



Social implications of residential demand response in cool temperate climates

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HIGHLIGHTS

- ▶ Demand response implies major change in governance of electricity systems.
- ▶ Households in cool temperate climates can be flexible, mainly with thermal loads.
- ▶ DR requires simple tariffs, appropriate enabling technology, education, and feedback.
- ▶ Need to test consumer acceptance of DR in specific conditions.
- ▶ Introduce tariffs with technologies e.g., TOU tariff plus DLC with electric vehicles.

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ABSTRACT

Residential electrical demand response (DR) offers the prospect of reducing the environmental impact of electricity use, and also the supply costs. However, the relatively small loads and numerous actors imply a large effort: response ratio. Residential DR may be an essential part of future smart grids, but how viable is it in the short to medium term? This paper reviews some DR concepts, then evaluates the propositions that households in cool temperate climates will be in a position to contribute to grid flexibility within the next decade, and that they will allow some automated load control. Examples of demand response from around the world are discussed in order to assess the main considerations for cool climates. Different tariff types and forms of control are assessed in terms of what is being asked of electricity users, with a focus on real-time pricing and direct load control in energy systems with increasingly distributed resources. The literature points to the significance of thermal loads, supply mix, demand-side infrastructure, market regulation, and the framing of risks and opportunities associated with DR. In concentrating on social aspects of residential demand response, the paper complements the body of work on technical and economic potential.

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1. From 'predict and provide' to responsive demand

In this section, we define and discuss demand response (DR), before setting it in the context of emerging smart grids and their stakeholders, and offering two assumptions about the future of residential DR for examination.

A major shift is under way from the 'predict and provide' model of electricity provision (McKenna et al., 2011). There are a number of reasons for this, including growth in non-despatchable and distributed modes of supply (Thomson and Infield, 2007), and emerging patterns of demand with additional loads for heating, ICT and electric vehicles. These changes in both supply and demand bring with them a need for measures to avoid network

congestion and maintain acceptable power quality—if possible, while avoiding costs of new generating capacity and network reinforcement (Strbac, 2008). Further impetus for change comes from the need to contain *overall* demand, in order to minimise resource depletion, pollution, and greenhouse gases (e.g., DECC, 2009), and from concern about the financial and environmental costs of meeting peak demand (Ericson, 2009; Faruqui, Harris and Hledik, 2010).

'Demand response' is increasingly seen as a way of meeting emerging needs for better system management and concerns about energy security and environmental impact. We begin with a definition from the US Federal Energy Regulatory Commission, that demand response (DR) is

Changes in electric usage by demand-side resources from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to

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induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized (FERC, 2012).

Demand response is here seen essentially as a response to a price signal (although other signals may also be relevant, as discussed below), which may involve time-shifting or load reduction, or both. This fits with a more specific definition of household DR as ‘a household action which *shifts and/or reduces* overall energy use in response to a price signal or other price stimulus’ (Owen and Ward, 2010, p.15).

A crucial element in the move towards DR has been the development of ICT that makes highly-responsive systems feasible. ‘Smart meters’, with their capacity to record and transmit high resolution consumption data rapidly, are perhaps the most widely-known ICT development in electricity systems, and are seen as a key enabler of DR (Darby, 2008; McKenna, Richardson and Thomson, 2012). A particular DR action can be automated, manual, or both, as discussed in Section 2.

1.1. Smart grids and stakeholders

Having indicated why there is increasing focus on DR, we now discuss the emerging context in which it operates, and the principal stakeholders involved.

Demand response may be seen as a form of *distributed energy resource*, along with distributed generation and storage¹. As such, it is necessary for the effective working of smart grids, broadly defined as

... electricity networks that can intelligently integrate the behaviour and actions of all users connected to [them] – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies. (SmartGrids European Technology Platform, widely cited, e.g., <http://www.esat.kuleuven.be/electa/research/descriptions/smartgridsetps.pdf>)

We are still at a very early stage in understanding social and governance aspects of smart grids during the evolution from highly centralised systems with relatively few large generators and relatively predictable demand patterns, to systems with multiple generators, less predictable supply, and more diverse and unpredictable demand. Wolsink (2012) offers a comprehensive guide to the issues.

Policy-makers typically aim for systems that achieve security, sustainability, economic and social goals (high-level drivers cited by the EU Commission Task Force for Smart Grids, EC, 2010a). The principal stakeholder groups in DR are transmission system operators (TSO), distribution network operators (DNOs), generators, electricity retailers, users, and government. Although most electricity users are still unfamiliar with the concept of smart grids, they have a stake in reliable, affordable energy services with reduced environmental impact. However, they are largely unaware of the reasons for, and potential benefits from, demand response. The EU Commission Task Force on Smart Grids recently concluded that:

The acceptability of new services by the customers is a main concern [and] all opportunities for evaluating customers’ interest must be used, specially involving them in demonstration projects ...As smart grids and their benefits still represent broadly misunderstood concepts by most ... consumers, and as many initiatives related to smart grids or smart metering have created concerns and questions towards the usefulness and relevance of such developments, [we] would recommend encouraging Member States to address

¹ Many of the considerations that apply to ‘classic’ residential demand response can also apply to residential generation and storage. Indeed, load-shifting can be seen as a form of storage.

communication and education ... [familiarise citizens with] operational and economic aspects of energy systems [and with] the meaning of smart grids ... (EC, 2010b, pp 36–37).

The aim of this paper is to contribute to understanding of social aspects of the proposed operation of smart grids, by assessing prospects for residential demand response in cool temperate climates from the user’s standpoint. Two widely-held assumptions are examined: that households in cool temperate climates will be in a position to contribute to network flexibility within the next decade, and that they will accept some automated load control. The paper complements work by authors such as Faruqui, Harris and Hledik (op.cit.), and Torriti, Hassan and Leach (2010), who offer more quantitative and economics-based analyses potential for DR in Europe. It also adds to the recent analysis by Kim and Shcherbakova (2011), which identifies a number of structural, economic and informational reasons for failures in demand response.

In Section 2 of the paper, we set out options for residential DR and assess them in terms of likely system requirements, and what these imply for users. This is done by outlining scenarios for electricity systems in the shorter and longer term, taking a more detailed look at options for residential load management, and then translating these into user choices and actions. Section 3 goes on to review examples of DR experience from selected regions and programmes; and in Section 4 we discuss the transferability of this experience, and what it tells us about the viability of the assumptions.

2. Residential demand response

Demand response will take different forms over time, as electricity systems evolve, and in this section we address several factors that shape response. After setting out the broad policy landscape into which DR is being introduced, there is a classification of residential DR options, derived from literature review, Commentary follows on issues raised by automation and the need for customer awareness, and on the value of timing in DR. The section concludes with an analysis of DR from the user’s perspective in an attempt to explain why householders might wish to participate in DR programmes.

Table 1 outlines short- and long-term scenarios for Great Britain. The long-term scenario is in accord with the concept of a low-carbon highly-distributed electricity future² with active user participation, and the short-term scenario assumes a continuation of current developments. The table highlights likely changes in the nature of user engagement with the system, as both demand and supply become less predictable.

In the short term, the implied policy goal is to encourage customers to reduce peak demand. In the longer term, it is to achieve flexibility, with a large component of automated response that can be activated rapidly. Implementing these goals for the residential sector poses considerable challenges, starting with the cost and effort involved in communicating with millions of small users, then equipping them with enabling technologies such as smart meters and appliances, customer display interfaces and remote switching. For example, more than two thirds of Great Britain’s electricity is consumed by fewer than 10% of users,

² This concept is central to the SuperGen HiDEF research programme—see <http://www.supergen-hidef.org/about/Pages/Home.aspx>. HiDEF investigates ‘a sustainable electricity supply system that makes optimum use of decentralised assets and in which *energy consumers participate actively* in appropriately structured decentralised markets... a major change from the present arrangement, where most consumers are passive users of externally supplied energy, and [one that] would require *new attitudes to energy and new ways of working*’.

Table 1
Short- and potential long-term characteristics of electricity systems in Great Britain.

	Short term (to 2020)	Longer term (post 2020)
Electricity system	Centralised	Highly distributed resources, including control and response
Critical issue for system reliability	Peak demand	Variability of renewable supply
Role of demand response	Shift load at regular times of day; reduce load	Shift load from times of low renewable generation (e.g., wind); store energy at times of high renewable generation; balance network to allow for electric vehicle charging and heatpumps in addition to traditional loads
Consumer response	Adoption of tariffs with cheap offpeak electricity (usually combined with electric storage heating; some voluntary manual load-shifting)	More automated load-shifting; adoption of more complex tariffs, either with fixed rates for fixed periods of time or dynamic rates according to supply availability
Likely means of achieving demand response	'Consumer engagement'. load-shifting in response to static time-of-use tariffs or other signals. Some continuation of storage heating.	'Active demand'. Dynamic pricing. Some conscious/manual load-shifting, but response is mostly automated. Some is programmed by householders, by agreement with energy services providers. Some comes from appliances responding automatically to pricing signals/ voltage fluctuations.

raising the question of whether investing in residential DR is worthwhile before the potential of larger users has been exploited (Owen et al., 2011). Aggregation of residential demand response is very rare, and aggregators struggle to find a business case for it (Appel, 2011). As recent modelling of German household demand and American plug-in electric vehicle charging has indicated, investment in smart appliances or in enabling technology for vehicle charging with real-time pricing (RTP) may not be justified in purely economic terms (Gottwalt et al., 2011; Lyon et al., 2012).

However, system management reasons for extending demand-side activity into the residential sector include the following:

- Residential demand often makes up a significant share of overall consumption—for example, 36% of the UK total in 2010 (DECC, 2011, Table 5.1.2). Electrification of personal transport and heating is likely to continue, even if not to the extent envisaged in plans such as the UK Low Carbon Transition Plan (DECC, 2009). This is likely to add to both peak demand and to unpredictability. Moreover, solar PV, heat pumps and electric vehicles are likely to be concentrated geographically, leading to local network management difficulties (McKenna et al., 2012).
- Electricity use in the home already contributes disproportionately to peak demand. In the UK, between 5–6pm, household demand was reported as being responsible for 45% of system peak in 2005. The relatively shiftable loads from water heating and wet appliances accounted for 23% of this (Lampaditou and Leach, 2005). More recently, it has been estimated that only around 9% of household electricity use is automatically switched or shifted to offpeak times, much of it for (stored) space heating (Brattle Group and Sustainability First, 2012). There may well therefore be unrealised potential for more residential DR, through shifting more electric space and water heating along with wet appliances (ibid.). This potential has been widely noted in many countries, (e.g., Stokke et al., 2010; Filippini, 2010; and Pavan, 2010 for north, central and southern Europe respectively).

2.1. Residential demand response options

From the user perspective, the extent to which people shift their consumption patterns will depend on factors such as perception of the need to do so, trust in the utility or energy service provider, incentives, and transaction costs (including cognitive costs). This is demonstrated in the analysis of consumer issues related to smart meter adoption by Roberts and Redgrove (2011), and in the review of demand response and feedback trials carried out by Strömbäck et al. (2011).

Table 2
Description of residential demand response options.

Demand response option	Description
Energy efficiency and conservation programmes	Encourages the purchase of energy-efficient appliances or building improvements, thereby reducing overall demand.
Static time-of-use pricing	Electricity prices vary according to the period of the day—prices are low when the demand is low (at night) and high when the demand is high (during the day). Prices do not vary on a day-to-day basis.
Critical day pricing	Similar to static time-of-use pricing, but where prices are considerably higher, throughout the whole day, on a 'critical' day compared to a non-critical day.
Critical peak pricing	Similar to static time-of-use pricing, but where the prices are considerably higher during the peak period on a 'critical' day compared to a non-critical day.
Peak time rebates	Similar to critical peak pricing, though where customers receive a rebate if their consumption is below a given threshold during the critical peak period.
Real-time pricing	Electricity prices vary throughout the day, typically on an hourly basis. Prices are, in theory, unpredictable, and follow some of the volatility of wholesale electricity prices.
Demand-side bidding	Consumers participate directly in the electricity market by bidding for their expected demand ahead of schedule. Typically, this would be an automated process performed by consumer appliances.
Dynamic demand	Appliances respond automatically to system frequency, by switching off when the frequency drops below a certain threshold.

Load-management options are also complex, according to purpose and mechanism (for example, Borenstein et al., 2002; Goldman et al., 2010). In an attempt to reduce the complexity, we concentrate here on those DR options that apply to the residential sector, and on the actions required for each from household occupants. The categories are derived from reflection on both academic and 'grey' literature on demand response. These are summarised in Table 2 and are described in more detail below.

Moving from the simplest demand response option, to the most sophisticated, in terms of time-sensitivity, we have:

- (a) Energy efficiency and conservation programmes. These can be aimed at entire buildings, or specific appliance groups. These can reduce peak demand, as well as baseload, but do not necessarily make systems more responsive.

- (b) Static time-of-use pricing (TOUP), when tariffs are stable for long periods, and users have time to get used to them. As the price bands reflect long-term average expectations of daily peak marginal costs, they do not provide *additional* incentives to reduce demand further on days when the system is most stressed (Herter, 2007).
(Note that at this point on the spectrum, a category shift occurs: we move from *static* pricing, for situations in which supply is relatively predictable, to *dynamic* pricing, where it both demand and supply may fluctuate unpredictably. This will be increasingly needed as distributed sources of supply come on stream, and if demand becomes more peaky and erratic with growth in electrical heating and transport.)
- (c) Critical day pricing (CDP) entails load curtailment over periods of a day or more, with day-ahead warning. The EdF 'Tempo' tariff, used by over 100,000 small businesses and roughly 350,000 high-consuming residential customers in France, is probably the best-known example. It is reported to cut national peak consumption by 4% (Torriti, Hassan and Leach, 2010). The year is divided into 'red' (22), 'white' (45) and 'blue' days. Unit prices for daytime on a red day are roughly 12 times as high as for night time on a blue day—dramatic and noticeable differentials. Variants of the tariff involve direct load control (DLC) of water heaters and space-heating thermostats. The main drawback for customers is the difficulty in managing as many as five 'red' days in a row, in cold, still weather (Crossley, 2008). This is relevant to the long-term scenario for demand response with distributed generation.
- (d) Critical peak pricing (CPP) over a few hours, with day-ahead warning to the customer, is used for very sharp peaks in demand. Feedback including ambient displays, which change colour according to the current unit price of electricity, may be used to alert customers to critical peak periods (Strömbäck et al., 2011).
- (e) Peak time rebates (PTR) are a variant on CPP, in which customers are given a rebate for electricity that they do *not* use during critical peak times. This is seen as more user-friendly than CPP, because it involves no risk, but it is less effective than CPP at reducing load (Faruqui and Sergici, 2010).
- (f) Real-time pricing (RTP) occurs when the customer pays prices that are liable to vary more rapidly and less predictably throughout the day than 'static' TOUP, posing more uncertainty to the customer. Although prices may change as rapidly as every five minutes, hourly pricing is a more realistic scenario for RTP (e.g., Allcott, 2009).
- (g) Demand-side bidding involves contracting to offer specific reductions in demand at given times, in return for specified sums (Albadi and El-Saadany, 2008). This is a complex arrangement for residential demand (tested in the Olympic Peninsula project, discussed below) but could become more feasible through aggregation.
- (h) 'Dynamic demand' (DD), at the far end of the spectrum is when appliance load is shifted, sometimes only for a few seconds, in response to changes in frequency (Short and Infield, 2007). This is a way of supplying ancillary services to network operators. Some 'smart' appliances, enabled for DD, are already on the market. Fridges show particular promise (Hirst, 2011).

2.2. Automation and awareness

When pricing is liable to change rapidly, or when response is critical to network stability, some degree of automation is needed for effective demand response. This could involve actions such as installing a remote switching device to a water heater,

programming several appliances to switch off when prices rise above a certain level, or signing up to a static time-of-use tariff such as Economy 7 (UK) or Tempo (France) that includes automatic control of heating. Strömbäck et al. (2011, pp 57–61) give an overview of options and responses, finding that automation boosts the level of peak clipping for all types of variable tariff except for RTP, where the few trials to date have produced a lower response than that from manual switching.

Automation, however, has at least three potential drawbacks: the enabling technology can be expensive; it reduces user control; and it can reduce users' awareness of their energy-related practices, possibly resulting in unintended consumption. Programmable thermostats offer a well-known example (see Nevius and Pigg, 2000, and Guerra-Santin and Itard, 2010, for analyses from the USA and Netherlands). There is therefore a need to test out and evaluate automated solutions carefully before mass deployment.

The recent review of demand response programmes by Strömbäck et al. finds that customer education (broadly defined), with its potential to raise awareness, has a significant impact on outcomes, as does improved feedback. The authors argue that 'education should be included within dynamic pricing programs, especially those involving automation, as it helps to decrease total consumption rather than only peak consumption' (p.67). They found that 92 trials of TOUP without any accompanying customer education gave an average 1% rise in overall consumption and a 4% fall in peak usage, whereas 122 trials that included some education led to 4% overall and 6% peak reductions. In summary, automation is not a substitute for awareness, and awareness boosts the impact of automation.

2.3. The value of timing

The value of different types of response to wholesale and ancillary markets can be inferred to some extent from the terms of interruptible supply contracts, and from TOUP and dynamic pricing schemes. But DR is something that has to be tested and then negotiated, until the value of an action to an end-user intersects with its value to the network. Where residential demand is concerned, this negotiation may be particularly complex. For example, if cooking can be delayed, this is particularly valuable over very short periods of time to a network operator. However, experience suggests that people are unlikely to alter their preferred cooking and eating times, so that an incentive would have to be very significant in order to persuade them to shift usage. It might also have to be communicated at very short notice.

Wood and Newborough (2007) offer a detailed analysis of the extent to which domestic appliances are suited to manual or automatic control. This is useful in any consideration of how demand response can best be arranged to meet different requirements, such as dynamic demand through 'smart' cold appliances, or short-term load-shifting through manual delay of wet appliance usage. Roscoe and Ault (2010) discuss the relative acceptability of shifting different end-uses, with modelling that indicates that UK load could be reduced by over 10% during times of high demand and low wind generation³.

Water heating, space heating, air-conditioning and freezing offer value in the medium term (from around 20 min to several hours). They can be switched remotely or manually; impacts on comfort and health will depend on the thermal characteristics of the building, storage tank or freezer. Wet appliances also have shifting potential in the medium term, although there is little

³ This estimate has since been supported by smart metering and TOUP trials in Ireland (CER, 2011) and Great Britain (AECOM, 2011).

evidence as yet on the acceptability of shifting wet appliance usage.⁴

Demand response for periods of several days in a cool climate, typically caused by a winter anticyclone, has great value (as illustrated by the price structure of the ‘Tempo’ tariff), but poses the most challenges for shifting and storage: it has to be viable in terms of day-to-day living. Overall demand reduction still offers the simplest way of avoiding the need for widespread storage over lengthy periods, but even in relatively low-demand systems, diversity of supply and some storage will be required to cope with lengthy periods of cold weather.

2.4. Demand response from the user standpoint: Why participate?

Likely participation rates are a critical consideration in making a business case for demand response. Where customers have to opt into a programme, these rates have typically been very low: a take-up rate for TOUP of around 1% among residential customers was given as typical for investor-owned utilities in the USA by Lutzenhiser et al. (2009), and it was suggested that such low involvement could be due to loss aversion as well as inertia (Letzler, 2006), indicating scope for better programme design. Higher participation rates in demand response are now being recorded, where utility-customer relations are good (Strömbäck et al., 2011). In Britain, a TOUP trial carried out under the Low Carbon Network Fund recently reported take-up of TOUP by 8% of customers following a direct marketing exercise⁵. Factors such as logical sequencing of messages, simplicity and a sense of purpose can assist take-up—price is not the only consideration (Strengers, 2010; McKenna et al., 2011). Non-economic or one-off incentives (such as the chance to take part in smoothing network operation, or the offer of a free programmable thermostat) have been associated with successful recruitment by some American utilities (SGCC, 2011).

Some household activities are highly time-sensitive, as noted above; householders may not be aware of the rationale for demand response and potential benefits; and there may not be the conditions to make it worthwhile. For example, some householders have very low loads; their homes may not be well-insulated enough to time-shift heating without discomfort; or they may not have storage capacity or micro-generation. In addition, mistrust of utilities can stand in the way of participation in an uncertain initiative. Table 3 examines what various DR options might look like from the householder’s perspective, based on descriptions of these options in the literature. It shows the potential value of manual override facilities and demand aggregation in maintaining users’ sense of control and reducing financial risk.

Levels of automation will depend on user inclinations, end-uses and system requirements. For example, someone with solar PV might already experience a variable price signal—if there is a price differential between export and import rates. When export rates are low compared to import rates, as in the UK, they may wish to minimise bills by checking weather forecasts and doing their washing on sunny days; or to invest in technology that switches loads on and off according to their PV generation. Conversely, electric vehicle owners are unlikely to wish to change from a situation where they can charge their cars at any time, on a ‘flat’ tariff; regulators and network managers may have to impose automated controls on charging in future, in order to maintain security of supply.

⁴ For example, night-time noise may be a problem, especially in small dwellings.

⁵ See slide 55 from presentations at the National Stakeholder Forum of the Customer-Led Network Revolution Project, May 9th 2012, at <<http://www.networkrevolution.co.uk/industryzone/projectlibrary>>.

Table 3
demand response from the user’s perspective.

Demand response option	Level of user involvement, and comments
Overall (grid) demand reduction	Invest in home retrofitting and efficient replacement appliances; switch appliances off; alter settings; change practices in relation to clothing, curtains etc; invest in microgeneration and renewable heat technologies.
<i>Static price response</i> Economy 7 or ‘bioraria’ -type pricing (two price bands only)	Some may be obliged to adopt this type of tariff because they have night storage heaters, in which case heating is switched on and off automatically. Some may choose it after calculating that they have enough shiftable load to justify washing, etc., in offpeak hours. Then they have to remember to do so, or manually or through automation.
(Static) TOUP (may have more than two price bands)	Active customer involvement can vary considerably. Potential for automating some end-uses, eg water heating, wet appliances, even some space heating, to optimise use of cheap electricity. User can cede control to supplier/network operator; manual override makes this more acceptable (Caird and Roy, 2007).
<i>Load response</i> CDP	Choose tariff, watch for day-ahead notification of high demand, reduce demand as far as compatible with comfort.
CPP	Choose tariff, watch for notification, reduce demand at critical peak times.
PTR	Choose tariff, watch for notification, reduce demand. More suitable than CPP for people on low incomes.
<i>Dynamic price response</i> RTP	Requires good understanding; customers may be able to set maximum prices they are willing to pay, and/or may install backup capacity or storage. Possible to reduce risk through forward contracts, in some regulatory situations. RTP is likely to involve high degree of automation of response, to keep pace with price changes. Offers advantages of RTP, with low threshold for customer involvement. Aggregators take financial risk (low at present, though likely to become more significant) and pass on some profit to the customer.
Demand aggregation	Aggregators take financial risk (low at present, though likely to become more significant) and pass on some profit to the customer.
<i>Frequency response</i> Dynamic demand	Customer needs to invest in DD-enabled appliances, i.e., those that switch on and off in response to frequency on the network.

(Based on Darby, 2011).

This section of the paper has shown some of the complexities of designing effective demand response, and also some of the potential. It has highlighted the wide range of options, the significance of thermal loads, the value of timing and of risk reduction, and the importance of combining selective automation with user feedback and education. The following section reviews some demand response initiatives in particular markets, with a view to selecting lessons that are applicable to cool temperate climates.

3. Demand response experiences from selected regions

The effectiveness of tariff options ‘depends critically on the nature of the system where they are implemented’ (Batlle and Rodilla, 2009, p15). Relevant factors include climate, built

environment, appliance ownership, supply mix, regulatory requirements, attitudes to data privacy, and everyday practices.

Tables 4 and 5 summarise findings from some residential demand response trials, with brief comments on qualitative aspects. They are far from exhaustive, but give an indication of technologies and tariffs that have been tested. They also demonstrate the range of outcomes, given the variety of technologies and practices employed, and the variety of regulatory frameworks, pricing structures, and living conditions. Even from areas with a high penetration of air-conditioning, there are sharply contrasting findings. For example, the Country Energy pilot achieved 30% demand reduction at critical peak times through a combination of advanced metering with in-home displays, TOUP and CPP; while the Chicago RTP pilot, with hourly RTP and day-ahead warnings of critical peak periods, produced no more than half that figure.

Below, we comment in more detail on examples of the two modes of pricing likely to be of most concern in cool temperate climates over the coming decade (static TOUP and RTP), and on potential enabling technologies. These two are the most relevant of those listed above in Section 2, because TOUP represents likely mainstream attempts to manage load through tariffing up to 2020 or thereabouts, while RTP is the more relevant tariff type for low-carbon future systems, as indicated in Table 1.

3.1. Static TOUP in Italy, Ontario, Finland and Ireland

In Italy, policy has focused mostly on efficiency, supported by tariffs related to peak loads (i.e., capacity) for many residential customers (Pavan, 2010; Owen and Ward, 2010). Almost all householders now have an interval (smart) meter, without an in-home display. A range of time-varying rates has been developed, with mandatory TOUP from July 2010 for the majority of customers who buy from the main supplier, ENEL. In advance of fully cost-reflective pricing, the regulator is running a major study in order to understand what impact this TOUP has on household consumption. (It is not necessarily popular: ENEL's competitors advertise flat rates as an inducement to switch supplier.) In the early days, it was reported in that Italian customers were only benefiting from the new tariffs if more than 70% of their usage occurred at off-peak times (Frontier Economics, 2010).

Residential customers in Ontario (like Italy, an early adopter of smart meters) have been through the process of converting from a two-stage rising block tariff (RBT) to a mandatory time-of-use regime. The government has attempted to incentivise both conservation and load-shifting. The average household now pays a very small amount more for electricity each year than under the old tariff—some 0.2%. A low peak to off-peak price ratio – slightly more than 2:1 – contributed to a muted reaction. High consumers usually gain by moving from the previous rising block tariff to TOUP, but not if they have particularly high consumption at peak times (Rowlands and Furst, 2011).

In Finland, sharp peaks in demand can occur at any time of day in extremely cold weather, so that static TOUP is not adequate for regulating demand (Koponen (2010, pers. comm.)). A form of DLC is being developed to switch storage heaters off when necessary, and to spread out 'rebound' demand when they are switched back on after peak times. This uses an algorithm based on heat demand (related to outdoor temperature in previous 24 h) and time (the cheapest available hours signalled by the day-ahead market) (Koponen and Seppälä, 2011). Challenges include multiple heating systems and higher system peaks following introduction of heat pumps. Insulation can improve the situation, lowering the heating load and making DLC more acceptable by reducing any loss of comfort when the heating is switched off. Koponen (pers. comm.) reports field tests of DLC in the winter of 1996–1997 with

Table 4
Summary of findings from selected non-European demand response trials.

Study+date	Location	Sample size and selection	Length of trial	Electric heating penetration	Tariff type	Direct load control	Overall demand reduction	Peak reductions and comments
Country Energy (2005)	Australia (NSW)	113, opt-in	18 months	Some water heating (WH) and space heating (SH)	CPP, P:OP ~5:1; TOUP, P:OP~2.5:1	No	~8%	30% at CP times. Educational programme accompanied CPP. In response to a CP alert, participants typically turned off a combination of TV/DVD/stereo (27% of respondents), wet appliances (20%), oven (18%) and lights (17%).
Quantec (2004)	Portland, Oregon	393, comparable with 205 controls	12 months	43% had electric SH; 64% had electric SH	TOUP		-2.4%	7/15% reduction of winter peak (morning/evening); 2% of summer peak, against controls. 76% and 54% of participants reduced demand during winter morning and evening peaks. 2/3 of customers very satisfied.
PNNL (2007)	Washington State	112	Approx. 12 months	All had electric SH and WH	TOUP and RTP; controls on standard tariff	Owners set automatic response based on comfort and price preference	TOUP gave more reduction than standard tariffs/RTP	Highest peaks reduced by 5–20%, depending on supply constraint. 73% of participants said they would be willing to choose price-responsive contracts in future.
Allcott (2009), Isaacson et al. (2006)	Chicago	693 opted in out of 7000 asked.	8 months in first instance	Some WH and SH	Hourly day-ahead RTP, with special signal for CP; P:OP ratio approx. 4:1	With and without	No net increase; 3–4% savings in summer	5–14% peak reduction in summer. First hourly RTP program for residential consumers. Air-con savings from RTP are comparable with those from investment in new window air-con units; RTP should perhaps be thought of as a peak energy conservation program, instead of a mechanism to shift load.
Faruqi and Sergici (2010)	North America	15 trials, various states	various	Some WH and SH	CPP, PTR, TOUP	With and without	Slight impact, TOUP and CPP	3–6% peak reduction for TOUP; 13–20% for CPP without DLC; 27–44% for CPP plus DLC

Table 5
Summary of findings from selected European demand response trials.

Study+date	Country	Sample size and selection	Length of trial	Electric heating	Tariff type	Direct load control	Overall demand reduction	Peak reduction and comments Comments
Renner et al. (2011)*	Czech republic	Large	Since 1970s	Storage heating and/or WH	Double tariff using two (dumb) meters	Ripple control		10–15% of max grid load.
Renner et al. (2011)*	Denmark	500+, probably opt-in	24 months	All had electric SH	New contracts with spot prices included.	46 had DLC		No savings from price info alone; approx 10% for those with DLC. Customers could specify prices at which with DLC of heating would take over.
Crossley (2008)	France	350,000+	Since early 1990s	High penetration of electric SH and WH	CPP 22 day/year; medium prices 43 day. P:OP ratio approx 12:1	Some DLC of boiler, water heater and thermostats.	Approx 45% on CPP days,	Average 1 kW reduction per customer Up to five CPP days in a row can be difficult for householders to manage.
CER (2011)	Ireland	5,028	12 months	Some electric space and water heating	TOUP. P:OP ratios from 1.7:1 to 4.2:1 were tested		2.5%	8.8%. In-home displays designed with customer assistance raised savings to average 3.2% overall, 11.3% peak.
Stokke et al. (2010)	Norway	443	3 months (Dec–Feb)	High penetration of electric SH	'Demand Charge grid tariff' for highest hourly usage at peak	Not stated—probably not		Average 5%. Consumers did not receive information on consumption or any reminders.
Saele and Grande (2011)	Norway	40	12 months	All had 2–3 kW WH; 10% had 12–15 kW SH	Hourly spot price combined with fixed price up to a given volume	Of SH and WH, with override available		1 kW for water heating; 2.5 kW for space heating. Some automated load reduction at peak times, plus reduction. Scaling result up gives potential 4.2% registered peak demand from 50% of Norwegian households.
Pyrko (2006); also Renner et al. (2011)*	Sweden	24,000	24 months	Likely high penetration of electric SH	Grid fees depending on average peak demand.	No		Approx 5%. Important that customers' understand difference between "power/load" and "energy" terms, and have good feedback.
Sernhed (2008)	Sweden	10	Brief	Electric SH and WH	No special tariff	DLC for up to 16 h, or 4 h, 3 times daily		Comfort and convenience negotiable against incentives. All households pay capacity-related tariff and have to adjust behaviour in very cold weather, to avoid fuse blowing.
Renner et al. (2011)*	Sweden	45 first winter, 93 s winter	Two winters		CPP, for a maximum of 40 h	Not stated		Approx. 50%. Customers given energy-saving tips, and day-ahead warnings of CP periods. Willingness to support local utility.
Renner et al. (2011)*	Sweden	50		All had electric SH		Yes		5 users showed reduction of 67% in heating load over 2-h period in very cold weather. No complaints about discomfort due to DLC.
Ofgem/AECOM (2011)	UK (GB)	Two trials in EDRP	24 months	Some electric SH and WH		No		Up to 10%.

Abbreviations: CPP—critical peak pricing, DLC—direct (remote) load control, SH—space heating, TOUP—static time-of-use pricing, WH—water heating.

* This report gives brief summaries of a number of residential demand response trials and projects (pp 115–148); it is not an exhaustive account.

almost 7000 homes, giving over 20 MW of controllable power, with fewer than one in a thousand customers complaining. Most did not notice that the DLC was occurring.

The trials of smart metering and static TOUP (with three or four price bands) carried out by the Commission for Energy Regulation in Ireland are among the most statistically robust to date (CER, 2011). They show average savings of 2.5% overall and 8.8% at peak times, compared with the control group, when a combination of TOUP and some form of customer feedback or incentive was offered; peak demand reduction rose to 11.3% when TOUP was combined with in-home displays and bimonthly informative billing. Households with higher consumption tended to achieve greater reductions, having more scope, but fuel-poor households also benefited from the new tariffs. Interestingly, there seemed to be no 'tipping point' or 'tipping price' beyond which electricity was seen as too expensive: peak demand was highly inelastic, regardless of the size of the peak:off-peak ratio (this ranged from 1.7:1 to 4.2:1). It appeared as though the main factor affecting customer response was the existence of time-varying prices, rather than the actual figures involved. The benefits at this early stage of introducing new tariffs were of a fairly general nature, with raised awareness among almost all customers and a response to the overall intention of the new tariffs, not the detail. The CER noted that safety and convenience considerations both affected the extent to which customers were willing to shift usage to night times, but that, in general, customer response to the trial was positive, with only 18% of participants reporting no impact.

3.2. Real-time pricing in Illinois, Washington State and elsewhere

The Illinois Energy-Smart Pricing Plan (ESPP) was 'the first significant effort to introduce hourly market-based electricity pricing to residential customers' with the aim of allowing them to capture some benefits of cost-reflective pricing (Summit Blue, 2006). It began 2003, with 750 members of the Chicago Energy Cooperative (CEC), mostly on low incomes, and grew to 1500 participants with a broader spread of incomes, ending in 2006. The ESPP was used as the basis for rollout of two large residential RTP plans by investor-owned utilities (Star et al., 2010). It involved day-ahead price notification by phone or website, with special arrangements for critical peak days when the price was going to be over 10cents/kW h, so that participants could adjust consumption manually. Prices never rose above 36c/kW h (there was a cap of 50c/kW h). The CEC provided customer education and individual usage feedback to help participants.

The participants responded to these relatively modest changes in hourly prices, even in extremely hot weather. There was an estimated conservation effect of 3–4% during the summer, though no significant difference in usage during winter between participants and the control group. Price elasticity was -4.7% overall for 2005, but roughly twice as great during late summer afternoons as earlier in the day; it was also greater on critical peak days than on normal days.

Response was boosted by around 50% when customers had a visual prompt (an orb that glowed in different colours according to price); it also increased when customers had automated cycling for their air-conditioners at peak times. When high-price days were clumped together, though, response tended to fall off—a similar effect to that noted when several 'red' days occur together on the Tempo tariff in France. Perhaps surprisingly, lower-income households were more responsive to price signals than those on higher incomes, although such households normally have lower overall consumption and less load that can be shifted. (This is in contrast to the CER findings reported above).

In qualitative terms, the ESPP appeared to have combined an initial, appealing incentive with a durable impact:

Three years of impact evaluations have demonstrated consistent reduction in peak load and a conservation effect. Education is a key factor in influencing this change, and the potential for lowering household electricity bills provides the incentive for changes in behaviour.

(Isaacson et al., 2006, p 7–127)

Later commentaries tend to take a more critical stance. Allcott, for example, concedes that advances in smart grid technology and greater variability in hourly prices could have led to more satisfactory results, but draws the policy message that

even in this selected group of households, RTP does not generate energy-related compensating variation that is large in an absolute sense, or in comparison to metering costs or the potential costs incurred by households in conserving energy... these results do not make a strong case for optional or population-wide residential RT pricing (Allcott, 2009, pp16, 18).

Another more recent analysis concludes that a good efficiency programme would be more productive than dynamic pricing with high peak prices, and that

'the notion that residential customers should be moved en masse to dynamic pricing is fraught with adverse consequences and, more importantly, is likely to contribute to a customer revolt against the 'Smart Grid' agenda.'

(Alexander, 2010, p40).

Some of the original evaluators reached the measured conclusion, after several years, that

Dynamic pricing remains a new idea for residential customers... the test of consumer acceptance of dynamic pricing remains very limited. It's going to take more than just a bill insert or one direct mail piece to get customers to change their electric rate voluntarily... getting customers to voluntarily embrace dynamic pricing...will take an ongoing, long term series of engagements, reminders, pokes and prods.

(Star et al., 2010, p. 2–267)

Another early documented attempt to introduce RTP was the Olympic Peninsula project in Washington State. This was more sophisticated than the ESPP, and one of the very earliest 'smart grid' projects. It tested demand-side bidding, more than one time-varying tariff, smart meters, programmable communicating thermostats, and water heaters and dryers that were automated to respond to price signals. Supply was artificially constrained. A combination of demand reduction and distributed generation reduced peak loads by up to 50%, reduced cost to the consumer by 10%, and had a conservation impact estimated at 6% for customer on TOUP, though no such impact for those with RTP (PNNL, 2007).

A recent review carried out for the European Smart Metering Industry Group analyses data from 15 RTP pilots and programmes worldwide (including the two mentioned above), and finds 12% peak reduction and 13% financial savings to the customer on average (Strömbäck et al., 2011). This sample includes short-term pricing signals, and also a widely-adopted form of RTP in Norway, where over half of residential customers are reported to be on tariffs based on average monthly spot prices, which relate to the amount of water in hydropower reservoirs and the expected rainfall. As noted in Table 4, potential residential demand response has been estimated at 4.2% of registered peak load. This assumes 50% participation, as about half of all Norwegian households with electric water heating are estimated to be willing to

accept DLC for this end-use (Saele and Grande, 2011; Saele, pers. comm.). In Sweden, too, a high and growing proportion of householders have time-variable contracts, with and without DLC—30% in 2009 (Strömbäck et al., op.cit.).

These examples illustrate the rapid growth in dynamic pricing, and some of the outcomes and issues in different parts of the world. How generalizable are these experiences? In particular, what are the social implications for demand response in cool temperate climates, without sharp summertime peaks (commonly associated with critical peak pricing and ‘emergency’ response mechanisms) and with growing reliance on distributed, variable generation? The following section considers these questions.

4. Discussion: Transferability of DR experience

Having seen something of what ‘active demand’ involves from the user’s standpoint, and reviewed what is known about user response from a range of residential DR programmes, we now ask whether it is safe to assume that households in cool temperate climates will contribute to network flexibility within the next decade, and whether they will accept some automated load control.

4.1. Willingness to contribute to network flexibility

Residential electricity users rarely ask for time-varying pricing if they are used to flat rates, may not understand the rationale for load-shifting, and may be wary about potential benefits (see above; also contrasting reports on TOUP in Great Britain and Ireland, from Opinion Leader (2009), and CER (2011)). However, the experience reviewed above suggests that this can be addressed by well-designed customer education programmes, attention to data privacy concerns, and carefully-structured tariffs. Static time-of-use tariffs could therefore be a staging post on the road to RTP. Also, as supply and storage become more distributed, network and grid management will take on a more obviously local character and this could aid public understanding.

Real time pricing, with its additional complexity and risk to the customer, is inherently more challenging than TOUP, but there is evidence that this too can be made acceptable. The ESPP experiment, for example, demonstrated that people respond mainly to average prices and to high price alerts, rather than to marginal prices, but also that tariffs that go beyond critical peak pricing in complexity are still viable, when well-supported by education and feedback.

The ESPP experience is not directly relevant to systems with a significant proportion of wind generation, where prices could fluctuate far more than was the case in Illinois. Sharp peaks in summer demand are also a different proposition from the broader-shouldered winter peaks of cooler and more temperate climates, especially where electricity is a minority heating fuel. However, the evidence from RTP to date shows how different combinations of tariffs, education, feedback and automation are being adopted and accepted in a range of locations and are demonstrating some flexibility.

4.2. Willingness to accept automation

The review above indicates that there is scope for automation of some end-uses. Provided the public accept the necessity of new measures to manage a system, trust the messenger, and are offered some incentive to change, perceptions and practices can alter. The Scandinavian experience of DLC shows that it can be organised in such a way as to be almost unnoticeable, at any rate

for water heating. In the UK and Czech Republic, electric storage heating is well-established and familiar, if not always popular.

From the network perspective, it makes sense to concentrate on heating or cooling and vehicle charging, which are large loads and need not be as time-sensitive as most other loads. Households can then choose to operate other, more discretionary, loads manually, in relation to prevailing prices or other signals. Already, there are examples of tariffs and DLC arrangements being set in such a way as to reflect the value of load management capability to the network, and also the value of manual overrides to the customer, while enabling technologies become part of package agreements between the two.

Demand response can involve both reducing demand and shifting it through time. The relationship between these is not straightforward and has been discussed by a number of authors (e.g., York and Kushler, 2005; Boshell and Velloza, 2008; Alexander, 2010). The last of these makes the point that high levels of consumption increase shifting opportunities for the electricity supply industry, which can actually disincentivise investment in efficiency measures. However, energy efficiency can considerably increase the time scales over which DR can happen, which is particularly valuable in power systems that rely heavily on wind generation in winter. It does this, effectively, by reducing discomfort or inconvenience and increasing the social acceptability of either manual or automated load-shifting.

Load-shifting and demand reduction can reinforce each other. For example, lower overall demand is likely to involve some reduction at peak, while shifting peak demand reduces distribution losses and hence overall demand (Shaw et al., 2009); energy-efficient housing not only reduces overall demand for heating but makes it possible to shift load from heat pumps over longer periods of time (Hong et al., 2011). This has been observed even when the average unit cost of electricity to the consumer is reduced and a rebound effect might be expected (Allcott, 2009).

Some researchers have made a case for bringing together efficiency and demand response as a ‘package’ for users (York and Kushler, 2005; Goldman et al., 2010). The LEED programme in the US is piloting a demand response option for certification of energy-efficient buildings⁶. This combination of efficiency and DR is highly relevant to European policy goals.

There is an equity dimension to DR, given that any type of tariff or direct control will affect people differently according to their ability and willingness to change daily routines, adopt new technology, invest in efficiency measures or participate more actively in energy markets (Darby, in press). More advanced forms of DR may involve making judgements about the appropriate *scale* of operating a given tariff, which inevitably affects equity. Prices could differ to reflect local congestion, with one street that hosts several electric vehicles or heat pumps paying higher rates than one without either.⁷ Such a shift in the allocation of electricity costs is highly significant in political and social terms.

5. Conclusions

In most versions of a distributed energy future, customers will effectively be enlisted as co-managers of the system, even if they are not conscious of it. This marks a major shift in the nature of electricity systems and their governance, and the social and

⁶ <http://www.usgbc.org/ShowFile.aspx?DocumentID=7711>.

⁷ The current smart grid programme on the island of Bornholm is exploring this and related issues. See <http://m.fco.gov.uk/travel;letter=A/http%3Aukin-spain.fco.gov.uk/resources/en/pdf/science-innovation/smart-grids-dec2011/Maja-Bendtsen>.

equity aspects of demand response will require as much consideration as is afforded to the technical and economic aspects.

Residential load forms a substantial and growing proportion of demand in many countries, especially at peak, and it is now being taken more seriously as an energy resource although it is so highly distributed and involves so many actors. The propositions that households in cool temperate climates will be in a position to contribute to grid flexibility within the next decade, and that that they will allow some automated load control, seem to be valid, broadly speaking.

However, reported participation levels from trials around the world demonstrate that residential demand response has to be worked for, even when some form of variable pricing has become the default option. Some useful general principles can be identified: for example, the importance of simple, clear tariffs, customer education and attention to data privacy and security; good feedback systems for users and (through trials and system monitoring) for suppliers.

There may seem to be a marked functional contrast between 'active occupancy' models of demand response with the energy-aware user at the centre, and more passive load-response systems in which many processes are automated. However, there are gradations between conscious and automated response, such as manual overrides to DLC allow for user flexibility when energy services are urgently needed. Careful selection and testing of enabling technologies is needed.

From the user's standpoint, there is a significant difference between static and dynamic tariffs. While static TOUP for residential customers appears less suited to systems with distributed energy resources than RTP, it may still have a part to play in cool temperate regions, shifting some load on a regular basis and preparing the way for RTP by accustoming users to the time-dependent value of electricity.

Managing several days at a time of cold, still weather is a challenge, pointing to the need to continue minimising loads through efficiency and conservation programmes: combining demand response with demand reduction.

Finally, it is worth noting that research is now turning towards the specifics of place, time, hardware, rules and practices in DR, and a flood of data is on its way. This is welcome, given the complexity of analysing and planning smart grid development. One of the main challenges for researchers and policymakers is to identify and integrate the social aspects and governance implications of smart grids with the body of knowledge on technical feasibility.

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