Title	The impacts of demand response participation in capacity markets
Authors(s)	Lynch, Muireann Á., Nolan, Sheila, Devine, Mel T., O'Malley, Mark
Publication date	2019-09-15
Publication information	Lynch, Muireann Á., Sheila Nolan, Mel T. Devine, and Mark O’Malley. “The Impacts of Demand Response Participation in Capacity Markets.” Elsevier BV, September 15, 2019. https://doi.org/10.1016/j.apenergy.2019.05.063.
Publisher	Elsevier BV
Item record/more information	http://hdl.handle.net/10197/10978
Publisher's statement	This is the author’s version of a work that was accepted for publication in Applied Energy. Changes resulting from the publishing process, such as peer review, editing, corrections, structural formatting, and other quality control mechanisms may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in Applied Energy (250, (2019)) https://doi.org/10.1016/j.apenergy.2019.05.063
Publisher's version (DOI)	10.1016/j.apenergy.2019.05.063

The Impacts of Demand Response Participation in Capacity Markets

Muireann Á. Lynch^{a,b,*}, Shelia Nolan^{c}, Mel T. Devine^{a,b,c}, Mark O'Malley^{c,d}

[a] *Economic and Social Research Institute, Dublin, Ireland*
[b] *Department of Economics, Trinity College Dublin, Ireland*
[c] *School of Electrical and Electronic Engineering, University College Dublin, Ireland*
[d] *National Renewable Energy Laboratory, Golden, Colorado, USA.*

Abstract

Demand Response is capable of reducing the total amount of generation capacity investment required to ensure electricity system security. We utilise this fact to devise a novel methodology to estimate the contribution of a load-shifting demand response resource to system adequacy. We then simulate an electricity market using mixed complementarity models to determine how the participation of demand response in capacity markets impacts on market outcomes. Demand response primarily affects the equilibrium outcome through the energy market, however demand response also reduces both equilibrium prices and consumer costs through its capacity market contribution. The effect is particularly pronounced when there is a high level of variable renewable generation and initial undercapacity. In the absence of demand response, increased wind generation leads to higher capacity prices as generators seek to offset depressed energy prices. However, we find that demand response's participation in the capacity market can combat these increased capacity prices. These results suggest that demand response participation in capacity markets can mitigate some of the market challenges of renewable integration, particularly that of the "missing money problem.

Keywords: Demand Response, Load-Shifting, Markets, Reserve, Capacity

---

1. Introduction

Demand Response (DR) is the term used to describe adjustment of electricity usage in response to system or market conditions. DR is often proposed as a means of reducing peak electricity demand, which reduces both spot prices in the short run and the requirement for investment in generation capacity in the long run. This leads to both operational and capital cost savings. DR is also often cited as a potential means of mitigating the challenges of integrating variable renewable generation, by reducing demand at times of low renewable supply and increasing demand when there is a surplus of renewable energy available. Nolan and OMalley (2015) provides a summary of the literature on DR in electricity markets. More recent publications on the topic of DR include designing commercial opportunities for DR (Eissa, 2019), capturing the DR capability of water delivery systems (Mkireb et al., 2019) and employing techniques from behavioural economics to capture DR (Good, 2019). Like the previous work reviewed by Nolan and OMalley (2015),

---

[*] Corresponding author

Email address: `muireann.lynch@esri.ie` (Muireann Á. Lynch^{a,})

these papers focus on the operational aspects of DR. However, given that DR can displace generation by thermal units as well as investment in thermal units themselves while maintaining system reliability, DR can therefore potentially participate in both energy and capacity markets (Cutter et al., 2012). There is a paucity of literature on this capacity value of DR, which is the focus of this research.

Capacity markets compensate generators for making generation capacity available for utilisation, regardless of the extent to which it is operated. This provides a revenue stream to generators in order to incentivise sufficient investment in generation capacity, thereby ensuring system security. Capacity markets are justified on the basis of the 'missing money' principle, the absence of an active demand side and the public good characteristics of electricity provision. For a full summary of the rationale behind capacity markets, see Lynch and Devine (2017) and Botterud and Doorman (2008).

Several publications have explored the potential for DR to displace generation capacity investments while maintaining a given level of adequacy. Zhou et al. (2015) use a Monte Carlo simulation to determine the impact that DR and electric energy storage have on various reliability indices, including expected energy not served, loss of load expectation, loss of load factor and individual capacity shortfall extent. Zhou et al. (2016) extends this work to specifically consider the capacity credit of DR and storage, given their ability to impact on the reliability metrics considered in **?**. Khan et al. (2018) uses agent-based modelling to consider market outcomes for a stylised energy and capacity market given price-responsive demand. DR and a capacity market are considered as competing methods of ensuring system adequacy, rather than considering the potential for DR to participate in the capacity market. Given the potential for DR to replace generation capacity, it follows that DR has an inherent capacity value. However the quantification of this value is a non-trivial exercise, not least because there is no reliable counter-factual - there is no way of knowing what the equilibrium levels of electricity demand would have been in the absence of DR. In addition, as highlighted in Radtke et al. (2010), there are a variety of possible definitions and calculation methods for capacity value metrics.

In this paper, we focus on the capability of DR to displace generation capacity investment, often referred to as the contribution to system adequacy of the resource. System adequacy is defined as the existence of sufficient generating capacity on the power system to maintain a supply-demand balance. It is usually expressed by capacity value metrics (Keane et al., 2011). In Zhou et al. (2016) a metric called the Equivalent Generation Capacity Substituted is proposed. This metric indicates the amount of conventional generation capacity that can be displaced by DR without impacting upon the original level of system adequacy. In Nolan et al. (2014), the Effective Load Carrying Capability (ELCC) is the metric used, which is the amount by which a system's load can increase when the generator is added to the system, while maintaining the system's adequacy (Kavanagh et al., 2013). By calculating the capacity value of a particular DR resource in this manner, we determine DR's contribution to system adequacy as a function of the particular characteristics of the resource itself.

Some recent advances have been made in the literature in quantifying the capacity contribution of DR, which tend to be on a case-by-case basis. Nolan et al. (2014) uses historical demand data from the USA to estimate the availability of DR for each hour of the year, and treats this as negative generation in order to calculate the LOLP in the presence of DR. Zhou et al. (2015) performs a similar exercise using agent-based and Monte Carlo modelling using data from the Netherlands. Nolan et al. (2017) use data from Ireland, which includes flexible demand derived from a building energy model, to determine the ability of DR to increase system reliability. Once the capacity contribution of DR has been determined correctly, the impact of DR's participation in capacity markets according to its adequacy contribution is of interest to policy-makers, market operators and industry participants. Nolan and OMalley (2015) highlights the importance of correct evaluation of DR's contribution to energy markets, as undervaluing DR could leave a beneficial resource underexploited, while overvaluing could lead to a situation where there is considerable investment in a resource that cannot be effectively realized. This paper aims to inform this discussion, by providing a methodology to calculate the adequacy contribution of DR. This methodology is then used to examine the impact of DR participation in capacity markets.

This paper utilises Mixed Complementarity Problems (MCPs) in order to determine the optimal decisions of profit-maximising firms simultaneously and in equilibrium. MCPs have been widely deployed in the literature for electricity market analysis. For a full summary, see Devine et al. (2019).

This paper considers an electricity system with energy and reserve markets and a quantity-based capacity market. Generation firms compete in the three markets in an effort to maximize their profits. The decision variables of each firm are the level of generation, reserve provision, capacity bid, investment and exit, subject to physical constraints, operating, maintenance and investment costs and the market clearing prices. A DR aggregator is also considered, whose objective is profit-maximisation and whose decision variable is the operation of a load-shifting DR resource. The DR aggregator's participation in energy and reserve markets implicitly contributes to system adequacy, and so the aggregator also participates in the capacity market on that basis. The aggregator is constrained by the obligation to satisfy consumers' usage requirements. The type of DR resource considered is a load-shifting DR resource.

There are several original contributions of this paper. On the methodological side, we introduce a method of determining the inherent capacity value of a load-shifting DR resource which represents a significant advance on the state of the art. In particular, we draw on the Equivalent Generation Capacity Substituted metric proposed in Zhou et al. (2016) when calculating the capacity contribution of load-shifting DR. In the models presented here, firms make investment and exit decisions based on their profitability which, for the large part, are driven by peak demand. Firms decide to invest in generation if there is a deficit during peak periods and there is scope for them to recoup their investment costs. On the other hand, firms will opt to exit the market if there is excess generating capacity, displacing their operation at the peak and impacting upon their profits. Thus a change in investment seen with the addition of a DR resource in an MCP model is representative of the contribution of the DR resource to system adequacy. Consequently, the change in generator investment due to the addition of the DR resource is the best possible estimate of the capacity value of the DR resource.

Following on from this methodological contribution, we also contribute to the literature by using the models developed to examine DR's impact in the capacity market. The contribution of DR to the capacity market is based on the rigourous methodology proposed and developed here. At present, DR participates in most capacity markets in a somewhat *ad hoc* manner (if at all), where the capacity contribution of DR is based on the peak demand of the DR resource itself, rather than any comprehensive estimate of the contribution DR makes to system adequacy. For this reason, the participation of DR in capacity markets currently, and the revenue earned in so doing, are not reflective of the underlying capacity value of the resource itself. In practice, current capacity market designs may overstate and overcompensate DR resources relative to the its true contribution to system adequacy (see for example SEMC (2018)). The methodology and results presented here are therefore not only novel but are also particularly pertinent for system and market operators, and indeed policy-makers, worldwide. This work also considers the participation of DR in energy and reserve markets in addition to the capacity market, which to the best of our knowledge has not been considered in the literature to date. The use of MCPs to examine the impact of DR participation in various electricity markets is also novel, with Devine et al. (2019) (which did not consider capacity market participation) providing the only other example of same.

The results of this work highlight the interaction and interdependencies between the energy, reserve and capacity markets. By examining DR participation in every possible combination of these markets, our work isolates the impact of DR on the equilibrium solution of each market, and the interactions and interdependencies of same. The current manner of including DR in capacity markets likely overstates the resource's contribution to system adequacy, by basing the capacity contribution on the capacity of the resource, rather than on the contribution the resource makes to the system's abiltiy to maintain a supply-demand balance, leading to inefficient market equilibria and less secure systems. Furthermore, we examine the sensitivity of these results to the specific characteristics of each individual system and market, by considering the impacts of increasing renewable generation, varying peak load levels and varying reserve targets on the economic equilibrium. These insights are very important for policy makers and industry players as they adapt and apply our results to their particular market.

Our results show that the consideration of DR in the context of capacity markets facilitates new applications of DR and therefore expands the potential for deployment and operation of DR. This in turn allows for enhanced operation of other electricity system resources, in particular wind generation, and so reduces final costs and emissions. Determining the optimal operation of the electricity system, while maintaining system adequacy and meeting consumer demand for reliable electricity, is therefore at the heart of this paper.

It should be noted that capacity value metrics typically include a reliability component. This is because generation availability, for both conventional and renewable generation, exhibit a degree of uncertainty, e.g., through unplanned outages. Consequently, system security can only be ensured to a given level of probability. Capturing this unreliability involves stochastic modelling, which is beyond the scope of this paper but may be included in future work.

This paper is structured as follows: Section 2 introduces the methodology employed and details the DR aggregator's and generators' problems. Input data, case study information and a description of the different market models employed is discussed in Section 2.5. Section 3 presents the results of the various case studies and sensitivities. Section 4 discusses the overarching findings and Section 5 concludes.

2. Methodology

In this section, we detail the methodology. We utilise MCPs to model different electricity markets which differ depending on DR participation. Each MCP consists of I generating firms and a DR aggregator. Each of these players has its own optimisation problem which we describe below. We also detail the Market Clearing Conditions (MCCs) which connect the optimisation problems of each player. The different MCPs are made up of these MCC along with the Karush-Kuhn-Tucker (KKT) optimality conditions for each player.

Throughout this section, parameters are denoted with capitals and primal variables are denoted with lower case lettering. Variables in parentheses, alongside constraints, are the Lagrange multipliers associated with the constraints and are denoted with lower-case Greek letters.

2.1. Generating Firm's Problem

Each firm may have multiple types of generation technologies. Its problem involves choosing the amount of generation ($gen^{t,i,j}$), reserve provision ($reserve_{gen}^{t,i,j}$) and capacity bid ($cap_{bid}^{i,j}$), as well as investment in new capacity ($invest^{i,j}$) and decommissioning of existing capacity ($exit^{i,j}$), for all of its generating units in order to maximize their profits, Π^i. These profits consist of profit from the energy, reserve and capacity markets, Π^i_{energy}, $\Pi^i_{reserve}$ and $\Pi^i_{capacity}$, respectively, where i is an index representing each different firm, j represents the generating technology and t represents hourly timesteps. Firm i's problem is:

$$\max_{\substack{gen\\exit\\invest\\cap}} \quad \Pi^i = \sum_j \Pi^{i,j}_{energy} + \sum_j \Pi^{i,j}_{reserve} + \sum_j \Pi^{i,j}_{capacity}, \tag{1a}$$

where

$$\Pi^{i,j}_{energy} = \sum_t (gen^{t,i,j}) \times (\lambda^t - MC^{i,j}), \tag{1b}$$

$$\Pi^{i,j}_{reserve} = \sum_t (reserve^{t,i,j}_{gen}) \times \mu^t, \tag{1c}$$

$$\Pi^{i,j}_{capacity} = (cap^{i,j}_{bid}) \times (\kappa) - (invest^{i,j}) \times ICOST^j - (CAP^{i,j} - exit^{i,j}) \times MCOST^j, \tag{1d}$$

subject to:

$$gen^{t,i,j} + reserve^{t,i,j}_{gen} \leq CAP^{i,j} - exit^{i,j} + invest^{i,j}, \quad (\theta_1^{t,j}), \quad \forall t, j, \tag{1e}$$

$$cap_{bid}^{i,j} \leq CAP^{i,j} - exit^{i,j} + invest^{i,j}, \quad (\theta_2^{i,j}), \quad \forall t, j, \tag{1f}$$

The variables λ_t, μ_t and κ represent the prices associated with the energy, reserve and capacity markets receptively. Each are exogenous to the firms' problems but are variables of the overall model determined via the market clearing conditions (equations (3)). All of the generating firm's primal variables are constrained to be non-negative.

The parameter $MC^{i,j}$ denotes the marginal cost of generating firm i technology j, $ICOST^j$ represents the investment cost of generating technology j, while $MCOST^j$ is the maintenance cost associated with technology j. The parameter $CAP^{i,j}$ represents the initial endowment of generating capacity for each firm i and for each technology j.

Equation (1a) is the objective function of the generating firm. Each firm chooses how to participate in each market in order to maximise their profit. Equation (1b) represents the energy component profit of the generator and consists of the revenue obtained from the energy market less the marginal cost $MC^{i,j}$ of producing energy. Equation (1c) denotes the reserve component of the generator's profit. As can be seen, there is no cost component associated with providing reserve as it is assumed that the cost of providing reserve is the opportunity cost of not providing energy. Equation (1d) represents the revenue from the capacity market less investment costs and maintenance costs associated with providing capacity. Maintenance costs for new builds are incorporated in $ICOST^j$. Equation (1e) constrains the power and reserve provided by a generating unit to be less than or equal to the installed capacity of the unit, taking any exit and investment decisions into account. Equation (1f) ensures the capacity bid of each generator does not exceed the installed capacity.

2.2. Demand Response Aggregator Problem

In this subsection we describe the DR aggregator's problem and how it is used to calculate the capacity value of DR. The DR aggregator's problem is to choose DR in both the downward and upward direction, dr_{down}^t and dr_{up}^t, respectively, and reserve provision $reserve_{dr}^t$ so as to maximise profits from the energy and reserve markets. The total load-shifting performed by the DR resource is the net result of a combination of dr_{down}^t and dr_{up}^t, the upwards and downwards change in demand at each time, t. In this paper, DR can only provide reserve in the downward direction (from the DR resource's point of view). Thus DR reserve is assumed to be analogous to a generator providing upward reserve, permitting the formulation of Equation (3c) to represent a reserve market. Furthermore, the contribution to system adequacy by DR is a function of its downward shifting only. Upward shifting of DR can bring about benefits for electricity market participants, for example by aiding the integration of wind generation by increasing system demand at times of high availability of renewable power, but the system adequacy contribution of DR relies exclusively on downward shifting of demand and so is the focus of this paper.

The DR aggregator also determines its optimal capacity bid (cap_{dr}) so as to maximise profits from the capacity market. However, as mentioned in the introduction, these bids are constrained by the change in generator investment due to the addition of the DR resource and, thus, represent the capacity value of DR. Consequently, to parametrise this constraint, the model must first be run without any DR (see equation (2h) and subsequent description).

It is assumed that, in future electricity markets, reference demands relating to DR resources will be knowable and obtainable by DR aggregators, and that reserve markets are non-discriminatory, permitting the participation of DR. DR aggregators are capable of responding to wholesale electricity market prices. Reference demand in the model is represented by $DREF^t$. Assuming the DR resource is capable of providing a response (dr^t_{down} and dr^t_{up}) and providing reserve in the same period as well as the ability to participate in the capacity market, the DR aggregators problem is:

$$\max_{\substack{dr_{down}\\ dr_{up}\\ reserve_{dr}\\ cap_{dr}}} \quad \Pi_{dr} = \Pi_{energy} + \Pi_{reserve} + \Pi_{capacity}, \tag{2a}$$

where

$$\Pi_{energy} = \sum_t (dr^t_{down} - dr^t_{up} - DREF^t) \times \lambda^t, \tag{2b}$$

$$\Pi_{reserve} = \sum_t (reserve^t_{dr}) \times \mu^t, \tag{2c}$$

$$\Pi_{cap} = cap_{dr} \times \kappa - MC^{slack} \times slack, \tag{2d}$$

subject to:

$$dr^t_{down} + reserve^t_{DR} \leq DREF^t, \ \ (\gamma^t_1), \ \ \forall t, \tag{2e}$$

$$dr^t_{up} + DREF^t \leq DMAX, \ \ (\gamma^t_2), \ \ \forall t, \tag{2f}$$

$$\sum_{t=t'}^{t'+23} (dr^t_{down}) = \sum_{t=t'}^{t'+23} (dr^t_{up}), \ \ (\gamma^{t'}_3), \ \ \forall t' \in H = \{1, 25, 49, ...\}, \tag{2g}$$

$$cap_{dr} \leq \sum_{i,j} INVEST^{i,j}_{NoDR} - \sum_{i,j} invest^{i,j}_{DR} + slack, \ \ (\gamma_4). \tag{2h}$$

Equation (2a) is the objective function of the DR aggregator. The DR aggregator choses how to participate in each market in order to maximise their profit. Equation (2b) represents the energy component of the DR aggregator's profit and consists of the revenue obtained from the energy market due to load-shifting as well as the cost of meeting the consumers' reference demand, $DREF^t$. Equation (2c) denotes the reserve component of the DR aggregator's profit, while Equation (2d) represents the capacity profits.

Constraint (2e) ensures that, in each time-step, t, the DR aggregator can only shift downwards and can only provide upward reserve (from the point of view of the power system) by an amount less than or equal to the reference demand. That is, there can only be downwards shifting load and reserve if the end-user appliances are on and available. Equation (2f) constrains the upward shifting of the resource to be less than the installed capacity of the end-user appliance, $DMAX$. Constraint (2g) represents the energy limited nature of the DR resource and ensures that any shifting downwards is balanced by shifting upwards over a 24 hour period time constraint, where H is the set containing the first hour of each day. The 24 hour period is chosen because the end use requirement of the flexible demand studied here (space and water heating) must be maintained over each day and so shifting demand beyond a 24 hour period would compromise the heating demand that must be met.

As is the case for the generating firms' problems, the prices λ^t, μ^t and κ are exogenous to the DR agregators problem and are determined via market clearing conditions (equations (3)). All of the DR aggregator's primal variables are constrained to be non-negative.

Equations (2d) and (2h) represent the manner in which the capacity value of DR is determined. To parametrise (2h), the model is first solved assuming there is no DR ('no DR' case), i.e., all DR values (dr^t_{down}, dr^t_{up} and cap_{dr}) are fixed to be zero. Equation (2h) ensures the capacity bid, cap_{dr}, is equal to the change in investment from the 'no DR' case (the parameter $\sum_{i,j} INVEST^{i,j}_{noDR}$) to the case 'with DR' case (the variable $\sum_{i,j} invest^{i,j}_{DR}$) and thus represents the capacity value of DR. The change in investment determines the system adequacy contribution of the DR resource. Given that this is driven by the operation of DR, the particular characteristics of the DR resource determine its capacity value and its potential participation in capacity markets.

The slack variable is included in order to ensure that there is no opportunity for the DR aggregator to over-estimate the system adequacy contribution of the resource. This variable represents generation from an expensive generating unit with a marginal cost of MC^{slack}, which would be required to make up any difference between the capacity bid of the DR and the actual, realized system adequacy contribution of the resource. If the change in investment between the 'no DR' case and the 'with DR' case is zero, the high cost associated with the slack variable forces the variable cap_{dr} to be zero also. Thus, while the slack variable represents generation, its sole function is to ensure that the DR aggregator problem is feasible; there is no participation of this generator in any of the electricity markets.

At this point, we note that the methodology above is employed here for the purposes of studying the impact of DR participation in a capacity market. We do not propose that a market operator employ this methodology when operating their capacity market. Thus, instead of assuming that a DR resource and/or a market operator determine $INVEST^{i,j}_{NoDR}$ *a priori*, we assume that a DR resource would choose its participation in the capacity market according to the regulations of the particular market and their own knowledge of the characteristics of their particular resource. While the particular resource studied in this paper is space and water heating, the same principle applies to any resource and any DR aggregator.

2.3. Market Clearing Conditions

The different MCPs consider different types of market clearing conditions, which connect each of the firms' problems and the DR aggregator's problem. The first type of market clearing condition is associated with the energy market without the consideration of DR:

$$\sum_i gen^{t,i} = DEM^t + E \times \lambda^t, \quad \forall t, \quad (\lambda^t), \tag{3a}$$

where the parameter DEM^t denotes the system demand in hour t and the parameter E represents the slope of the demand function, which is calculated from (but is not equivalent to) the elasticity associated with demand or price-responsive load. This price-responsive load is distinct from the DR resource's load shifting. When DR is included, Equation (3a) becomes:

$$\sum_i gen^{t,i} = DEM^t - DREF^t + dr^t_{up} - dr^t_{down} + E \times \lambda^t, \forall t, (\lambda^t). \tag{3b}$$

To avoid double counting, the parameter $DREF^t$ is removed from the supply-demand equation (3b) as it is the demand which is satisfied by the load-shifting operation of the DR resource. Wind generation is also incorporated, however it is assumed that wind is a price-taker and does not provide any reserve or a contribution to the capacity market.

The reserve market clearing conditions, with and without DR participation are:

$$\sum_i reserve^{t,i}_{gen} = RESERVE_{REQ}, \quad \forall t, \quad (\mu^t), \tag{3c}$$

$$\sum_i reserve^{t,i}_{gen} + reserve^t_{DR} = RESERVE_{REQ}, \forall t, \ (\mu^t), \tag{3d}$$

where the parameter $RESERVE_{REQ}$ is the total reserve required. Similarly, the capacity market MCCs, with and without DR participation are:

$$\sum_i cap^i_{bid} = TARGET, \quad (\kappa), \tag{3e}$$

$$\sum_i cap^i_{bid} + cap_{dr} = TARGET, \quad (\kappa), \tag{3f}$$

where the parameter $TARGET$ represents the amount of generating capacity required.

2.4. MCP Models

The market clearing conditions presented in the previous section are utilized in different combinations in conjunction with the KKT conditions of the firms and the DR aggregator in order to produce a number of different MCP models according to Table 1. As each individual optimisation problem is linear, the KKTs are both neccessary and sufficient for optimality. Thus, each MCP solves the different optimisation problems simultaneously and ensures a Nash-Equilibrium (Gabriel et al., 2012).

The different models allow consideration of the impact of DR participation in each combination of markets. In each case, the conventional firms participate in all markets. All of the models are run for varying wind capacities and varying peak demand.

Table 1: MCP models considered

DR Participation	**No DR**	**En Only**	**En & Res**	**En & Cap**	**All**
Energy	—	✓	✓	✓	✓
Reserve	—	—	✓	—	✓
Capacity	—	—	—	✓	✓

The MCP models are developed in the General Algebraic Modeling System (GAMS) and solved using the PATH solver (Ferris and Munson, 2000). Due to the considerable computation time, the MCP analysis is performed for the first 100 days of the year, which covers the peak period.

2.5. Test System

We consider I=6 generating firms and J generating technologies. The initial endowment of generating capacity for each firm, $CAP^{i,j}$, is shown in Table 2 and the corresponding cost characteristics are presented in Tables 3 and 4. The marginal costs, maintenance costs and investment costs are all based on the values employed in Lynch and Devine (2017).

The reserve requirement, $RESERVE_{REQ}$, is 500 MW for all cases, unless otherwise stated. The capacity target, $TARGET$, is 1.2 times the system peak load for all cases. In all cases examined, all firms are assumed to be price-takers.

The reference DR data, denoted as $DREF^t$, utilised in this paper is the space and water heating demand profile for 100,000 apartments on the Irish system, as determined by Neu et al. (2014) and Devine et al. (2019). Space and water heating is a particularly appropriate resource due to its inherent thermal inertia, rendering it suitable for load-shifting whilst maintaining the ability to meet customers heating demands. However the methodology can also be applied to any other source of DR, with the contribution to system adequacy of same being determined by the particular characteristics of each resource. It should be noted that it is exclusively heating, and not cooling, loads that are under examination in this study. The installed

Table 2: Initial endowment of capacity $CAP^{i,j}$ for each firm (MW)

Tech	**f1**	**f2**	**f3**	**f4**	**f5**	**f6**
Baseload	1000	800	500	500	400	—
Mid-Merit	—	500	400	—	400	—
Peaking	—	—	200	300	200	200
Total	1000	1300	1100	800	1000	200

Table 3: Marginal Cost $MC^{i,j}$ for each firm (€/MW)

Technology	**f1**	**f2**	**f3**	**f4**	**f5**	**f6**
Baseload	30	45	55	55	65	—
Mid Merit	—	50	35	—	35	—
Peaking	—	—	93	83	93	93

Table 4: Generation Cost Characteristics for each technology considered (€/MW)

Technology	**Maintenance** $MCOST^j$	**Investment** $ICOST^j$
Baseload	25	100000
Mid Merit	12	65000
Peaking	7	45000

capacity of the DR resource, $DMAX$, is 556 MW, while the marginal cost associated with the slack variable, MC^{slack} is €10,000 /MWh.

A set of reference dwellings was modeled in detail by Neu et al. (2014), using EnergyPlus, a deterministic building energy analysis and thermal load simulation program. The importance of considering weather conditions and building design in the determination of heating requirement profiles can not be overlooked and such considerations were at the heart of the EnergyPlus models. Furthermore, the importance of understanding consumers behavior prompted the utilization of time-of-use survey data in order to extract the behavioral patterns of building residents, in terms of occupancy and use of electrical appliances. Thus, the model developed by Neu et al. (2014) applies Markov Chain Monte Carlo techniques to time-of use survey activity data to develop activity-specific profiles for occupancy and domestic hot water requirements, thus taking into account consumers behavior. In this way, daily and seasonal variations in temperature as well as varying occupancy and use of electrical appliances are accounted for in the creation of the underlying demand for space and water heating ($DREF$).

An annual system demand profile from Ireland for the year 2009 (SEMO, 2011) is employed, and scaled linearly as appropriate to produce the parameter DEM^t, with different peak load levels. Realised wind data from Ireland from 2009 is employed. The slope of the demand curve (E) is chosen to be -0.11. This value is calculated using the elasticity of demand for residential and commercial consumers as determined by Cosmo and Hyland (2013) and using system demand data for the intercept of the demand curve.

3. Results

3.1. Capacity Bids of the DR Resource

We first consider the capacity values determined by the proposed methodology. These values are non-zero, and so DR succeeds in reducing the total investment in generation capacity. Thus load-shifting DR as

Table 5: Capacity bids of DR, cap_{dr} with a reserve requirement of 500 MW

Wind Level **Peak Load**	**0**	**1500MW**
2500 MW	71 MW	0 MW
5000 MW	123 MW	110 MW
7500 MW	126 MW	114 MW

Table 6: Capacity bid estimation, cap_{dr}, vs Effective Load Carrying Capability estimation at a peak load of 7500 MW and with 0 MW of wind generation

Metric	**MW Estimate**	**CV**
cap_{dr}	126 MW	23%
ELCC	132 MW	24%

modelled in this paper has a positive capacity value.

Table 5 shows the capacity value of DR under various levels of wind and reserve. The capacity contribution of DR increases in peak load, despite the fact that the DR resource itself does not change as peak load changes. This is because higher levels of peak load lead to a higher demand for generation capacity and higher capacity prices and so higher participation of DR in the capacity market proves optimal.

Increased wind generation reduces DR's capacity value. As wind functions in this model purely as a reduction in net load, this effect is analogous to the impact of increasing peak load: lower net load decreases the economic value of generation capacity, and thus decreases the incentive to participate in capacity markets. This results suggests that, even though it is not explicitly modelled in the capacity market, wind also has a capacity value.

Table 6 compares the capacity bid values of the DR resources, cap_{dr}, with the Effective Load Carrying Capability (ELCC) estimations obtained from the methodology developed and presented in Nolan et al. (2014).

The values for the capacity value of DR are broadly similar under both methodologies. This is in spite of the fact that the model presented here lacks many of the technical characteristics of Nolan et al. (2014), such as unit commitment, stochasticity, forced outages, more detailed and granular generation units, and more detailed reserve requirements.

3.2. Impact of Demand Response on Reserve and Capacity Markets

We now consider the impact of the DR resource on reserve and capacity markets. When reserve requirements are low ($RESERVE_{REQ} = 500MW$), the reserve price (μ^t) is €0 in every timestep, with and without DR participation in the reserve market. This is because, at such a low reserve requirement level, the generating firms invest to meet the capacity target, which far exceeds the reserve requirement. This is not

Table 7: Capacity Prices with reserve requirement of **500 MW** and 1500 MW wind generation (€/MW)

Load Level	No DR	En Only	En & Res	En & Cap	All
2500 MW	7	7	7	7	7
5000 MW	5	25	25	25	25
7500 MW	110	1402	1402	272	272

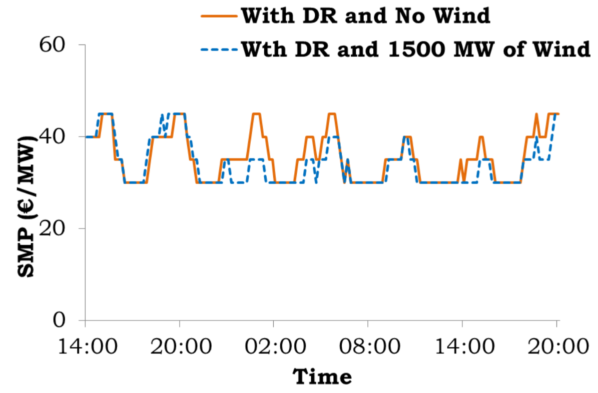

Figure 1: Energy price suppression at a peak load of 7500 MW with high wind generation

surprising as TSOs or market operators tend to calculate capacity requirements taking reserve requirements into account, and so meeting the capacity target means the reserve requirement will also automatically be met. Investment in capacity can be considered a substitute good for reserve.

Table 7 shows that the capacity price (κ) does not change following DR participation in various markets at lower peak load levels. At a peak load of 2500 MW, there is a slight increase in the installed capacity of peaking plants in the system generating portfolio from the initial endowment of capacity and the capacity price is €7 per MW for each subset of DR market participation (energy only, energy and reserve only, energy and capacity only or all three markets). At a peak load level of 5000 MW, the capacity price increases to €25 per MW. Furthermore these results hold whether or not there is price-responsive demand.

At a peak load level of 7500 MW, the capacity price increases dramatically (see Table 7). This increase is driven by the suppression in electricity market prices, which can be seen in Figure 1, as a result of high wind generation and DR participation in the energy market. This suppression in electricity prices reduces generator revenue. However, the firms' problem is to maximize profits. Consequently, equilibrium capacity prices increase in order to cover the costs associated with the high investment at high peak load levels, particularly when DR does not participate in the capacity market itself.

When DR does participate in the capacity market, however, there is a reduction in total capacity investment. This reduces the need for high capacity prices in order to render such investments profitable. These results highlight the added value of explicit DR participation in the capacity market over and above any inherent DR capacity contribution such as that reported in Devine et al. (2019).

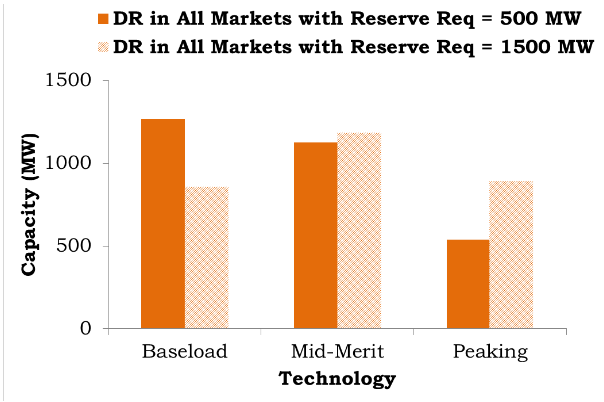

Figure 2: Change in Installed Generating Capacity with increasing reserve requirement with no wind generation - peak load of 2500 MW

3.2.1. Increasing the Reserve Requirement

We now consider the impact of increasing the reserve requirement to 1500MW. At the highest load level, 7500 MW, there is, initially, considerable under-capacity, as mentioned earlier. Thus, increasing the reserve requirement to 1500 MW has no impact on the reserve price, which remains at €0, as the generating firms are continuing to invest in order to meet the capacity target.

At lower peak load levels 2500 MW and 5000 MW, the higher reserve requirement impacts upon both the reserve price (at the peak hour only) and on the capacity price. At these lower peak load levels, the necessity to meet the more stringent reserve requirement dominates investment decisions, that is the reserve market constraint becomes binding, and, thus, firms invest in order to meet the reserve requirement, not the capacity target. This is the opposite effect of that seen in Table 7, where the capacity target dominated the reserve requirement. This results in capacity prices of €0 for all cases, while the reserve price is extremely low at all hours, except at the peak hour where the reserve price is €25. The resulting technology mix is impacted, as shown in Figure 2.

At a peak load of 7500 MW, capacity prices greater than €0 are observed, depending on DR's capacity market participation. In the cases where DR does not participate in the capacity market, the capacity price is €25, while it is €0 when DR does provide capacity. This is again due to the lower capacity investments due to DR's inherent capacity value.

3.3. Impact of Demand Response on consumer costs and Optimal Demand Response Portfolio

In order to determine the consumer costs, Equation (4a) is utilized for the model without DR, while Equation (4b) is employed for all models with DR. These calculate the total costs incurred by consumers (rather than fuel, carbon and other costs incurred by the generating firms).

$$Cost^{noDR}_{System} = \sum_{t}\sum_{i}\sum_{j}(gen^{t,i,j} \times \lambda^{t} + Reserve^{t,i,ij}_{gen} \times \mu^{t}) + \sum_{i}\sum_{j}(Cap^{i,j}_{Bid}) \times \kappa + WIND^{t} \times \lambda^{t}, \quad (4a)$$

$$Cost^{withDR}_{System} = \sum_{t}\sum_{i}\sum_{j}(gen^{t,i,j} \times \lambda^{t} + Reserve^{t,i,ij}_{gen} \times \mu^{t}) + \sum_{i}\sum_{j}(Cap^{i,j}_{Bid}) \times \kappa + WIND^{t} \times \lambda^{t}$$
$$+ \sum_{t}(Reserve^{t}_{DR} \times \mu^{t}) + Cap_{DR} \times \kappa. \quad (4b)$$

Table 8 displays the percentage difference between these equations (4a) and (4b) for different levels of DR participation. It shows how DR participation in energy markets decreases consumer costs by between 0.8% and 7.4%. However DR participation in reserve or capacity markets does not lead to a further change in costs in general. This stems from the fact that reserve and capacity prices are in general unaffected by DR participation in those markets. This suggests that optimal DR participation is a case by case consideration.

However, the exception is the scenario where peak demand is 7500MW and wind capacity is 1500MW, where DR participation in the capacity market brings about additional savings (1.83% to 2.02%). This stems from the decrease in capacity price, κ, following the introduction of the DR resource in the capacity market, see Table 7. This suggests that when both wind and peak load are relatively high, the optimal participation of DR is in all three of the markets considered.

We note at this point that, by varying peak demand but leaving the magnitude of the DR resource unchanged, we implicitly assume that the DR resource is independent of any factor that would also bring about a change in space and water heating demand, such as the weather. While this assumption may not be realistic, our purpose in varying peak demand here is to study the impact of varying levels of DR as a proportion of peak demand. The resulting market equilibria give insights as to the extent to which the impacts of DR are driven by DR's penetration relative to peak demand, as opposed to the absolute value of DR. These results should thus be interpreted as providing insights into the effect of DR as a proportion of peak demand, rather than predicting the extent to which space and water heating demand will vary as peak demand varies.

Table 8 also shows that, as wind power is introduced to the market, consumer savings increase, for most of the cases considered. However, when DR only participates in the energy market and peak demand is 7500MW, consumer savings decrease (1.83% to 0.84%) as a result of wind being introduced. Because wind does not participate in the capacity market, firms still need to meet the same capacity target and require higher revenues to do so. The higher capacity price is needed as wind power depresses energy prices. This is not the case when peak demand is 2500MW and 5000MW as there is more capacity in the system to begin with.

In contrast, when DR also participates in the capacity market and peak demand is 7500MW, the introduction of wind increases savings. This is again because DR's participation in the capacity market reduces the amount of generation capacity firms must provide in order to meet the capacity target. Consequently, the capacity price is reduced. This again suggests that when both wind and peak load are relatively high, the optimal participation of DR is in all three of the markets considered.

Table 8: Reduction in consumer costs relative to no DR with different DR market participation (%)

Peak (MW)	Wind (MW)	Energy Only	En & Cap	En & Res	All
2500	0	5.84	5.84	5.84	5.84
2500	1500	7.36	7.36	7.36	7.36
5000	0	2.80	2.80	2.80	2.80
5000	1500	2.81	2.81	2.81	2.81
7500	0	1.83	1.83	1.83	1.83
7500	1500	0.84	2.02	0.84	2.08

4. Discussion

The first and most important result of this paper is the calculation of the inherent capacity value of DR, and the demonstration that subsequent DR participation in capacity markets can lead to considerable changes in the market equilibrium. As such, load-shifting DR resources make an inherent contribution to system adequacy as a result of their operation. Given that the ability of the DR resource to participate in the capacity market is, in effect, a consequence of the operation of the resource in the energy market, there does not appear to be any indication that participation in both the energy and capacity markets results in a trade-off.

The combined impact of high demand and high wind suggest that the capacity value of DR has the highest economic value in a market with generation undercapacity and depressed energy prices due to wind generation. Capacity markets are often proposed as a remedy for the challenges of increased deployment of variable renewable generation sources, including their price-suppressing effect. As outlined in Sioshansi (2010), this price-suppression may in turn lead to underinvestment in generation capacity, particularly in the absence of capacity markets. These results suggest that load-shifting DR can mitigate these effects through its impact on energy markets but also by means of its inherent capacity value.

The ability of DR participation in the capacity market to mitigate high capacity prices is a particularly important result. Variable renewable generation that with a low or zero marginal cost is considered to worsen the ”missing money” problem via two mechanisms: by reducing the capacity factors of conventional generators, and by reducing energy prices. This in turn raises capacity prices, as generators require higher capacity compensation to fill the “missing money” gap. The results of this paper show that participation by DR in the capacity market can mitigate this effect and reduce consumer costs.

The impact of the DR resource’s participation on the equilibrium prices in each market varied considerably depending on the particular market parameters such as peak demand and wind penetration. Modern electricity markets are beginning to include more complicated ancillary services markets, in which DR is well-placed to participate. The results of this paper highlight the interdependencies of various markets and equilibria and so research on the impact of DR participation in ancillary service markets should be prioritised.

Policy makers and market operators should be cognisant of the results of this paper in designing electricity markets. As renewable generation with a low or zero marginal cost makes up larger shares of electricity generation, both DR and capacity markets become increasingly important. The findings of this research show quite clearly that the omission of DR from capacity markets will move the resulting equilibrium farther from the socially-optimal solution as variable renewable generation increases. It is, thus, particularly important that capacity markets are conducive to DR participation. Furthermore, capacity markets should be equipped with appropriate penalties to prevent DR resources from over-declaring their capacity, in order to prevent a DR resource from taking undue advantage of any provision to include DR in the capacity market.

There is no scenario under which a different equilibrium is arrived at depending on DR's participation in the capacity market vs. the reserve market. This is a result of the substitutive nature of capacity and reserve, where meeting the capacity constraint entails automatically meeting the reserve constraint, or vice versa. However, the limited modelling of detailed operations may explain this effect. In particular, reserves are required to ensure adequate energy provision in the presence of stochastic output from variable renewable generation, as well as uncertainties in the reliability of thermal generators. Including these in future work may see an economic value associated with DR reserve provision.

While the DR resource considered here was space and water heating, there are many other sources of demand that may potentially provide DR. Examples include flexible charging of electric vehicles or operation of household white goods (particularly with the expansion of smart appliances), or potential industrial applications. Of course, many other sources of demand, eg air conditioning or cooking appliances, are unlikely to prove suitable for the provision of DR as the demand cannot be easily shifted to another time period. The primary method through which alternative sources of DR can be modelled is by varying the time series of the DR resource available as well as varying the time constraint over which the DR must be recovered. In this paper, shifted demand must be recovered over a 24 hour period, which is appropriate given the thermal inertia of space and water heating, but other sources of DR may require that the demand be recovered over shorter or longer time periods.

Capacity value metrics typically include a reliability component. This is because generation availability, for both conventional and renewables, exhibit a degree of uncertainty, e.g., through unplanned outages. Consequently, system security can only be ensured to a given level of probability. Capturing this unreliability also involves stochastic modelling, which may be included in future work.

5. Conclusion

This paper examined the participation of a load-shifting demand response resource in energy, reserve and capacity markets in order to inform the discussion on the impact of demand response. The markets are modelled as MCPs, permitting optimization of generating firms' problems and a demand response aggregator's problem simultaneously. A novel approach to determine the contribution of the demand response resource to system adequacy is also presented, permitting demand response participation in the capacity market.

The results indicate that the demand response resource has an inherent capacity value, reducing equilibrium levels of generation capacity and yielding consumer savings. The impact is most pronounced at high peak load levels, where there is significant initial under-capacity. Demand response's participation in the capacity market is also greatest at high levels of wind generation. Therefore, the two technologies can be considered complementary goods, particularly in systems that have undercapacity. Reserve provision and capacity provision, on the other hand, can be considered substitutes, from the firm's point of view. The optimal set of markets for demand response participation is energy, reserve and capacity markets.

Acknowledgments

Lynch and Devine acknowledge funding from the ESRI's Energy Policy Research Centre (EPRC). Devine also acknowledges funding from Science Foundation Ireland (SFI) under the SFI Strategic Partnership Programme Grant number SFI/15/SPP/E3125. Nolan acknowledges the Irish Research Council Embark Initiative. The authors sincerely thank Dr. O. Neu who provided some of the data used in this paper and whose help proved invaluable.

References

Botterud, A., Doorman, G., 2008. Generation investment and capacity adequacy in electricity markets. International Association for Energy Economics Energy Forum second quarter.

Cosmo, V. D., Hyland, M., 2013. Carbon Tax Scenarios and their Effects on the Irish Energy Sector. Energy Policy 59 (59).

Cutter, E., Taylor, A., Kahrl, F., Woo, C. K., 2012. Beyond DR Maximizing the Value of Responsive Load Limits of the Current DR Paradigm. In: 2012 ACEEE Summer Study on Energy Efficiency in Buildings. pp. 77–88.

Devine, M. T., Nolan, S., Lynch, M. Á., OMalley, M., 2019. The effect of demand response and wind generation on electricity investment and operation. Sustainable Energy, Grids and Networks 17, 100–190.

Eissa, M., 2019. Developing incentive demand response with commercial energy management system (cems) based on diffusion model, smart meters and new communication protocol. Applied Energy 236, 273–292.

Ferris, M. C., Munson, T. S., 2000. GAMS/PATH User Guide Version 4.3.

Gabriel, S. A., Conejo, A. J., Fuller, J. D., Hobbs, B. F., Ruiz, C., 2012. Complementarity modeling in energy markets. Vol. 180. Springer Science & Business Media.

Good, N., 2019. Using behavioural economic theory in modelling of demand response. Applied Energy 239, 107–116.

Kavanagh, D., Keane, A., Flynn, D., 2013. Capacity Value of Wave Power. IEEE Transactions on Power Systems 28 (1), 412–420.

Keane, A., Milligan, M., Dent, C. J., Hasche, B., Annunzio, C. D., Dragoon, K., Holttinen, H., Samaan, N., Söder, L., Malley, M. O., 2011. Capacity Value of Wind Power. IEEE Transactions on Power Systems 26 (2), 564–572.

Khan, A. S. M., Verzijlbergh, R. A., Sakinci, O. C., De Vries, L. J., et al., 2018. How do demand response and electrical energy storage affect (the need for) a capacity market? Applied Energy 214 (C), 39–62.

Lynch, M. Á., Devine, M. T., 2017. Investment vs. Refurbishment: Examining Capacity Payment Mechanisms Using Stochastic Mixed Complementarity Problems. The Energy Journal 38 (2).

Mkireb, C., Dembélé, A., Jouglet, A., Denoeux, T., 2019. Robust optimization of demand response power bids for drinking water systems. Applied Energy 238, 1036–1047.

Neu, O., Sherlock, B., Oxizidis, S., Flynn, D., Finn, D., 2014. Developing building archetypes for electrical load shifting assessment: Analysis of Irish residential stock. In: The CIBSE ASHRAE Technical Symposium.

Nolan, S., Neu, O., OMalley, M., 2017. Capacity value estimation of a load-shifting resource using a coupled building and power system model. Applied Energy 192, 71 – 82.
URL `http://www.sciencedirect.com/science/article/pii/S0306261917300181`

Nolan, S., OMalley, M., 2015. Challenges and barriers to demand response deployment and evaluation. Applied Energy 152, 1–10.
URL `http://linkinghub.elsevier.com/retrieve/pii/S0306261915005462`

Nolan, S., O'Malley, M., Hummon, M., Kiliccote, S., Ma, O., 2014. A methodology for estimating the capacity value of demand response. In: IEEE Power and Energy Society General Meeting.

Radtke, J., Couch, S., Dent, C., 2010. Capacity value of large tidal barrages. IEEE 11th International Conference on Probabilistic Methods Applied to Power Systems, 331–336.
URL `http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5528894`

SEMC, 2018. Capacity Remuneration Mechanism (CRM) 2019/20 T-1 Capacity Auction Parameters and Enduring De-rating Methodology. Decision Paper. Single Electricity Market Committee.

SEMO, 2011. SEMO Market Data.
URL `http://www.sem-o.com/marketdata/Pages/default.aspx`

Sioshansi, R., 2010. Evaluating the impacts of real-time pricing on the cost and value of wind generation. IEEE Transactions on Power Systems 25 (2), 741–748.

Zhou, Y., Mancarella, P., Mutale, J., 2015. Modelling and assessment of the contribution of demand response and electrical energy storage to adequacy of supply. Sustainable Energy, Grids and Networks 3, 12–23. URL `http://www.sciencedirect.com/science/article/pii/S2352467715000387`

Zhou, Y., Mancarella, P., Mutale, J., 2016. A Framework for Capacity Credit Assessment of Electrical Energy Storage and Demand Response. IET Generation, Transmission & Distribution, 1–17.