Working Paper No. 603

November 2018

Subsequently published in "The impacts of demand response participation in capacity markets", *Elsevier*, Vol. 250, 2019, pp. 444-451, https://doi.org/10.1016/j.apenergy.2019.05.063

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The Impacts of Demand Response Participation in Capacity Markets

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Abstract

Demand Response (DR) is capable of reducing the need for generation capacity investments in order to ensure system security. We utilise this fact to devise a novel methodology for estimating a load-shifting DR resource's capacity contribution and therefore determining DR's potential for participation in capacity markets. DR primarily affects the equilibrium outcome through the energy market, however DR also reduces prices and consumer costs through its capacity market contribution when there is a high level of variable renewable generation and initial undercapacity. As wind levels increase, so do capacity prices as generators seek higher capacity prices to offset depressed energy prices. However, we find that DR's participation in the capacity market can combat these increased capacity prices. These results suggest that DR participation in capacity markets can mitigate some of the market challenges of renewable integration.

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 et al., 2014). Thus 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).

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

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characteristics of electricity provision. For a full summary of the rationale behind capacity markets, see Lynch and Devine (2017) and Botterud and Doorman (2008).

Given the potential for DR to displace generation capacity investments while maintaining a given level of adequacy as shown in Sioshansi (2010); Zhou et al. (2015, 2016); Khan et al. (2018), 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 generation adequacy of the resource. Generation adequacy is defined as the existence of sufficient generating capacity on the power system to meet peak load. 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 generation 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).

Some recent advances have been made in the literature in quantifying the capacity contribution of DR (Nolan et al., 2014; Zhou et al., 2015; Nolan et al., 2017b), which tend to be on a case-by-case basis. 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 (Lynch and Devine, 2017; Höschle et al., 2015; Ventosa et al., 2000; Liang et al., 2011; Bushnell, 2003; Khalfallah, 2009; Daoxin et al., 2012; Dietrich et al., 2012; Kirschen et al., 2012). For a full summary, see Nolan et al. (2017a).

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 generation 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. 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 generation adequacy. Consequently, it is proposed here that the change in generator investment due to the addition of the DR resource is an indication of the capacity value of the DR resource, and the DR resource is then in a position to participate in the capacity market.

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 results highlight the interaction and interdependencies between these different markets. Moreover, we specifically consider the impacts of increasing renewable generation, varying peak load levels and varying reserve targets on the economic equilibrium.

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 ($reserve^{t,i,j}_{gen}$) and capacity bid ($cap^{i,j}_{bid}$), 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:

$$gen^{t,i,j} + reserve^{t,i,j}_{gen} \leq CAP^{i,j} - exit^{i,j} + invest^{i,j}, \quad (\theta^{t,j}_1), \quad \forall t, j, \tag{1e}$$

$$cap^{i,j}_{bid} \leq CAP^{i,j} - exit^{i,j} + invest^{i,j}, \quad (\theta^{i,j}_2), \quad \forall t, j, \tag{1f}$$

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^t_{down} and dr^t_{up}, respectively, and reserve provision $reserve^t_{dr}$ 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^t_{down} and dr^t_{up}, 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.

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. Reference demand in the model is represented by $DREF^t$. It is also assumed that DR aggregators are capable of responding to wholesale electricity market prices. 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:

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

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

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

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

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, where H is the set containing the first hour of each day.

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 is an approximation for the generation adequacy contribution of the DR resource.

The slack variable is included in order to ensure that there is no opportunity for the DR aggregator to over-estimate the generation 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 generation 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.

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 determined by 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:

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

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

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.

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

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 $DREF^t$, utilized 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 Nolan et al. (2017a). The installed capacity of the DR resource, $DMAX$, is 556 MW, while the marginal cost associated with the slack variable, MC^{slack} is €10,000 /MWh.

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 as determined by Cosmo and Hyland (2013).

Table 4: Generation Cost Characteristics (€/MW)

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

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%

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 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).

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

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

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

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 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 Nolan et al. (2017a).

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

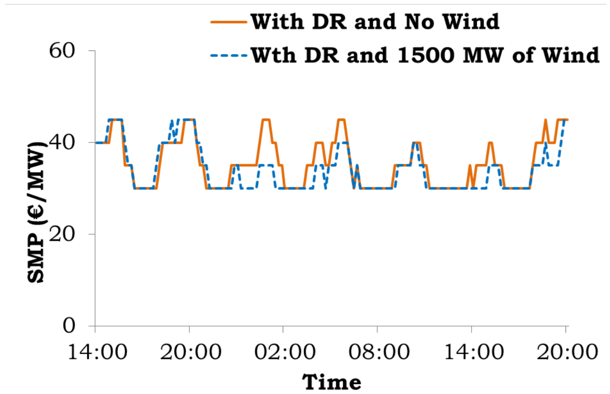

Figure 1: SMP suppression at a peak load of 7500 MW with high wind generation

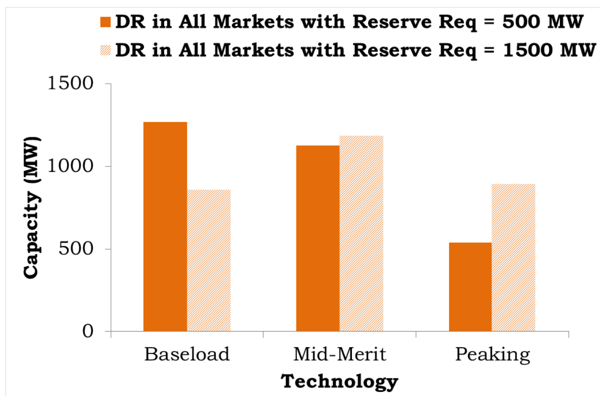

Figure 2: Change in Installed Generating Capacity with increasing reserve requirement with no wind generation - peak load of 2500 MW

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).

$$Cost_{System}^{noDR} = \sum_t \sum_i \sum_j (gen^{t,i,j} \times \lambda^t + Reserve_{gen}^{t,i,ij} \times \mu^t) + \sum_i \sum_j (Cap_{Bid}^{i,j}) \times \kappa + WIND^t \times \lambda^t, \quad (4a)$$

$$Cost_{System}^{withDR} = \sum_t \sum_i \sum_j (gen^{t,i,j} \times \lambda^t + Reserve_{gen}^{t,i,ij} \times \mu^t) + \sum_i \sum_j (Cap_{Bid}^{i,j}) \times \kappa + WIND^t \times \lambda^t + \sum_t (Reserve_{DR}^t \times \mu^t) + Cap_{DR} \times \kappa. \quad (4b)$$

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.

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.

4. Discussion

The first and most important result of this paper is that DR has an inherent capacity value and 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 generation adequacy as a result of their

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

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 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.

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. This, in turn, implies that the omission of DR from capacity markets will move the resulting equilibrium farther from the socially-optimal solution as variable renewable generation increases.

The methodology for calculating the capacity value of DR proposed here aligns with other methodologies that have been proposed in the literature to date. However, this result may be driven by the fact that the only markets modelled here are relatively simple energy, reserve and capacity markets. Furthermore, 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.

Moreover, 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 DR resource in energy, reserve and capacity markets in order to inform the discussion on the impact of DR. The markets are modelled as MCPs, permitting optimization of generating firms' problems and a DR aggregator's problem simultaneously. A novel approach to determine the contribution of the DR resource to generation adequacy is also presented, permitting DR participation in the capacity market.

The results indicate that the DR 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. DR'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 DR 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.

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