Benefits and Challenges of Electrical Demand Response: A Critical Review

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Abstract

Advances in IT, control and forecasting capabilities have made demand response a viable, and potentially attractive, option to increase power system flexibility. This paper presents a critical review of the literature in the field of demand response, providing an overview of the benefits and challenges of demand response. These benefits include the ability to balance fluctuations in renewable generation and consequently facilitate higher penetrations of renewable resources on the power system, an increase in economic efficiency through the implementation of real-time pricing, and a reduction in generation capacity requirements. Nevertheless, demand response is not without its challenges. The key challenges for demand response centre around establishing reliable control strategies and market frameworks so that the demand response resource can be used optimally. One of the greatest challenges for demand response is the lack of experience, and the consequent need to employ extensive assumptions when modelling and evaluating this resource. This paper concludes with an examination of these assumptions, which range from assuming a fixed linear price-demand relationship for price responsive demand, to modelling the highly diverse, distributed and uncertain demand response resource as a single, centralised negative generator, adopting fixed characteristics and constraints.

Keywords

Demand Response, Real-Time Pricing, Economic Efficiency, Electricity Markets, Direct Load Control, Indirect Load Control

1 Introduction

Power systems are experiencing a period of rapid evolution. The previous status quo of large centralised generators operating within a monopoly is being replaced by a paradigm within which sustainability and competition are key priorities [1, 2]. Vertically integrated power utilities have been dismantled and competitive market places [3, 4] have been established to encourage the most effective use of generation and network resources. The push towards sustainability has resulted in the introduction of emission limits [5], carbon taxes, and most importantly going forward, ambitious renewable energy targets [6, 7]. Under current operating practices, high levels of uncertain, renewable generation necessitate large amounts of expensive, and often carbon intensive system operating reserves to ensure the security of power supply. A number of solutions have been proposed to remedy this situation. Flexible generation resources are typically employed to maintain the system balance, while interconnection between power systems and regions can increase geographical diversity and smooth fluctuations in renewable power output. Electricity storage can also be used to balance periods of over- and under-supply of power. Demand response is a further option that is widely explored in the literature, but to date has had limited widespread usage. Demand response is regarded as an elegant solution to the issues of uncertain and fluctuating power supply, as the potentially significant latent flexibility of electrical demand can be harnessed to provide the required power system services to support renewable power generation. It is important to note that the benefits of demand response for renewable resources are neither the only, nor the primary, driver for demand response. Rather, the abilities of demand response are a fortunate coincidence with the recent focus on renewable generation.

A key advantage of demand response is the lack of major technological impediments, as much of the required communications and monitoring technology has been developed, with the roll out of advanced metering infrastructure already under-way in a number of regions [8, 9]. The central remaining technological obstacle is the development of standards and protocols so that all components of this complex system are harmonised, and efficient communication can be achieved across the system. The greatest remaining challenge for demand response as a whole is to develop accurate control and market frameworks to ensure that this diverse and geographically distributed resource can be optimally employed, considering the needs of both the power system and the individual consumer. This is not an insignificant challenge, requiring the development of complex models of electrical demand at both the component and system levels. Simulation and forecasting models of demand are required to establish a realistic view of this resource for planning and evaluation purposes. These will facilitate the determination of its suitability for the provision of various system services and the value it can provide to the system. Going forward, operational models of demand will be required so that appropriate and accurate control signals can be issued. Such models are highly complex, as they must represent the highly diverse, dynamic and uncertain nature of demand, as well as the complexities of end-user interaction with the system.

1.1 Existing Uses of Demand Response

Demand response is not a new phenomenon and has been employed in various forms across the globe for decades. The most obvious form of demand response is systematic load shedding, a last resort to avoid system blackout, however more sophisticated approaches have been implemented in a number of power systems.

Time of use (TOU) rates where consumers are subject to expensive tariffs during fixed peak hours, or cheaper rates during night hours, have traditionally been used to incentivise reduced peak consumption, and so-called “night-valley filling" behaviour respectively [10]. The objective of TOU rates is to reduce the difference between the peaks and troughs of the demand profile, thereby reducing the need for generator cycling or part-load operation. This allows a more efficient usage of generation, transmission and distribution resources.

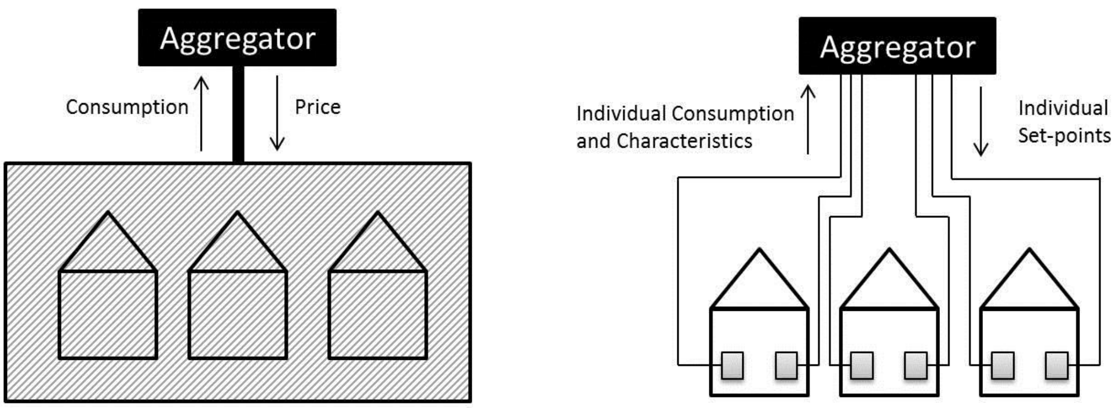
Critical peak pricing (CPP) is an event-based tariff scheme employed for larger commercial and industrial consumers with the objective of decreasing peak loads. Under this scheme, higher electricity rates are applied during peak demand events. This approach has been adopted by the Californian independent system operator (ISO), and is most commonly employed to reduce loads during hot summer days from noon to 6 p.m. when the load from air conditioning units is excessive [11].

1.2 Future Developments in Demand Response

Traditional approaches for demand response were adopted due to the predictable and cyclic nature of electricity demand and the dispatchable nature of generating resources. While this is appropriate in power systems dominated by conventional generation, systems with large penetrations of renewable resources require demand, and the system as a whole, to behave in a flexible manner on a continuous basis.

This will allow the optimal usage of the renewable resource and ensure that the system balance is maintained. As such, continuous demand response is the focus of this paper. The concept of continuous demand response, and in particular the use of price signals to elicit this response, was proposed as far back as 1988 in the seminal work of Schweppe et al. [12] on spot pricing of electricity. In this work it was proposed that price signals at a resolution of five minutes could be used to maximise the economic efficiency of the power system, revealing the true cost of electricity provision to consumers and thereby providing an economic signal to maintain the system balance. The use of price signals to this effect is termed indirect load control. At a time resolution exceeding five minutes, it was deemed that direct load control was required to ensure the stability of the system. This view is shared by Callaway and Hiskens [9], however they prefer the use of direct control for all ancillary services as the system operator has greater certainty when demand is controlled directly rather than indirectly through a price signal where the price response must be predicted.

Figure 1 shows a conceptual illustration of indirect and direct control. Under indirect control, the aggregator has limited information about the demand that is being controlled, and must estimate the price response of its demand portfolio. Prices are then issued to induce an expected response. Prices can be geographically varying, up to the resolution of information available to the aggregator, which may be at the level of several hundreds or thousands households. Direct control involves direct communication with individual appliances, and detailed information on their interactions with the surrounding environment. This is more computationally and communicationally intensive, but allows a more precise response and individual control set-points can be sent to each appliance, facilitating control of demand response at the highest possible geographic resolution. The interested reader can consult the works of Koch and Piette [13] and Jónsson et al. [14] for more information on the relative benefits of direct and indirect control.



(a) Indirect Control (b) Direct Control

Figure 1: Demand Response Control Mechanisms

1.3 Contribution of this Work

Demand response has been established as a promising method to increase power system flexibility and consequently facilitate the integration of renewable energy. However, if the response is to be provided on a continuous basis across all sectors of electrical demand, significant investment is required to establish a communications, control and monitoring infrastructure. While the control and computational requirements for direct control will be more intensive than for indirect control, both paradigms will require investment in communications, measurement and control. It is therefore imperative that the benefits of such an investment are clear. A substantial body of work has accumulated analysing the benefits and challenges posed by demand response and this paper aims to compile those works and present a clear overview of the issues pertaining to widespread demand response. A key concern is the lack of experience with demand response, particularly at high temporal resolutions and at the level of residential loads. This has resulted in the need for significant modelling assumptions in the evaluation of demand response, which may unduly influence the outcome of such evaluations and present misleading conclusions. The central assumptions in this field are critically discussed within this paper.

This work outlines the benefits and challenges posed by demand response in Sections 2 and 3 respectively, while Section 4 details a critical analysis of some of the key modelling assumptions employed in works analysing demand response. Closing remarks and conclusions are given in Section 5.

2 Benefits of Demand Response

The benefits of demand response are widely lauded in the literature in this field. Advances in modelling and IT capabilities have made demand response an attractive option to increase power system flexibility and allow a more efficient use of system assets and resources. This coincides with the recent focus on increased penetrations of renewable generation in power systems. The flexibility provided by demand response can be used to meet the fluctuations of renewable generation and facilitate a higher penetration than could be achieved by relying on conventional generation alone. Although the energy cost of renewable resources, for example wind generation, is typically quite low, the associated system costs can be substantial [15]. Operating costs are increased as both online (spinning) and quick start (standing) reserve generation is required to manage the frequent and often extreme fluctuations in the wind power output. Demand flexibility has been highlighted as a mechanism to facilitate higher penetrations of wind generation, while also reducing the system cost of its integration [15, 16, 17]. Traditionally variability and uncertainty from wind generation has been managed through a combination of ramping and part-load operation of conventional generating plant, interconnection to neighbouring regions, and storage. Going forward, the many benefits brought about by demand response may make this a more attractive option than the traditional solutions. These benefits are not limited to the reduction in system operating costs, but also include more profitable use of interconnection, reductions in generation capacity requirements, transmission and distribution network congestion management, and increased economic efficiency.

2.1 Operating Benefits of Demand Response

Operating a system with large amounts of wind generation under current operating practices requires a significant amount of reserve generation to safeguard against fluctuations in the wind output. In this manner, wind displaces energy from conventional generators, but the capacity of these generators is required to maintain system security. Demand response can provide these security services through load curtailment and shifting. Some authors predict that the reliability of demand for the provision of system services may be greater than that from conventional generators; Kirby [18] and Callaway and Hiskens [9] hypothesise that the variability of a small number of large generators is likely greater than that of a large amount of small loads.

Furthermore, a central benefit of many load types is that their power consumption can be adjusted instantaneously, allowing a much larger effective ramping rate from the aggregate demand resource than can be achieved by larger generating plants [19]. This is particularly true of appliances that provide an energy service rather than a power service, such as heating or cooling loads, where power consumption can be adjusted and shifted significantly in time with limited or no immediate impact on the energy service, such as heating or cooling to maintain a given indoor temperature range, provided to the consumer. The physical characteristics and operating constraints of large generating plants limit the rates at which they can change their power output. While the diverse nature of demand means that a certain proportion of demand may be limited in their ability to alter consumption rapidly, the aggregate demand portfolio may have a highly competitive ramping capability. The use of demand response to provide system security reduces the need to operate generating plant at part load, which is inefficient and results in higher fuel costs [20]. Part load operation is required if generators are providing spinning reserves as this allows them to either increase or decrease power output as required. Additionally, ramping of generators is reduced, and the associated cycling costs can be avoided [21].

In addition to reducing the use of generators to balance wind power fluctuations, the dependence on power import and export through interconnections to neighbouring regions can be reduced through effective use of demand response. This is particularly economically attractive as it allows these inter-regional links to only be used when it is profitable, rather than out of necessity to balance the system. Often when countries have high penetrations of wind power they rely heavily on interconnection to maintain system balance. Unfortunately, due to the nature of weather patterns, when the wind output is high in one region it is likely also high in the neighbouring regions, causing the exported wind power to be sold at a very low price [22]. Effective co-optimised planning and operation of generation, inter-regional power flow and demand response shows potential for significant welfare gains over the current operating standards, as it allows the best combination of resources to be employed.

2.2 Planning Benefits of Demand Response

In the power industry, the cost of acquiring and maintaining generating capacity is a significant component of the total costs [23]. Using demand response to reduce the capacity requirements of the system could result in substantial cost reduction. The ability of flexible demand to balance wind fluctuations and reduce peak demand through demand shifting reduces the need for investment in expensive and often inefficient peaking and flexible plant such as open cycle gas turbine (OCGT) units. This increases the utility of existing plant as they can maintain a more constant output while allowing demand to meet the fluctuations in wind generation [20]. This is most effective in systems operating with market based demand response mechanisms as even a relatively minor demand response will tend to displace the most expensive peaking units, reducing the system marginal cost and resulting in substantial welfare gains [24, 25]. A further consequence of this is the potential for a reduction in emissions from power generation. Generally, a reduction in generation from fossil sources will result in a reduction in greenhouse gas (GHG) emissions, however if those generating units with the highest marginal cost have a greater emissions rate than lower cost units, the potential savings are even greater [23].

The temporal diversity of demand has clear benefits as outlined here, however the geographic diversity can equally provide benefits. Congestion on transmission and distribution networks is a long standing issue which drives the need for costly network upgrade and reinforcement. Many power markets have resorted to using locationally differentiated pricing mechanisms to divert power flow away from congested regions and avoid the excessive degradation of the network through overloading. A number of studies have highlighted that demand response through real time pricing that is not locationally differentiated may exacerbate this issue [26]. Traditionally networks were designed considering that the peaks of individual loads do not occur simultaneously and it is therefore sufficient to set the power flow capacity according to the magnitude of the coincident peak (a proportion of the potential maximum peak), rather than the sum of individual peaks [27]. The use of a global signal to elicit a response, for example to maintain the system balance, has the intention of increasing the coincidence of demand. On a local level, this has the potential to induce congestion as the coincident peak may exceed the power flow capacity on the network. Demand exhibits a natural diversity, with a wide range of flexible appliances operating in different states with distinct operating constraints and control strategies. The degree to which the load coincidence will be increased at the local level is therefore uncertain, and the diversity may be sufficient to prevent power flow on the network exceeding its capacity, however there is a risk that congestion will be caused by responsive demand. Fortunately, whether or not congestion becomes an issue, research has found that the spatial diversity of demand can be harnessed not only to avoid this additional congestion but also to maximise the utility of the network, thereby delaying or eliminating the need for network upgrade and reinforcement [20, 28, 29].

2.3 Economic Benefits of Demand Response

In recent years, efforts to increase the economic efficiency of the power system have seen a broad movement from the vertically integrated model, to one in which competition exists across the system. As yet, however, there is limited participation of demand in the power market, an omission that must be corrected to ensure a fully competitive electricity market [30]. Unfortunately, in those markets that do permit demand to submit bids, participation is generally limited to loads that can offer bids in units of 1MW, allowing only the largest consumers to participate [11].
Many markets in the United States include frameworks for demand bids in both day-ahead and ancillary services markets, the most well-known example being the Texan market, ERCOT, where demand provided half of all spinning reserves as of 2008 [18]. However, the structure of these markets, with minimum bid sizes and advance notification requirements, precludes a large proportion of demand from participating.

The participation of responsive demand in the power market brings about a number of key benefits. Both supplier and locational market power can be reduced by allowing demand to respond to locationally differentiated and time varying price, as this limits the ability of larger producers to manipulate the wholesale price of electricity [31, 32, 33]. A further benefit is the reduction in average wholesale prices, as well as a reduction in volatility of peak prices [34]. In addition to short term efficiency gains related to prices, demand response demonstrates significant long-term efficiency gains in the form of efficient capacity planning, as explored by Borenstein [25].

Exposing consumers to time varying prices, particularly at high resolutions such as the 5-minute price suggested by Schweppe et al. [12], provides them with an incentive to consume electricity in an economically efficient manner. Under the traditional at rate pricing structure this efficiency signal is not passed to the consumer, and they have no incentive to alter their consumption behaviour [35]. Consumption patterns are therefore determined only by the consumers' behaviour, often resulting in the use of low value appliances during periods of high wholesale prices [25]. For example, the use of many common household appliances can simply be delayed with minimal burden on the consumer, but only if the consumer is aware of the need or economic benefit of doing so. Corradi et al. [36] illustrate the capability of residential demands to respond to 5-minute prices; automated control of heating appliances was found to reduce peak residential consumption by 5%, and achieve a shift in consumption of 11% over the period of a day. Another inefficiency of at rate tariffs is the phenomenon of cross-subsidising, where those customers that consume primarily during off-peak periods are subsidising customers who consume during peak periods [20]. Off-peak consumers clearly have a lot to gain from a switch to time variable prices, while on-peak customers will be incentivised to shift their consumption to off-peak periods.

Flat rate tariffs are widely accepted as highly inefficient, and the introduction of time varying prices presents substantial potential for increases to consumer welfare [23, 17, 37]. Consumer welfare refers to the benefit that consumers experience from consumption of electricity, given the cost of purchasing that electricity. Studies have shown that the increase in welfare for larger customers far exceeds the cost of responding to this varying price [25]. However, for smaller consumers the cost benefit analysis is not as attractive, as the expenditure on electricity represents only a small proportion of a typical household budget. A study conducted by Allcott [23] found that moving from a at rate tariff to real time pricing (RTP) resulted in an average increase in welfare for households of only $10 per year, which is approximately 1-2% of the expenditure on electricity and is insufficient to justify the investment in metering infrastructure. This figure has little relevance as a general result as it is highly system dependent, however the fact that this is such a small value clearly indicates that demand response from residential demand may provide an insignificant financial benefit to the household, even if demand response as a whole provides benefits on a societal level. This view is supported by the findings of Borenstein [25] who finds that the overall welfare gains that can be achieved through RTP are significant, although the incremental benefits decrease as the share of total consumption responding to real time prices increases. Furthermore, the cost of increasing this share increases as the customer size decreases. This indicates that focussing on the most responsive consumption types with the greatest potential for net welfare gain is the optimal strategy when rolling out real time pricing. Net welfare gain is used as a metric here as it reflects the ability of a particular load type to shift demand in time and take advantage of time differentiated prices. It also considers the scale of the demand, with a larger shift or adjustment in demand generating a correspondingly larger increase in welfare. Finally, welfare gain reflects the value that this flexible demand provides to the system, where this value is reflected in the price of electricity. By considering the net welfare gain, the cost of both installing the required infrastructure and responding to the resulting price or control signal is included in the evaluation.

While residential loads have been demonstrated as possessing a great potential for demand peak reduction and shifting over many hours [36], the greatest potential for net welfare gain may lie with industrial and commercial loads. Loads such as supermarkets and shopping centres with significant heating and cooling requirements, swimming pools or commercial refrigeration warehouses appear possess the necessary flexibility capabilities and scale to benefit significantly from real time pricing. Ma et al. [38] discuss how certain commercial buildings are capable of achieving temporary reduction in consumption of 25%-33%. Aside from the physical capabilities, the financial incentive to consume flexibly will likely be a determining factor in the success or otherwise of demand response programs. As an example, expenditure on electricity accounts for only 4.4% of the typical household budget in Ireland [39], and only 2.6% in Australia [40], so a 10% decrease in electricity costs would have a negligible impact on the household budget. In comparison, expenditure on electricity in a supermarket typically accounts for only 1% of costs, however this is approximately equal to a typical supermarket operating margin [41], so a 10% decrease in electricity costs would have a significant impact on profits, making flexible consumption an attractive option. Furthermore, the widespread use of automation in industrial processes implies that power consumption can be shifted in time without many of the complexities of end-user interaction that are expected with residential demand response. Detailed modelling is required to determine the exact flexibility achievable from such resources, and the value that such flexibility could provide to the system. Industrial and commercial applications are likely designed with efficiency in mind, and may not have a great scope for adjusting power consumption without breaching their operating constraints. However, if demand response appears to be financially lucrative, this should be included in commissioning assessments and may reveal an interesting option of over-sizing capacities for the express purposes of providing flexibility.

3 Challenges for Demand Response

While it is true that much of the monitoring and communications technologies required for widespread demand response are currently available, the challenges for the control and optimisation of the response are not insignificant. Here we detail the central obstacles for the adoption of demand response as a contributor to system services, and some of the challenges that will remain if it is successfully implemented. These challenges are wide ranging and include establishing an efficient market environment for demand response, building a profitable business case, and effectively controlling demand through price signals, considering that the consumer will not behave in an entirely economically rational manner. The term economically rational is employed here in the sense that consumers will seek to minimise their cost of consuming electricity above all other priorities, and consequently that electrical demand exhibits a linear demand curve, where any change in price of electricity will induce a proportional change in demand.

3.1 Market and Regulatory Framework

One of the greatest barriers for demand response is the lack of appropriate market mechanisms in current market structures [42]. Currently, demand response is primarily employed for the provision of emergency contingency support and ancillary services, with limited participation in the day-ahead market. This participation occurs in the form of direct market bidding as well as contracts between individual market stakeholders. The restrictive nature of these markets and contracts often requires that demand response is planned many hours ahead, or that substantial advance notice is required before the demand is adjusted in emergency scenarios. Such limitations, as well as stringent telemetry and performance standards, prevent demand from participating effectively in the power market [38]. Concerns over the burden placed on consumers limit the frequency and duration of demand adjustment events in many cases. System operators recognise that demand is a valuable resource, but that consumers may withdraw from demand response programmes if the inconvenience of participating becomes too great. The requirement of advance planning of demand response causes uncertainty in the response that can be achieved in real time. Furthermore, the requirement for advanced warning of adjustment events reduces the effective flexibility that demand response can provide, regardless of its physical capabilities. A particular load may be capable of adjusting demand instantaneously, but if regulations require an advance warning of 3 hours, the effective switch-on time of this resource becomes 3 hours, which is simply not competitive with existing flexible generation. Cutter et al. [42] have evaluated that while demand response is capable of providing substantial flexibility to the system, under current market structures the effective flexibility is not comparable to current combustion turbine (CT) generating plants. The central issue is that current markets are designed in a centralised homogeneous manner, which does not suit the diverse and distributed nature of demand.

A further barrier for demand response relates to current regulatory and tariff structures, particularly for residential customers. If customers are to respond to a price signal, a basic requirement is that this price signal is visible to them. Currently, the actual price of electricity in a customer's bill is not obvious, as the final bill includes other charges such as taxes, public service obligation (PSO) payments, and transmission and distribution network charges. Figure 2 shows a breakdown of the electricity prices for residential and industrial consumers in the UK and Denmark. The UK clearly has a more favourable pricing structure for demand response as the energy costs account for over 70% of the electricity cost for both industrial and residential consumers, while the Danish pricing structure filters the cost of energy heavily, with the share barely exceeding 30% for residential consumers.

An overhaul of this structure is required, however careful consideration is required to ensure that any redesigned market ensures the economic stability of the system. For example, while a move to real time pricing would increase social welfare, such tariffs do not adequately reflect capacity costs under the current market structure where generators bid their marginal costs. The use of marginal cost pricing in general is limited in its ability to reflect the overall cost of supplying electricity, considering both capital and operating costs, and to ensure that investment in system resources can be recouped. Introducing demand response into a marginal cost market framework is a complex task, as the marginal cost of demand response is not immediately evident as there is no direct equivalent to the marginal cost components of generators. Further complications are introduced when the capital cost of demand response is considered, and a method of compensation is sought. The question can be posed whether the capital cost should be compensated at all or to what degree, as the primary purpose of demand is not to provide flexibility but to serve the consumer with a particular service. Such complexities warrant a thorough examination of possible market frameworks to ensure that all parties are adequately compensated and the stability of the market is ensured.

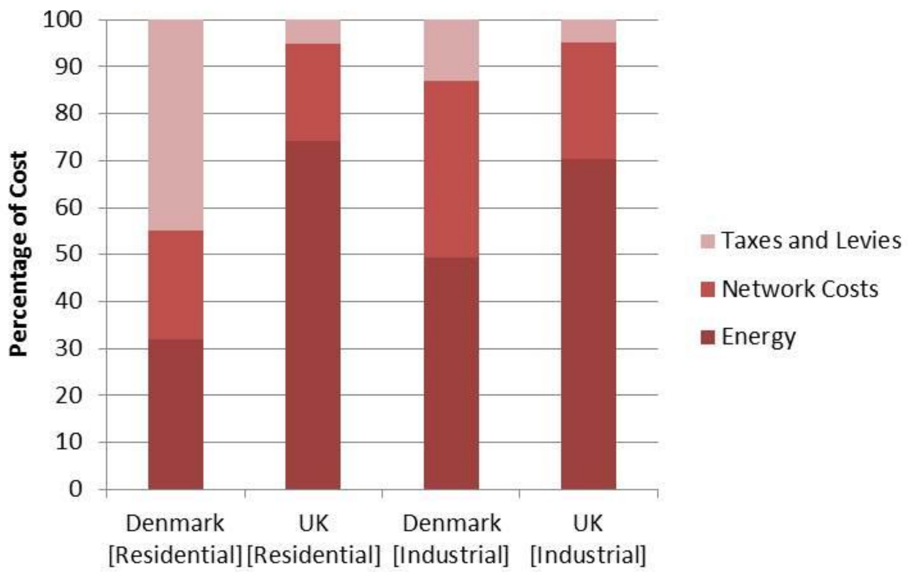


Figure 2: Electricity Price Components

Any regulatory or market redesign must consider that the market must remain stable, providing efficient signals for generation capacity and network upgrades, while maintaining reasonable rates for consumers. Historically, the system operator was responsible for maintaining system security by requesting certain actions from generators and compensating or charging them appropriately. By moving to a framework in which price responsive demand is employed to provide certain system services, the responsibility for maintaining system security is partly shifted from the system operator to the end-user. Without appropriate limitations, end-users may be exploited to provide system services by exposing them to extremely high, or fluctuating, prices. This places an excessive burden on the end-user to provide a services that was previously the responsibility of the system operator. A suggestion to this issue is provided by Zugno et al. [43] where end-user tariffs could be restricted to a given range so that the burden of providing system services is not excessive, and other system stakeholders are still required to contribute to maintaining system security. Jónsson et al. [14] further suggest that customers could pay a premium to restrict the range over which prices vary. This would have the effect that the least flexible customers could remain at a fixed tariff, but would be required to pay a substantial premium. While this option may be attractive for consumers, a certain level of price variation may be required to ensure the viability of dynamic pricing and demand response. Strbac [20] notes that the economics of demand response are heavily dependent on the price differentials in dynamic tariffs. If the price varies over only a small range, the savings for consumers may not be sufficient to induce investment in demand response programs [23]. With smaller price variations, the incentive to shift demand is reduced, and even the most flexible and responsive of consumers may not be able to recoup their costs of installation or justify the burden of responding to prices. Additionally, if the demand response is limited, the system benefits of demand response may not be sufficient to cover the cost of the control and communications infrastructure. On the other hand, if the price differentials are substantial, and consumers have the ability to respond sufficiently rapidly to them, the financial benefit could be significant, particularly in the case where the price of electricity is negative, as has been occurring with increasing frequency on a number of power markets. A striking example occurred on Christmas Day of 2012 where the wholesale price of electricity in Denmark sank to -200DKK/MWh for six consecutive hours, a magnitude far greater than the average price in 2012 of approximately 37DKK/MWh [44].

The impact of demand response on the power market is difficult to predict. Previous discussion in this paper has highlighted how a reduction in price volatility is commonly seen as a key advantage of demand response, as demand will respond to extreme prices, thereby reducing their incidence over time. If extreme price events are caused by a scarcity of certain resources, such as regulating power, and demand response can provide this service at a lower cost, then such extreme price events will certainly be reduced in frequency or magnitude. This is an intuitive result, however, and it overlooks the complexity of the market such that the true outcome may be quite different. There is a clear conflict of priorities here, as the market seeks to find the most efficient solution, which may coincidentally reduce the variability in price, while the consumer sees the most benefit when prices are highly variable. This uncertainty over the impact of demand response on price variability brings into further question the results of studies such as that by Allcott [23] which provide numerical values for the benefit of demand response, particularly as that study considered a limited population of responsive demand acting as a price taker rather than having an impact on the determination of the price. Without more accurate market and demand response models, it is difficult to predict the true impact of demand response on the market, so the financial benefit for consumers could be significantly different from that calculated using existing market models. A similar argument can be applied to electrical storage technologies; demand response and storage share a number of key characteristics, most importantly the possibility of consuming power during low price periods to reduce consumption (or to discharge stored energy) during high price periods. Thus, the need for detailed market studies is not limited to systems with high levels of demand response, but is required on all systems that expect a high penetration of technologies capable of energy arbitrage.

3.2 Establishing a Business Case for Demand Response

Strbac [20] highlights a central issue that is not generally considered, that of the difficulty in establishing a business case for demand response. While it is acknowledged that extending the electricity market to incorporate demand results in a more efficient market with increased social welfare, this welfare is distributed among a number of different parties. It may be quite difficult to develop a business model that can collect a sufficient amount of this increased welfare with sufficient certainty to make the business viable and to justify the required investment in infrastructure [38]. For example, if a wind plant owner operates a demand response resource it will benefit from the balancing services that demand can provide. At the same time, this behaviour may result in more efficient use of transmission or distribution capacity, resulting in a benefit for the otherwise separate transmission system operator. Another example of unintended redistribution of welfare occurs in the case where only a portion of the customer base is subject to time varying prices. In this case, the overall cost of electricity is reduced through the behaviour of flexible customers, resulting in a transfer of wealth from generators to inflexible customers [33]. This occurs as flexible consumers respond to peak prices by reducing consumption, thereby reducing the need for peak generation plants and reducing the average price of electricity. Consequently, generators lose out through reduced operating hours and revenue while consumers on a flat rate tariff see the reduction in the average wholesale price reflected in their bill.

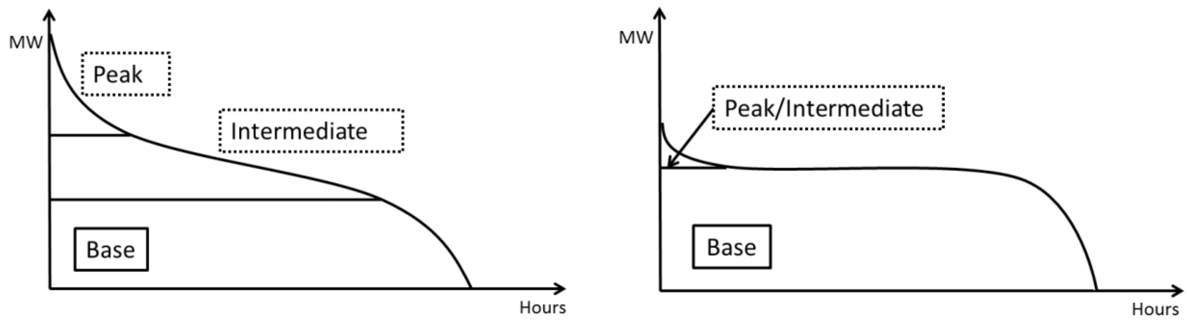
A number of suggestions for business and market models are presented in the literature. A common proposal is the use of an aggregator to represent the flexible behaviour of a large number of demands in existing market models [45, 46, 47, 48]. Under this proposal, the aggregator bids into the market and must then meet its obligations through its demand portfolio. This can be achieved either through direct or price-based control. In the case of price-based control, the price that customers see may vary significantly from the price that cleared on the market, as its intention is simply to induce a demand behaviour that meets the aggregator's obligation. The aggregator will submit a bid to the market, however this doesn't mean that the aggregator's bid price is the market clearing price, so the aggregator must issue a separate price to its demand portfolio. This price has no relation to the marginal costs of electricity, so while the aggregator is capable of meeting its contractual obligation with the market, the end-user is not paying the true marginal cost of providing electricity, as is commonly presented as a benefit of real time pricing.

An alternative approach that is discussed in a number of works is to allow demand to respond directly to the market price in real time. The response of demand in this case can be expressed in the form of a price elasticity value, which relates a change in price and the consequent change in demand. If this price elasticity value can be observed, an aggregate demand curve can be constructed which allows the responsiveness of demand to be considered when clearing the wholesale market [47, 49]. Difficulties with this approach can be experienced when the demand curve is not sufficiently well approximated. Roozbehani et al. [50] discusses the issue of demand and price volatility under real time markets, where this volatility is due to control issues and is separate from the variability in price discussed previously. In particular, asymmetry of information is found to contribute to oscillatory behaviour in demand. Asymmetry of information occurs when there is a delay between price setting and consumption, so a prediction of the response is required, that is, the market operator must predict information which the end-user already knows. In the case that consumers are very flexible they have no incentive to reduce the price volatility as their flexibility allows them to minimise their costs. If, however, customers have a constraint on the rate at which they can alter their consumption, it is in their interest to reduce price volatility. Price volatility could be reduced by consuming power in a more predictable manner or by providing the system operator with information on the intended consumption profile. A similar discussion is presented by Callaway and Hiskens [9] where plug in electric vehicles (PEV) are subject to time varying prices while charging. The demand from vehicles displayed oscillations when the population of vehicles became very large, this oscillation was driven by the interaction between demand and price. This work suggests that real time pricing may not introduce such oscillations where the population of responsive demand is small, as the impact of the demand response on the price is reduced. However, the nature of the PEV fleet as a homogeneous load, where each PEV has similar operational characteristics, may have improved the prediction of price response in this case, resulting in a more stable system. Roozbehani et al. [50] notes that appropriate control laws could be used to regulate the interaction between demand and the market to reduce demand and price volatility caused by information asymmetry, although this would cause a loss in economic efficiency.

This issue raises the question of the value of information on the responsiveness of demand. Indirect control is generally favoured as this price-based control allows for the most economically efficient outcome, however if the uncertainty and instability associated with this control paradigm are excessive it may be necessary to consider direct control. Direct control requires detailed information on the demands subject to control and their surroundings, as well as substantial computational power to process this information. In comparison, indirect control simply estimates the responsiveness of demand from aggregated demand and price data. If the benefit of the certainty of response provided through direct control exceeds the associated computational costs and the loss of economic efficiency due to the elimination of price signals, direct control is an attractive option.

3.3 Difficulties Establishing Demand Response as a Valuable Resource

Widespread adoption of demand response may not be viewed favourably by all participants in the power market. In particular, if the capacity value, or the availability in times of need, of demand response is significant, owners of peaking plants will likely see their capacity factors decrease as demand response takes over some or all of the responsibility for regulation, load following and ramping [45, 42]. Figure 3 shows a possible outcome of widespread demand response adoption; under an extreme scenario, demand response will be sufficient to meet almost all fluctuations in power output from non-dispatchable renewable resources, and the net load will consequently be almost constant, allowing conventional generators to operate at a constant power output. Sub-figure 3(a) shows a typical load duration curve (LDC) on conventional power system, where fluctuations in both (non-flexible) demand and renewable resources mean that the net demand profile is variable, and flexibility is required from generators to maintain the system balance. The LDC orders the demand on a power system in descending order for each hour of a year, where the highest demand levels (furthest left on the LDC) are met by peaking plant, which have a very high marginal cost, while intermediate demand levels are met by intermediate generators. These peaking and intermediate generators are required to be quite flexible as they are typically brought online to meet ramps in demand. Base demand is approximately the minimum level of demand on the system for the year, and is met by inflexible, low cost generators such as nuclear plants, which operate most efficiently at a constant output. Sub-figure 3(b) shows the extreme demand response scenario. The load duration curve shows that inflexible base generation is sufficient for almost all hours of the year, while flexible generation is required to meet any fluctuations that demand response cannot eliminate. Under such a scenario, the operating hours (and consequently the capacity factor) of the flexible (intermediate and peak) plant will be significantly reduced. This will have a significant impact on the potential for generator owners to recover their investment, possibly leading to the decommissioning of otherwise operational plant. Such a scenario would clearly be greatly opposed by operators of flexible generators, even though it may present an efficient solution for the system as a whole. The decommissioning of such generators may additionally cause difficulties for the system operator as conventional generation will still be required to provide such services as inertial and voltage support, which demand response is incapable of providing [45].



(a) Typical Load Duration Curve (b) Possible Load Duration Curve with Demand Response

Figure 3: Comparison of Load Duration Curves

Even if opposition from existing stakeholders is overcome, demand response may not be a valuable addition to the system if the existing power system has a high proportion of flexible plants in its generation portfolio. The most significant factor affecting the value that demand response provides to the system is the flexibility of the existing generation on the system [20, 51]. Systems with large amounts of inflexible base load generation and a high penetration of wind generation show the greatest potential for demand response to provide additional system value. In fact, Strbac [20] shows that it is only in such systems that demand response becomes competitive over traditional flexible generation plants. Their analysis is based on a comparison between demand response and conventional generation for the provision of spinning reserves[1], and the reduction in fuel costs brought about by using demand response over conventional plant. However, the note is made that demand response doesn't provide spinning reserves, but standing reserves, so the true competing resource would be plants capable of a rapid start such as open cycle gas turbines (OCGT). The additional capitalised value of demand response over OCGT is calculated as less than $50/kW which is most likely insufficient to fund the implementation of demand side management, and furthermore unlikely to be considered sufficiently attractive to drive investment in an as yet unproven technology over a tried and tested approach.

3.4 End User Behaviour

Human nature is a further issue which compounds the problem of market design for demand response. While large generators typically exhibit economically rational behaviour through their profit maximising objective, smaller customers do not show the same rationality in their consumption decisions. End-users, particularly in the residential sector, have many different priorities, and minimising their electricity bill may not be at the forefront of their concerns. In contrast, the profit-driven objectives of generators means that their behaviour fits established economic models. Consequently, enough information can be drawn from their bidding behaviour for their supply curve to be revealed [52]. The corresponding demand curve is much more difficult to extract from demand behaviour due to its dependence on many different and time varying external factors, ranging from the weather to whether the consumer cooks dinner using an electric oven or a gas cooker. Empirical studies have demonstrated some of the ways in which consumer demand doesn't fit the conventional economic model.

[1] Spinning reserves are provided by generation units which are already online, or spinning, and have the ability to increase or decrease their production. Standing reserves are provided by generators which are not online and must start up, which typically takes some time. Generally only quick start units are employed for standing reserves.

Thorsnes et al. [24] consider 400 households in Auckland, New Zealand which were subject to TOU rates. Their price elasticity of demand was found to vary with time and according to the external temperature. During winter peaks the demand was less elastic as home heating became critical, even though this is when demand response would be most beneficial to the system. This indicates that although demand may be present, it may not be capable of providing flexibility. Furthermore, the households were divided into two groups with different price differentials between on and off-peak periods, however no significant difference was found between the consumption patterns of the two groups. This indicates that the consumption change is not linearly related to the price change as is conventionally assumed, but that the consumption change to any price change will be similar regardless of the magnitude of that price change. If the conventional linear price-demand relationship were applicable in this case we would expect the housing group subject to a larger price differential to exhibit a correspondingly greater change in demand. This conclusion may only hold in the particular case of TOU tariffs, where the price differential is fixed and known to the consumer. Under real time pricing, this effect may be reduced, however other effects may be experienced, such as consumer fatigue. Requiring consumers to interact with the power market and adapt their consumption pattern to a continually changing price is very intensive, and may lead to the case where only the most extreme prices induce a response from demand.

An additional aspect of demand response behaviour that doesn't fit the conventional economic model was found by Thorsnes et al. [24] when comparing the consumption patterns of TOU consumers to their previous fixed-tariff consumption patterns. Consumers exhibited asymmetric response to prices, with limited reduction in demand during peak periods, but with a significant increase in consumption during off-peak periods. This effect was particularly evident in higher income households. A similar study is discussed by Allcott [23] where households in Chicago were subject to hourly varying prices. Asymmetry of response was also evident here, but interestingly it was in the opposite direction, with a substantial decrease of consumption during peak periods, but no increase during cheaper periods.

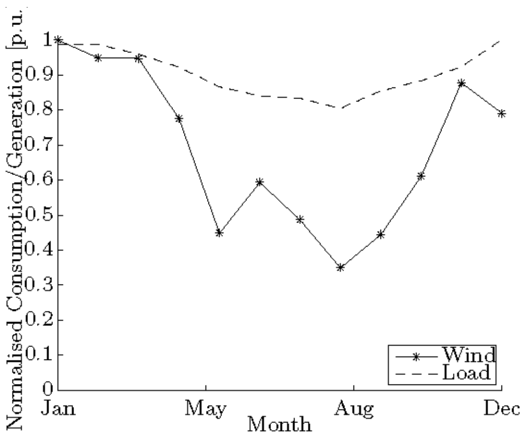
These seemingly irrational features of demand behaviour are said to stem from two central issues. Firstly, there is a lack of understanding of the need for demand response and about electricity consumption in general. Kim and Shcherbakova [53] highlight the fact that the vast majority of consumers have little to no understanding of electricity markets, or even of their own consumption. Studies have shown that simply informing the consumer of their consumption in real time through a display mounted in the home can have a dramatic impact on their consumption. Faruqui et al. [54] show that even with a fixed tariff total consumption can be reduced by between 7% and 14% by installing an in house display of current consumption. Allcott [23] discusses a similar phenomenon where information on the price is provided to the consumer in real time. This study showed that by placing coloured lights on flexible appliances which change colour according to the current price of electricity, the elasticity of consumers can be significantly increased.

Secondly, the manner in which consumers view their purchase of electricity makes them less likely to exhibit rational economic thinking. For most consumers, electricity is viewed as a service rather than a commodity, making it difficult to understand variations in price and the need to consume flexibly. A comparison between buying a new car and paying for electricity is made by Kim and Shcherbakova [53]. Both of these actions account for approximately the same proportion of annual household expenditure (when considering annualised car payments), but significantly more thought is put into the car purchase. This is because payment for electricity is a passive action which occurs at regular intervals, so does not require substantial consideration from the consumer. This lack of interest results in a low response to price changes; Kim and Shcherbakova [53] suggest that moving customers to a pre-payment plan could make purchasing electricity into a discrete purchase. The payment for electricity would then no longer be at regular intervals, and would require more consideration from the consumer. Increasing consumer awareness in this manner can increase their flexibility to price signals.

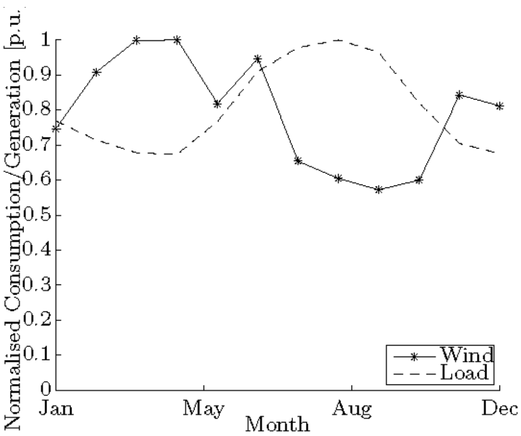
It is evident that requiring consumers to respond directly to prices is suboptimal and results in behaviour that cannot be explained by conventional economic models. This is a clear argument for the use of extensive automation for demand response, both to reduce the burden of price response on consumers and to ensure a more predictable and efficient response from demand. Consumer interaction could be simply limited to the selection of temperature limits and the on/off state of the appliance, while allowing a controller to determine the optimal consumption profile in response to the price signals. Nevertheless, there will still be a degree of human interaction that should not be overlooked and should be incorporated into demand models for price setting. This is because the impact of human interaction with demand is not limited to economic decisions, but also influences the physical availability of the flexible demand resource. Even if appliances are controlled automatically with limited input from the consumer, if an appliance is not switched on, it cannot be used for providing flexibility. Similarly, if the appliance must operate at its maximum output level just to meet the end-use demand, it cannot provide flexibility. An example of this was provided previously from the work of Thorsnes et al. [24] where heaters cannot provide flexibility when the demand for heat is critical. As such, the consumer's need for a particular appliance dictates the demand flexibility available to the system.

Kirby [18] considers the diurnal profile of consumption and explains that on a diurnal scale, demand is well suited to providing flexibility as demand is typically highest when spinning reserves are scarce. This conclusion was reached following an analysis of the diurnal profile of air conditioning loads in the United States and the corresponding profile of prices for contingency reserves. The peaks in reserve price and demand were well correlated, indicating that demand is available when reserves are most expensive, or equivalently most scarce, however it doesn't consider whether demand is capable of providing flexibility at these times.

This argument raises the question of the capacity value of demand response. The capacity value of demand response as employed here refers to the availability of demand for the provision of flexibility, and its correlation with the need for system services. If demand is frequently available to provide flexibility, but not at those times when critical balancing services are required, then it provides limited value to the system, that is, it cannot replace many MW of capacity from an ideal generator which has 100% availability. The presence of demand can be considered as a necessary (but not sufficient) condition for the availability of demand flexibility (as employed by Kirby [18]). If we consider the example of demand response balancing fluctuations in wind power output, the most ideal scenario would be a high correlation between wind and demand. Figure 4 shows the average normalised seasonal profiles of demand and wind generation on the Irish and ERCOT power systems. The Irish system shows a reasonable correlation between wind and demand, giving a high level indication that demand response could be a valuable resource in terms of balancing wind fluctuations. In comparison, the ERCOT system shows a distinct lack of correlation, where a high wind output in the winter months coincides with lower electricity consumption. This indicates a reduced availability of demand to manage wind fluctuations when wind output is greatest, which may suggest that another resource such as flexible generation or storage may be better suited to provide this service. The simple illustration in Figure 4 shows that the value of demand response is highly system specific; depending on consumption behaviour, prevailing wind and weather conditions, and the availability of, or need for, support services. However, it is important to consider this capacity value on a number of different time scales. Averaged seasonal profiles provide easily digestible results, however they don't reflect the operational challenges faced on an hour-to-hour and minute-to-minute basis. A favourable seasonal correlation may give a false indication of the value of demand response if the demand is either unavailable, or incapable of providing flexibility when it is required.



(a) Irish Power System



(b) ERCOT Power System

Figure 4: Correlation between Wind and Demand on the Irish and ERCOT Power Systems [55], [56].

This discussion highlights two key points; firstly, that the capacity value of demand response should be considered on many different time scales, and secondly, that this capacity value should be incorporated into resource capacity planning. The long-term benefits of demand response primarily concern a more efficient use of system resources. Previous discussion in this paper has shown that this is mostly considered in terms of a reduction in generation capacity requirements. It is imperative that the capacity value of demand response is considered when evaluating the impact on generation capacity requirements, as the intuitive concept that demand response will reduce the operating hours, or capacity factor, of the most expensive generators may not apply in all cases, particularly when the seasonal variations in availability of demand flexibility are considered. Furthermore, the long-term impacts of demand response are not limited to generation capacity requirements, but will influence the composition of the entire system resource portfolio, including generation, storage, interconnection and transmission, while also encompassing adjacent systems such as natural gas distribution, district heating and water treatment and distribution. An integrated approach to portfolio planning is required to ensure the development of the most efficient portfolio of resources, considering the interaction and complementarity between different components, in particular considering a range of different time scales.

4 Demand Response Modelling Assumptions

The works in this field have outlined the many benefits that can be brought about by increasing the responsiveness of electrical demand. Unfortunately, a lack of experience with demand response has necessitated the employment of numerous assumptions in the modelling approaches adopted. As a consequence, it can be argued that the estimations of the benefit of demand response are dependent on these assumptions and an accurate evaluation has yet to be achieved [34]. The widespread implementation of demand response requires significant investment, and at such a critical stage in the development of policy and technological strategies for demand response, it is essential that all of the involved parties are correctly and fully informed. Here we detail some of the most significant assumptions used, and highlight their shortcomings.

4.1 Economically Rational Demand Behaviour

One of the most common assumptions is that all demand behaves in a completely economically rational manner and can be described by a linear demand function, most commonly based upon an elasticity value. The value selected for the elasticity of demand is often selected at random, with limited consideration for the physical characteristics and constraints of demand [17, 16, 49]. While this is a tempting approach as the concept of an aggregate demand bid curve fits well with the current wholesale market model, the representation of demand in this manner is unrealistic. Firstly, previous discussion in this paper has highlighted that the responsiveness of demand is dependent on a number of external variables such as temperature, that it may be non-linear [24], and asymmetric, where the magnitude of the response to a high price may be different to the response to a low price [23]. Secondly, modelling demand response based on a single elasticity value assumes that demand can only increase or decrease its consumption instantaneously, and cannot shift in time. In order to represent this behaviour, an elasticity matrix would be more appropriate as it incorporates both self- and cross-elasticity, where cross elasticity considers the shift of demand to another time period due to a change in price at the current period. An elasticity matrix therefore considers that energy which is not consumed now, through a reduction in demand, must be recovered later; a simple elasticity value doesn't consider this at all. The need for consideration of cross elasticity has been acknowledged in a number of works; however it is employed in very few cases. Sioshansi [49] argues that consideration of cross elasticity can only serve to support the case for demand response. The example is given where wind generation in a given period is lower than was expected and the price is consequently higher. In this case the demand would respond to a greater extent if cross elasticity is considered, as it responds to the higher price in the current period (self-elasticity) and the relatively cheaper price in adjacent time periods (cross-elasticity) where the wind output was as forecast. A contradictory position is adopted by De Jonghe et al. [17], as their numerical calculations conclude that consideration of the cross- elasticity value reduces the demand response attainable. The authors considered the case where several consecutive hours have similarly high prices; in this case the demand reduced in one period is shifted to another period, or over multiple periods, and this occurs for each of the periods during which the price is high. This results in the combined effect that some demand from a given period is reduced, but demand from many other periods may be shifted to this period. Thus, the total demand response attainable when both self- and cross-elasticity are considered is reduced from the case where only self-elastic behaviour is exhibited. These two contradictory viewpoints clearly demonstrate the lack of understanding pertaining to this area. Figure 5 is a very simple example of the impact of considering self- and cross- elasticity of demand. In this case, the basic demand level is constant, and the objective is to induce as much flexibility as possible through a varying price signal.

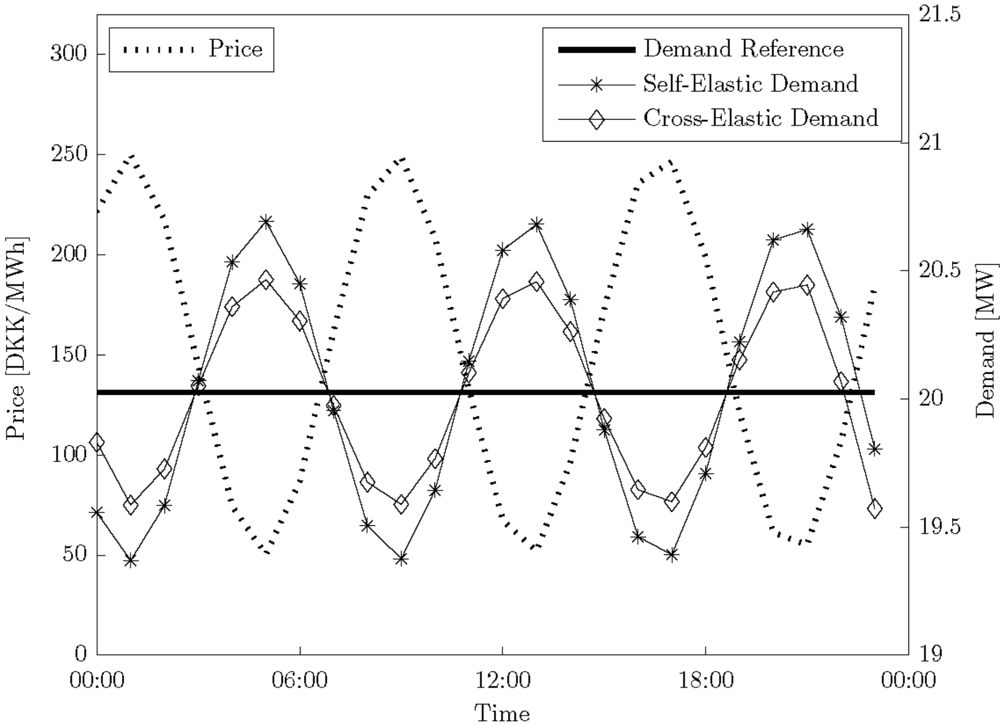


Figure 5: Comparison of the Effects of Self- and Cross- Elasticity on the Achievable Demand Response

The benefit function of demand is derived as by De Jonghe et al. [17], using two separate elasticity matrices; one with only self-elasticity and the other with the same self-elasticity but also incorporating cross-elasticity. The resulting demand levels are found by maximising the benefit of demand with respect to the price signal shown in the figure. It is clear here that the flexibility achieved in the self-elastic case exceeds that in the case where both self- and cross-elasticity are considered, however this simple example only stands as an illustration of the impact of considering different forms of elasticity, as demand response is very poorly represented in the form of an elasticity matrix and more detailed modelling is required to achieve a realistic representation of its capabilities.

A further phenomenon that is not represented through an elasticity value is that of response saturation, that is, the energy limited nature of demand. Taking the example of a household space heating appliance, consider that the power system conditions dictate that a decrease in consumption is required over a prolonged period, and the necessary price signal is issued. The appliance will comply initially by reducing its consumption, but its local constraints dictate that the temperature cannot fall below a given threshold so the response can only be maintained until the minimum temperature is reached, at which point the local control will require that the appliance commence power consumption again. This phenomenon is acknowledged in certain works, but is not considered in any of the modelling approaches adopted. Saturation is a clear illustration that even when demand response is controlled automatically and operates in a least cost manner, the resulting demand behaviour may not fit the conventional economically rational model. The phenomenon of saturation is discussed by Roozbehani et al. [50] who described price responsive demand as having a dependence on both price and the current state of the demand, that is, the amount of demand that was scheduled for consumption previously but has been delayed until now due to price conditions. This behaviour mimics that of a storage facility, where balancing support can only be provided until its storage capacity is reached, or the stored volume has been expended.

4.2 Demand Response as Negative Generation

Another commonly adopted modelling approach is to incorporate demand response into a unit commitment model[2]. This is predominantly employed in studies considering the impact of demand response on the system capacity requirements and the need for generation reserves [45, 47, 57]. In such studies, demand response is modelled as a few large units, with the assumption that individual loads are grouped together through an aggregator which participates in the market on their behalf. There is no consideration given to how this aggregator will achieve the required demand response, with generic constraints imposed on demand within the unit commitment formulation. Demand is modelled similarly to negative generation in these cases, with minimum and maximum consumption constraints as well as ramp rate limitations. A slightly more detailed approach is considered in [45] where demand is categorised into load clipping and load shifting units, which reflect the general categories of demand response commonly considered; demand shedding and deferral of demand. Consideration of demand deferral is also given in [58] which examines the capacity value of demand response from air conditioning units; in this work demand response is considered for peak load events and load is clipped for a given period and then repaid over five hours following the clipping event.

While these approaches are useful to find high level conclusions about the contribution of demand response, a lack of investigation at a more detailed level means that many of these models may be awed and the conclusions reached may be misleading. A key oversight in such studies is the lack of consideration for uncertainty in demand response. As unit commitment is a day-ahead optimisation, the uncertainty of the demand response that can be attained in real time is significant. This uncertainty would undoubtedly impact on the amount of reserve generation that is required to ensure the stability of the system. Furthermore, the diverse nature of demand makes it ill-suited to be represented as a single generation unit with fixed constraints. The aggregated demand is composed of many different load types with many diverse operating characteristics and constraints; it therefore likely that both the magnitude of the resource and its ability to respond to a price or control signal vary in time. This could equivalently be viewed as time varying capacity and ramping ability respectively. Incorporating these effects into the unit commitment model would have significant impact on the optimal generation schedule and may substantially alter the conclusions regarding both the total required generation capacity and the amount of flexible spinning reserves required. Extending this analysis to an annual scale, the seasonal availability of demand response will have a considerable impact on longer term generation capacity planning.

4.3 Perfect Knowledge of the System and Demand

A third modelling method applied in a number of works assumes perfect knowledge of the system. Zugno et al. [48] and Zhang et al. [59] employ this approach for market design and aggregate demand model building respectively, where a thermal model of the load and its temperature constraints are directly included in the system model. Model predictive control is also commonly used in studies considering building climate control for demand response [60, 61, 62], and again in these studies the thermal parameters and constraints of the system are taken as known. Such studies provide great insight into the capabilities of the system for the specific scenarios considered, but the behaviour of the larger system may not be well represented by these isolated cases, particularly as the characteristics of individual households and appliances would not be known by the system operator. Furthermore, the population of responsive demands can be expected to be

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[2] Unit Commitment is a combinatorial optimisation problem that is employed in power systems on the day before operation to determine which generation or demand resources should be online, or committed. It allocates sufficient generation to meet predicted demand, as well as providing reserve generation to insure against contingencies and uncertainty in renewable generation.

highly diverse, with many different appliance types operating subject to different constraints and environments. The aggregate demand response is therefore not well represented by these in depth studies that consider a single appliance type operating in a given environment. Even if all the necessary characteristics of the system and appliances are known, such that the demand behaviour resembles that of these studies, the calculation time and power required to process this information in real time would be prohibitive. In the case that prices are issued every 5 minutes, it may not be possible to determine the optimal control or price strategy before the deadline for price issuance has passed.

These studies consider specific cases, however, on a real system the load response is likely to be highly heterogeneous, as already experienced with commercial loads [19]. Therefore, consideration of this heterogeneity is essential when modelling demand response in order to attain results that are applicable in a wider setting. Halvorsen and Larsen [63] explain that it is not possible to infer conclusions about demand behaviour from aggregated data when the load base is heterogeneous, and while their study considers long term policy decisions, the same conclusion can be applied to short term demand response. Zhang et al. [59] have conducted some initial work on managing heterogeneity of load, and have employed clusters to use a single representation of price response for a group of demands with similar characteristics. Their findings showed that heterogeneity introduces a natural damping of demand oscillations into the system and results in a more stable response, however the study was limited to thermal appliances with similar control architectures, so this conclusion may not hold in a wider setting. The concept of employing clusters to characterise demand response is an interesting one however, and was also proposed by Zugno et al. [48].

5 Conclusions

The discussion in this paper has shown that while demand response has the potential to bring about a great number of benefits, there are a number of challenges that must be overcome before it can be considered as a valuable contribution to the power system. The overriding issue is the lack of experience and understanding of the nature of demand response. Too much of the work in this field is based upon simplistic models with superficial results. At this crucial stage in the development of demand response it is imperative that a clear and concrete understanding of demand response is established, so that a realistic evaluation of its suitability for the provision of system services can be determined.

Demand is clearly a highly diverse and complex resource, varying according to a multitude of external factors. Despite the limited understanding of the nature of demand response, particularly at the system level where the response of demand from many different sectors and applications is aggregated, it is clear that the resource is highly diverse, so using a single model type to represent all demand is unrealistic. Similarly, it is evident that demand does not fit the conventional model of economic rationality. The interaction of end-users with demand and the constraints of appliances themselves mean that the resulting demand profile exhibits a non-linear, time varying, dynamic and stochastic relationship with price, even in the best-case scenario where the price response is determined through automated control rather than a response from the end-user. It is therefore necessary that novel modelling approaches are adopted. In particular, it is necessary to extend the models to incorporate demand of many different types, and to consider the aggregate behaviour at the system level, and how it interacts with other system resources.

A further aspect of demand response that warrants attention is the uncertainty of the response. Demand is affected by a number of stochastic variables, including the weather and the sheer randomness of end-user behaviour, and consequently the response of demand to price or other control signals is uncertain. If the intention is to use demand response for the provision of system services, it is imperative to determine the reliability at which the service can be provided. If the reliability of demand response cannot be guaranteed to be sufficiently high for a particular system service, it will simply be disregarded in favour of more reliable resources. The primary concern of the system operator is to maintain system security, and if demand response cannot contribute to this, it should be limited to those activities that do not impact on the stability of the system, such as the conventional night-valley filling behaviour that is commonly incentivised today through TOU rates. Furthermore, if it is determined that the required reliability can be achieved through direct control, where price plays no role in determining the demand response, a thorough system wide economic analysis is required to determine if this option presents an improvement over the current set-up, particularly as many of the economic efficiency benefits brought about by price based demand response are not present in the case of direct control.

Demand response, where it is currently employed, participates to a limited extent in the power market. Current market structures are poorly suited to demand response, and consequently its most beneficial aspects cannot be accessed. Novel market structures should be investigated, and this should be conducted in conjunction with the development of detailed demand response models. The financial benefit of demand response will be accessed through these market structures, and a poorly structured market could prevent demand response from achieving economic viability. Appropriate market structures that consider not only demand response, but all other system resources, will ensure system wide economic efficiency, and may further strengthen the economic case for demand response. A number of fundamental questions remain with regards to the interaction of demand response and the power market. The most prominent of these is perhaps how exactly demand response should be priced, considering both the capacity and operational costs of providing a response. Again, demand simply doesn't fit into the conventional models for calculating marginal cost as there is no direct equivalent to generator fuel cost in this case. Furthermore, the cost structure of demand response in terms of capital and operating costs is unclear as the primary purpose of a responsive appliance is not to provide demand response but an end-user service.

When evaluating demand response, it is imperative that it is considered in the context of the entire energy system. Demand response alone may offer certain benefits, however when the interaction with other system components is considered demand response may become a very attractive option. Integrated resource planning should be employed to consider how the relative benefits of demand response, inter-connection, storage, conventional and renewable generation can be optimally combined to result in the most efficient use of the system as a whole. Broadening the scope of consideration to encompass previously distinct systems such as natural gas distribution, district heating and biomass may facilitate a truly optimal global solution, revealing opportunities that would not be seen with a narrower focus on the traditional power system. In an operational context this would ensure that the most effective resources are used to maintain total system security on a day-to-day basis, while in a planning context this would ensure that the optimal capacities of each resource are installed on the system. Planning should be considered on a portfolio basis, rather than examining resources in isolation, and on a range of different time scales. As more focus is placed upon renewable resources and demand response, the climate will play a greater role in determining the availability of system resources on a seasonal scale. This will have a great impact on portfolio planning, as complementary resources will be important to ensure that system balance can be maintained at all times without requiring excessive redundancy of resources. Capacity planning is an important area here, and applies not only to generation and transmission resources, but also to demand. In fact, the capacity of demand response can have a significant impact on the economic benefits of participating in demand response programmes. Demand response is provided by appliances and devices that have an alternative primary use, that of providing the end-user with a service. Such appliances are typically sized according to the maximum end-use demand; however when we consider their use for demand response this may limit the flexibility achievable. Depending on the appliance type, the inability to provide flexibility may correlate with periods of power system stress, particularly if they are affected by weather conditions, such as heating or cooling loads. There may be an economic or operational case in certain circumstances to over-size certain flexible demands so that they can provide a highly valued flexibility service at those times where other demand types are incapable of responding. Clearly, an integrated energy system approach is required to evaluate the merits of such an action.

By considering demand response in isolation, using simplistic models, and in the context of existing market frameworks, a full and accurate impression of the benefits of demand response cannot be established. Novel, integrated approaches are required to reveal its full potential.

Acknowledgments

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