricity prices in return for a willingness to be disconnected on short notice. Other demand responses include commercial air conditioning loads and diesel generators located ‘behind the meter’, thus appearing to reduce load when generating (Grünewald and Torriti 2013). Residential demand response does not yet play a noticeable role in system operation and will be discussed in the next section.

Having listed these forms of flexibility, it is worth noting the fundamental differences between them. The origin of flexibility is very diverse, as is the cost they incur. All of them rely on facilitating conditions, such as sufficiently oversized capacity or networks. This concept of redundancy will re-emerge in the next section in the context of residential demand response.

Load following has a material cost due to the stress is causes the plant itself, whereas grid frequency borrows from society’s ‘tolerance’ of fluctuations in power quality. This effect may largely go unnoticed and it thus a very mild form of the sacrifice made by the contractor of interruptible supply.

The comparison has shown that interconnectors do not provide flexibility themselves and merely facilitate access to flexibility, which could be any of the above forms of flexibility, depending on the way in which flexibility is provided in the connecting system.

Storage appears to have an inherent ability to respond to load changes, which applies to technologies other than pumped hydro in similar ways. The cost of providing this service is partly in the opportunity cost of having a limited capacity with which to satisfy potentially more valuable future response requests, as well as depreciation of a limited cycle life.

It is worth noting that system flexibility is provided in concert. The range of time-scales concerned allow a portfolio of solutions to hand response along a sequence of action. For instance, the rapid availability of frequency drops only needs to be maintained for as long as the next response mechanism needs to prepare and take over. In this sense the breadth of demand side mechanisms could offer a valuable resource, provided the time scales are well understood and aligned.

In summary, supply side flexibility incurs not only operational costs, but relies on a combination of infrastructure and material redundancy, system tolerances and operational knowledge.

2.2 Flexibility on the demand side

Unlike supply side flexibility, which can be observed directly as a change in power, demand side flexibility is a change with respect to a 'counterfactual' or 'baseline' profile. Once a change has occurred, the baseline can no longer be observed, making the 'measurement' of flexibility at household level statistically more challenging. Figure 3 shows three modes of change which a baseline could experience.

Two fundamentally different categories can be distinguished (at least theoretically):

Appliance led: A appliance, automation or remotely initiated change in the physical operation of an appliance. This is often claimed to have no bearing on the energy service recipient.

Practice led: A change in load which is brought about by people doing things differently. Unlike the appliance led response, the energy service provision can be different in time, place or nature.

This seemingly clear distinction quickly blurs when interrogating the origins of flexibility more deeply, as we will attempt to do in the next section.

2.2.1 Appliance led responses - efficiency and 'smart' appliances

Automation and smart appliances are often cited as modes that do not necessarily have a bearing on everyday life.

We can distinguish four mechanisms of flexibility offering such automated solutions:

1. Reduce load (type a)
2. Substitute energy vector or location (type a*)
3. Shift load backward in time (type c)
4. Shift load forward in time (type b)

These four modes are shown in Figure 3 and can be further illustrated by examples. A more extensive list of examples is shown in Table 1.

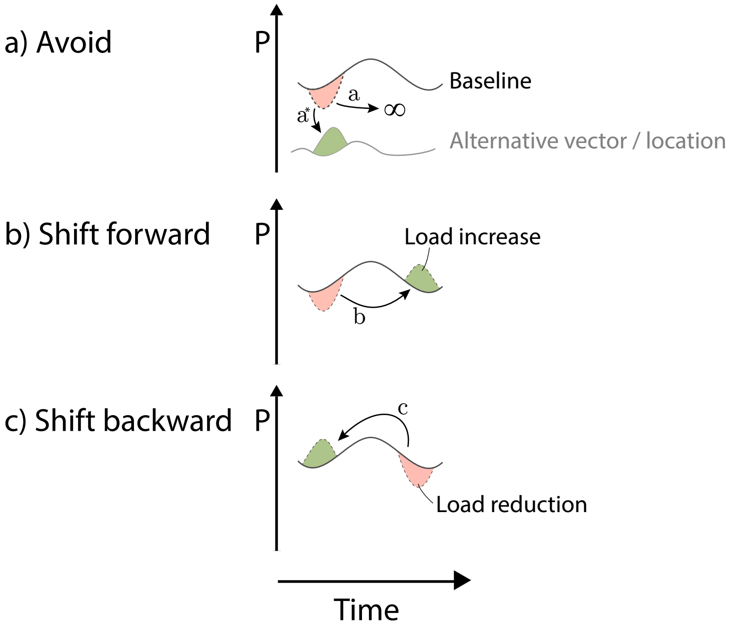

Figure 3: Shift modes and their effect on load profiles

1. Load reduction: A reduction of load can be achieved with more efficient appliances or 'smart' automated features.

Efficiency measures have persistent and long lasting effects on load profiles. As illustrated in Figure 3a, the reduction in load resulting from efficiency is persistent, notwithstanding possible rebound effects (Sorrell 2007). For example, the roll out of more efficient lighting has contributed to a reduction in peak demand, especially because the timing of lighting coincides with peak demand periods (see Figure 2). (Boardman 2014)

Smarter use of electricity could facilitate the avoidance of waste. An example could be a motion sensitive light that switches off when no person is around. This energy is not so much shifted, as it is avoided altogether or 'shifted to infinity' (Figure 3a).

2. Substitute energy vector or location: An alternative means to achieve an indefinite displacement of load is to shift towards an alternative form of energy or relocate the use of energy. A switch of fuel could be provided in the form of a dual fuel boiler or heating system that automatically switches between electricity and gas. The switch of vector need not have any bearing on the service provision itself. It does however require redundancy of capacity in the system (including it's supply infrastructure).

Many households already have (and routinely make) a choice between energy vectors, when choosing between electric kettles or gas fired hobs to boil water.

This choice is currently driven by factors such as speed, convenience, quantity required and final use. System benefits are not necessarily a consideration.

A location switch may still use the same energy vector, but in a remote and therefore potentially less constrained part of the network. Energy intensive computations can be performed on remote machines, some of which are deliberately located in places where energy and cooling power are abundant. As with the fuel switching example, redundant computing capacity and appropriate network infrastructure is needed to be able to make such a switch.

3. Shift load forward in time A classic example of a forward shiftable load is the washing machine with a delayed start feature. If the wash is not required immediately, a delay function will allow the appliance to schedule the exact time for the run based on price or other signals. While this may appear ‘automated’, several interactions with the user still apply. The machine may make a noise which is not amenable at certain times, either because people wish to be in that space, or because it falls into a period when quietness is expected. The unloading time required forward planning by the user, especially when wet clothes being left in the machine are a concern. Data on combined washer-dryer usage suggests that these are more likely to be used over night, avoiding the issue of damp clothes at the expense of higher consumption on the drying cycle. The tension between efficiency and flexibility will return later on.

4. Shift load backward in time Fridges or air-conditioning units operate cyclically and could shift their chilling cycle in both direction to an earlier or later time. This is possible because the temperature tolerance with upper and lower temperature bands, combined with the thermal mass of the chiller and any contents, provide the capacity that affords flexibility in time. This capacity can be used to front load the chilling operation, or to suspend it for some time. The term ‘tolerance’ appeared above in the context of power quality where it referred to gird frequency. We will return to the underlying relationship when interrogating who the ‘tolerating party’ is in Section 3.

The difference between a load suspension (a) and a load shift (type b) can be subtle. For instance, reducing the power of a kettle or mower will not result in an energy saving, since the same amount of energy is still required for the service to be completed. Using less power means the activity takes proportionally longer and total consumption may in fact increase, because thermal losses (in the case of the kettle) are higher over the longer heating cycle.

Reducing the power of a TV by dimming its display, on the other hand, is a load suspension, since the device will not operate for longer in response. Washing machines could do either. The cycle could be lengthened, reducing power, but keeping the total energy consumption constant, or the cycle time could be kept constant, but running at lower power (less hot water, lower spinning speed), resulting in power and energy reduction.

These examples have already shown that the claim these measures would not impact the users does not stand up to scrutiny. Even in cases where the operation barely touches everyday life, the technology choices have cost implications and take up space - space being one of the enablers of flexibility, as we will discuss later on.

2.2.2 Practice led responses - changing what we do

All of the examples above were intended to show how load profiles could be altered without impacting (at least in theory) on the service provision and their users in very noticeable ways. We now consider a very different category of flexibility, one that has a distinctively human element involved.

Turning from the appliance to the energy service itself offers further mechanisms for flexibility.

These are:

5. Shift the practice in time
6. Substitute the practice
7. Substitute service provision to metabolic energy
8. Change the practitioner

Again, these cases and their sources of flexibility are best illustrated with practical examples.

5. Shift the practice in time: Changing the timing of a practice is what is traditionally thought of as 'behavioural load shifting'. The assumption is that all the same activities still take place and that merely their sequence is reordered. If one would normally eat before watching TV, reversing the order results in a load shift. Evidence available to date does not allow to say whether this type of shift is in fact performed in practice. It serves here more as a theoretical concept. Why it may not be as common as perhaps assumed in some studies becomes apparent when exploring what is involved on the user side.

Activities are linked to each other (preparing food before eating it), they can be place specific (the TV in in the living room, meals are prepared in the kitchen and consumed in a separate room), time bound (screening of a TV event) and, most complex of all, can relate to other people who may have their own set of constraints and dependencies (not wanting to watch that TV programme, being hungry now, having other plans).

Any change in the timing of one practice can therefore trigger a whole web of consequential 'fallout'. All of these constitute costs of the flexibility provision and include material, time, space and mental flexibility.

6. Substitute the practice: Instead of shifting a practice in time, it is also possible to maintain the sequence of activities, and to substitute practices that deliver similar outcomes. Having a cold meal instead of a hot one, or watching TV on a battery powered mobile device instead of a large stationary screen, would result in a load reduction and/or shift. The capacity required includes both material (the mobile device, a fridge to keep different food options on offer), skills (different means to prepare a meal) and a willingness to make a sacrifice (less taste, smaller screen).

7. Substitute service provision to metabolic energy: Substituting an energy service to metabolic energy is a special case of 2. and 6. combined. In practice this is a return to the manual performance a practice, be that using a hand mower instead of a motorised one, mixing dough with a spoon rather than a blender, using body heat to keep warm by wearing a jumper, cycling or waling instead of driving. These examples suggest a possible upside to changes in practice for health and well-being. However, lifestyle changes not only carry a cost to the practitioner to learn and adopt them, the advocacy of such changes could have a high political price.

7. Changing the practitioner: Changing the practitioner could take many forms. Having laundry done by a service provider would move the energy consumption to another part of the grid and potentially a different time. The energy intensity of the service may further be reduced through efficiencies of scale. Other examples in Table 1 include going out for dinner instead of cooking. Often the additional condition for such flexibility is the presence of such external offerings. If the only local pup has been closed, the cost of going out increases.

As with the supply side forms of flexibility, a comparison of the origins of flexibility can give a sense of the diversity at play.

2.3 Origins of Flexibility

Table 1 gives an overview with examples of possible response mechanisms for different activities. Five columns indicate the resources that are required for each response mechanisms.

Personal change captures any impact, small or large, on at least one individual, such as a change in the quality of their experience or a change to timing or location of their activities. The cost associated with this resources is one of personal satisfaction.

The second column captures *related changes*, including impacts on others, friends or family members, who are affected by a change in collective activities, sequences or space allocation. Flexibility drawing on this resource may require an element of negotiation and could bring about inter-personal tensions.

Some responses require *skills or knowledge* to be performed. Where such skills already exist, they form part of the flexibility capacity, where they don't, learning forms part of the cost of flexibility.

Appliance features, such as material requirements, 'smart' features or additional equipment, are marked in column four. Resources that are physically remote,

	Shift mechanism	Shift type	Boil water with electric kettle for meal	Personal change	Related changes	Skill / knowledge	Appliance feature	External resource	Mow the lawn with electric mower	Personal change	Related changes	Skill / knowledge	Appliance feature	External resource
Appliance led	1 Reduce load	a	More efficient kettle	●	○	○	●	○	More efficient mower	●	○	○	●	○
	2 Substitute energy vector	a*	Heat water with gas	●	◐	●	●	◐	Use a petrol mower	●	◐	●	●	◐
	3 Shift forward	b	Boil with less power (delaying the meal)	●	●	◐	●	○	Reduced power, slower mow	●	●	◐	●	○
	4 Shift backward	c	Smartly anticipate and pre-boil	●	●	●	●	○	Higher power, earlier completion	●	●	●	●	○
Practice led	5 Shift practice in time	b,c	Change mealtimes	●	●	●	○	○	Reshedule mow	●	●	◐	○	○
	6 Substitute practice	a	Change the meal plan (no need for hot water)	●	●	●	○	○	Adopt a preference for longer grass	●	●	●	○	○
	7 Substitute metabolic energy	a	Eat uncooked food	●	●	●	○	○	Use a hand mower	●	●	●	●	○
	8 Substitute practitioner	a*	Go out for dinner or order in	●	●	●	○	●	Employ gardener, robot mower	●	●	●	○	●

	Shift mechanism	Shift type	Run washing machine	Personal change	Related changes	Skill / knowledge	Appliance feature	External resource	Watch TV	Personal change	Related changes	Skill / knowledge	Appliance feature	External resource
Appliance led	1 Reduce load	a	Low energy cycle	●	●	◐	●	○	Dimmed screen	●	●	◐	●	○
	2 Substitute energy vector	a*	Pre-heat water with gas boiler	○	○	○	●	◐	Use a mobile device (charged elsewhere)	●	◐	●	●	○
	3 Shift forward	b	Run a slow / delayed programme	●	●	●	●	○	Use a mobile device (charge later)	●	◐	●	●	○
	4 Shift backward	c	Run faster programme	●	●	●	●	○	Use a mobile device (pre-charged)	●	◐	●	●	○
Practice led	5 Shift practice in time	b,c	Put the washing on earlier or later	●	●	◐	◐	○	Watch earlier or later	●	●	◐	◐	○
	6 Substitute practice	a	Wear less clean clothes	●	●	●	○	○	Read a book	●	●	●	○	○
	7 Substitute metabolic energy	a	Wash by hand	●	●	●	●	○	Enact a play yourself	●	●	●	●	○
	8 Substitute practitioner	a*	Use laundrette	●	●	●	○	●	Go to the cinema	●	●	●	○	●

	Shift mechanism	Shift type	Fridge cycle	Personal change	Related changes	Skill / knowledge	Appliance feature	External resource	Home heating using heat pump	Personal change	Related changes	Skill / knowledge	Appliance feature	External resource
Appliance led	1 Reduce load	a	Upgrade to more efficient fridge	●	○	◐	●	○	Insulate home	●	●	●	●	○
	2 Substitute energy vector	a*	Switch to CHP with absorption chiller	○	○	○	●	◐	Switch to gas boiler	○	○	○	●	◐
	3 Shift forward	b	Delay the chilling cycle	●	◐	○	●	○	Delay the heating cycle	●	◐	◐	●	○
	4 Shift backward	c	Pre-chill	●	◐	○	●	○	Pre-heat	●	◐	◐	●	○
Practice led	5 Shift practice in time	b,c	Shop outside peak ours	●	●	●	○	○	Be at home earlier or later	●	●	◐	◐	○
	6 Substitute practice	a	Higher set point	●	●	◐	●	○	Wear a jumper	●	●	●	○	○
	7 Substitute metabolic energy	a	Get fresh foods on demand from shop	●	●	●	○	◐	Exercise	●	●	●	○	○
	8 Substitute practitioner	a*	Coolth storage service provider	●	●	●	○	●	Go out (somewhere warm)	●	●	●	○	●

Key:
○ not required
◐ potentially required
● required

Figure 4: Examples of activities, associated response mechanisms and origins of flexibility

such as an external service provider are captured in the last column under *external resources*.

The allocation of markers is intended to be illustrative and is no judgement whether such changes are easy or difficult to achieve, nor whether these changes are likely to be realised.

The table does highlight the breadth of conditions associated with most response mechanisms. Nearly all responses have some bearing on the individual involved. The exceptions are substitutions of energy vector, where a multi-fuel appliance could switch from one source of energy to another, without any noticeable change to the service provision. However, this response is only possible when redundancy has been built into the appliance and its supporting infrastructure is available. In most cases this will incur additional costs and reduce utilisation.

3 Discussion

The comparison of supply and demand side flexibility, while fundamentally different in nature, still reveals some parallels. In both cases an element of redundancy or overcapacity appears to play an important role in facilitating flexibility. In order to deliver flexibility tolerances are required and other costs are incurred in diverse locations.

3.1 The cost of flexiblity

Flexibility requires some degree of redundancy or spare capacity, which can put it add odds with objectives of efficiency or utilisation. The cost of flexibility is often not incurred at the time of ‘use’, but is a rather persistent capacity. Redundant systems of provision need to be invested in and maintained to be available when flexibility is required. This redundancy extends to space, time, material good, as well as skills and knowledge.

3.2 Tensions between efficiency and flexibility

Efficiency measures were behind most responses delivering ‘load reductions’ and provide a sustained means to reduce peak demand in particular. In other examples, such as the ‘smart kettle’, efficiency can be directly at odds with flexibility. Owning multiple appliances, capable of using different forms of primary energy, increases flexibility, but is less efficient in terms of cost and space allocation. This tension can also be translated to everyday activities. A very efficient use of time, with little slack or contingencies, is likely to offer fewer opportunities for responsiveness.

3.3 Observing flexibility

Flexibility is a dynamic property and therefore more difficult to measure than static features of a system. Power stations and storage units have well characterised ramping properties, which are understood based on extensive development and experimentation.

Flexibility on the demand side is arguably more complex and less experience has been gained in its 'use'. Time of use tariffs have been deployed to observe responses in load (CER 2011,Bulkeley et al. (2014)). Typical peak reduction are around 5% on average, but with large variations between studies (Parrish, Heptonstall, and Gross 2016). It remains unclear which of the mechanisms in Table 1 is at work when such changes are observed, making it harder to appreciate whether the price incentives are effective and what measures could encourage better responses.

Torriti et al. (2015) developed an approach to infer flexibility from time use data. Five indices of synchronisation, variation, non-shared activities, occupancy and spatial mobility are combined into a single 'Flexibility index'.

Time use data relies on self reported activity diaries, spanning one or two days per individual. Such data give rich insights into the distribution of activities within a population. The relationship between the number of reported activities, which forms the bases of the 'variation' component of the flexibility index, and the ability to change such activities is not necessarily a simple one.

Synchronisation of activities between individuals (joint meals) and whole societies (working and schooling hours) play an important role in shaping the profiles of energy use (Shove, Pantzar, and Watson (2012)). This can act as a barrier to flexibility (negotiation new meal times with others, who in turn have a cascade of implications to consider) or be a powerful amplifier to collective changes (daylight saving time, flexible working hours).

As a dynamic property, it is therefore at times of change that flexibility reveals itself. This change can be longer term, such as the response to the emergence of smart phones and their impact on TV watching routines. Or it can be short term, such as the response to an emergency.

Both cases reveal a 'response' to an 'intervention'. In the light of the breadth of response mechanisms in Table 1, a great many interventions may need to be tested to gain an appreciation of the dynamics underlying them. The observation would need to be significantly more sophisticated than mere load data. Activities form an important additional insight, which could be further enhanced by an understanding of the origins (i.e. cost bearers) of a response and how their presence or absence shape the availability of flexibility.

This is to say, not only the observable responses should be focus of investigation, but the multitude of capacities and conditions that are required to be in place for flexibility to become forthcoming.

4 Conclusions

This paper reviewed mechanisms by which flexibility is provided on the supply and demand side. While fundamentally different in nature, very similar capacities are required for both. These extend well beyond the ‘operational costs’ targeted with price based mechanisms.

Conditions for flexibility included:

- (Over-) capacity in infrastructure and material assets
- Tolerances (physical, personal and inter-personal)
- Skills and knowledge

Eight distinct mechanisms for providing demand side flexibility have been identified. Across all of them flexibility is found to be deeply bound up with practitioners, even in cases where automation is thought to take full agency of response management. Most forms of demand side flexibility further have repercussions beyond the individual ‘being flexible’. They draw on a wide range of capacities, including time and space shared with others, which has to be negotiated as part of everyday life.

Some of the responses are therefore unlikely to be enabled by tariff structures alone. Load shifting of washing machines was shown to potentially be inhibited by the noise level of the appliance or the way it handles wet clothes after the cycle. Neither of which are influenced by electricity price signals.

Offering flexibility has been shown to have opportunity costs. If it is used for one purpose, it cannot be used for another, competing purpose. This tension places demand response at the heart of everyday activities and inter-personal arrangements.

We discussed the implications for the observation of flexibility and concluded that flexibility is a dynamic property, which can only be observed through time and in conditions of change. It may therefore be unavoidable to perform trials in which large group sizes are exposed to differing conditions, if relatively weak responses are to be captured reliably.

Analysis of flexibility is made more challenging by the range of possible responses. As the contribution from each mechanism can be relatively small, it is even more important for studies wishing to expose their relevance to be performed at the appropriate scale. Greater emphasis in research on the dynamics that enable and inhibit flexibility, grounded in a more activity centred perspective, rather than focusing on the responses observed in load profiles alone, may therefore yield valuable insights into the potential for demand side flexibility.

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