Working Paper No. 507

July 2015

Investment vs. Refurbishment: Examining Capacity Payment Mechanisms Using Mixed Complementarity Problems With Endogenous Probability

Muireann Á. Lynch* and Mel T. Devine[a]

Abstract: *Capacity remuneration mechanisms exist in many electricity markets. Capacity mechanism designs do not explicitly consider the effects of refurbishment of existing generation units in order to increase their reliability. This paper presents a mixed complementarity problem with endogenous probabilities to examine the impact of refurbishment on electricity prices and generation investment. Capacity payments are found to increase reliability when refurbishment is not possible, while capacity payments and reliability options yield similar results when refurbishment is possible. Final costs to consumers are similar under the two mechanisms with the exception of the initial case of overcapacity.*

Keyword(s): Capacity markets; Reliability; Mixed Complementarity Problem; Stochastic Modelling

JEL Code(s): Q4, D43, D47, L13, C61

**Corresponding Author: muireann.lynch@esri.ie*

[a] University of Limerick, Limerick, Ireland

Acknowledgements: Lynch acknowledges funding from the Programme for Research in Third Level Institutions and is co-funded by the European Regional Development Fund (ERDF). Devine is funded under Science Foundation Ireland award 09/SRC/E1780. We are grateful to Seán Lyons and participants at the Mannheim Energy Conference for helpful comments and suggestions. All omissions and errors are our own.

1 Introduction

Electricity markets worldwide have undergone a process of liberalisation in recent decades. Electricity generation, which was the preserve of state-owned vertically integrated utilities, is now a competitive industry. However, electricity market structures differ from one country to the next. One of the significant differences that can arise between markets is whether they have a specific capacity remuneration mechanism (CRM), and if so, the form it takes.

A CRM aims to compensate generation firms for owning generation capacity, regardless of the extent to which it is utilised. An electricity market which includes a CRM is usually considered as the alternative to an 'energy-only' market, in which generators are compensated on the basis of the energy they generate only. Electricity cannot be easily or economically stored, and blackouts or brownouts are not socially or politically acceptable. There is thus a requirement for sufficient generation capacity to meet demand at all hours of the year, including peak demand hours, and so some peaking units are required which cannot expect to generate for more than a few hours per year. Ensuring sufficient revenue to render such units economically viable is the main reason for CRMs.

There are several arguments put forward as to why such low-load units would not prove viable in the absence of a CRM. The first is the absence of an active demand-side in electricity generation markets, which means that consumers cannot signal their desired level of reliability of supply (Cramton and Stoft, 2005). There is therefore a weaker price signal for reliable supply, and consequently for electricity generation capacity. There is also an opportunity and incentive to exercise market power, particularly in the period close to real time. Another argument in favour of CRMs is the the shared nature of the electricity network. This introduces a 'free-rider' problem, whereby it is not possible to differentiate between consumers who had entered into a contract for reliable supply. The imposition of price caps in electricity markets, often for political reasons, is also argued to reduce investment incentives for low-load units (Grigorjeva, 2015). Finally it can be argued that electricity has public good characteristics (Abbott, 2001), and so policy-makers may be reluctant to leave the secure supply of generation capacity to market forces. Each of these factors, alone or in combination, mean that generators face a 'missing money' problem in relation to recovering their fixed costs (Stoft, 2002). Thus separate capacity remuneration mechanisms have been proposed as a means of compensating generators for the cost of holding capacity, separate from providing energy (Cramton and Ockenfels, 2012; Cramton and Stoft, 2008; Botterud and Doorman, 2008).

In recent years, the increase of variable renewable generation, such as wind and photovoltaic solar, in modern power systems has given rise to more calls for some form of CRM. Such generation is semi-dispatchable (i.e. can only be dispatched down) and has zero or near-zero marginal costs. Thus the units enter the market at the bottom of the supply curve and displace thermal generators, as well as depressing the prices earned by all generators in the spot market. However, given the fact that the output of renewable generators is variable and relatively unpredictable, there is still a need for excess thermal generation units to ensure sufficient supply at all hours of the year. These effects exacerbate the 'missing money' problem (Cramton and Stoft, 2008).

Capacity markets exist in several markets worldwide to date. In the USA, capacity markets exist in the Pennsylvania-New Jersey-Maryland (PJM), New York Independent System Operator (NYISO) and the Mid-Atlantic System Operator (MISO) markets. The European Commission is skeptical at best on the requirement for CRMs (European Commission, 2013). However according to Caldecott and McDaniels (2014), in 2013 European energy companies announced mothballing of over 20 GW of gas power plants, giving rise to concerns that capacity remuneration was necessary. At present in Europe, capacity payments exist or are planned in Spain, Portugal, Great Britain, and Ireland and are under consideration in Germany, France, Italy, Spain and the Netherlands (CREG, 2012). For an extended discussion on the capacity payments under consideration, see ACER (2013) or CREG (2012).

Capacity mechanism designs can be broadly categorised as 'price-based' or 'quantity-based' ACER (2013). Price-based mechanisms provide a regulated payment designed to mimic the inframarginal-rent an otherwise-marginal generator would receive, and is distributed equally among all generators. Quantity-based mechanisms see supply companies or the System Operator contracting ahead for a fixed amount of capacity, typically equal to the expected peak demand in a given period. Within each of the price and quantity categories there are numerous types of CRMs; for an overview see Botterud and Doorman (2008) and for a more detailed discussion see De Vries (2007).

While capacity markets are found in many modern electricity markets and are under consideration in many more, the optimal design of CRMs is an area of active research. Hobbs et al. (2007) considers the implications of using dynamic demand curves rather than specific demand targets in quantity-based mechanisms, and finds that demand curves reduces costs and risk for consumers and producers. Khalfallah (2011) use a dynamic model under Cournot competition, and find that 'market-based' mechanisms are more efficient than non-market based mechanisms in securing generation investment, but that under cartel and monopolistic situations market-based mechanisms increase installed capacities and consumer costs. Meyer and Gore (2014) consider the cross-border effects of using strategic reserve and reliability options to ensure capacity adequacy in two interconnected markets.

One question which has not been addressed in the literature is the extent to which the reliability of the units themselves impacts on capacity payments, and whether and how to incentivise generators to invest in refurbishing existing generation capacity in order to improve their reliability. The reliability of a unit can be broadly interpreted, but it should not be ignored in capacity payment design[1]. The reliability can be thought of as the number of hours of the year where the unit can be expected to be available for generation. In terms of thermal generators, the reliability is therefore one minus the forced outage rate, whereas for a renewable generator the reliability is a function of the weather, and is linked to the capacity value of the unit in question.

The reliability of generation units has an impact on market clearing prices, both directly, by seeing market prices increase when units are unavailable to generate, and indirectly, by inducing different levels of investment by generation firms, which impacts on market-clearing prices. Thus, the price paid by consumers, the total reliability of the system, the final levels of generation and the profits of generators are all dependant to some extent on the reliability of generation units. This paper considers the equilibrium prices and generation capacity that arise on a system with unreliable units.

The paper considers these market outcomes when generators, each with a given reliability, compete in a market that includes energy and capacity payments. We consider one price-based capacity payment mechanism and one quantity-based capacity payment mechanism, both of which are found in energy markets. The effect of refurbishment of exiting units, and the impact on prices and unserved energy, is considered. A case study is presented with stylised generation firms. Cost parameters are chosen from a variety of sources and reliability and elasticity parameters are taken from the Single Electricity Market (SEM) of Ireland.

In order to model these markets, we construct the problem as a stochastic Mixed

---

[1] The appropriate design of penalties in the case of nondelivery of energy by units in receipt of capacity payments, for example, is a difficult issue that has not been resolved

Complementarity Problem (MCP). MCPs allow the optimisation problems of multiple players (in our case we consider multiple electricity generation firms) to be solved in equilibrium by comparing the Karush-Khun-Tucker (KKT) conditions for optimality of each of the players and connecting them via market clearing conditions (Gabriel et al., 2012).

The stochasticity of the models arises from the uncertainty surrounding the availability of units in any given period. As we wish to compare the effects of investing in new units and refurbishing existing units, we allow firms to invest in refurbishment, which increases the probability of their unit being available. Thus the stochastic MCPs we employ incorporate endogenous probabilities.

The remainder of this paper is structured as follows. Section 2 outlines the mathematical formulation of the three different capacity remuneration mechanisms considered. Section 3 describes the input data used. Section 4 outlines the results obtained. Section 5 discusses the results and section 4.1.2 concludes.

2 Methodology

Consider the case of n generation firms. The firm's objective is to maximise profits, which they earn in both energy and capacity markets.

We compare three different capacity payment mechanisms. The first mechanism is a price-based mechanism, whereby a capacity pot is calculated on the basis of the investment cost of new generation multiplied by the amount of generation required to meet the peak electricity demand. Thus, the pot is calculated so as to mimic the inframarginal rent an otherwise-marginal unit would require in order to break even, as mentioned above. This pot is divided evenly among all generators on the basis of their capacity[2].

The second mechanism is a quantity-based capacity payment mechanism, whereby generators compete in an auction to hold reliability options. Generators in possession of reliability options can be called on by the Transmission System Operator (TSO) to generate at a predetermined strike price during times of system stress, thereby shielding consumers from very high spot prices. For a full description of reliability options see Vázquez et al. (2002).

The models for each of the mechanisms are outlined below.

---

[2] This resembles the capacity payment mechanism which is in place in the Single Electricity Market (SEM) of Ireland at present (CER and NIAUR, 2006)

2.1 Capacity pot mechanism

2.1.1 Firm f's problem

Firm f maximises their profits by choosing the amount of generation, refurbishment of existing capacity, investment in new capacity and decommissioning of existing capacity as follows:

$$
\begin{aligned}
\max_{\substack{inv_{f,t},\\ gen_{f,t,p},\\ exit_{f,t}\\ refurb_{f,t}}} \Pi_f = \max_{\substack{inv_{f,t},\\ gen_{f,t,p},\\ exit_{f,t}\\ refurb_{f,t}}} & \sum_t \Big((inv_{f,t} + CAP_{f,t} - exit_{f,t}) * cp - (inv_{f,t} ICOST_t) \\
& - (CAP_{f,t} - exit_{f,t}) MCOST_t - refurb_{f,t} RCOST_t \Big) \\
& + \sum_{t,p,s} pr_s B_{f,t,s} gen_{f,t,p,s} (\gamma_{p,s} - MC_t)
\end{aligned}
\qquad (1)
$$

subject to:

$$
\begin{aligned}
gen_{f,t,p,s} &\leq inv_{f,t} + CAP_{f,t} - exit_{f,t},\ \ \forall t, p, s\ \ (\lambda^1_{f,t,p,s}), & (2)\\
R_{f,t} + refurb_{f,t} &\leq \overline{R_{f,t}}\ \forall t, (\lambda^2_{f,t}), & (3)
\end{aligned}
$$

where t represents different energy technologies and p represents different time periods. The decision variables for firm f are $inv_{f,t}$, $exit_{f,t}$, $gen_{f,t,p,s}$ and $refurb_{f,t}$ representing market investment, market exit, generation and refurbishment decisions respectively. Each scenario s represents a different combination of units being available/unavailable.

The energy price at each period for scenario s is ($\gamma_{p,s}$) while cp is the capacity price paid for each unit of installed capacity. The prices $\gamma_{p,s}$ and cp are exogenous to firm f's problem but are variables of the overall problem. The parameters $RCOST_t$, $ICOST_t$, $MCOST_t$ are the costs of refurbishment, investment in new generation and the maintenance cost of existing generation[3] for each unit respectively, while CAP and MC are the initial endowment of generation capacity and the marginal cost of production of each technology, respectively. The parameter $B_{f,t,s}$ is a binary indicator, describing whether firm f with technology t is available ($B_{f,t,s} = 1$) or unavailable ($B_{f,t,s} = 0$) in scenario s. The reliability (or probability of being available) for firm f with technology t is $R_{f,t} + refurb_{f,t}$ where $R_{f,t}$

---

[3] New investments are considered to have a lower maintenance cost, and so $MCOST$ can be thought of as the premium on maintenance costs for existing capacity over and above new capacity.

is a parameter representing initial reliability before refurbishment. Hence the probability associated with scenario s is:

$$pr_s = \prod_{f,t} (R_{f,t} + refurb_{f,t})^{B_{f,t,s}} (1 - R_{f,t} - refurb_{f,t})^{1-B_{f,t,s}}. \tag{4}$$

Constraint (2) ensures that generation for given unit and time period cannot exceed the amount of installed capacity while constraint (3) provides an upper bound for the reliability of each unit. The variables in brackets alongside constraints (2) and (3) are the Lagrange multipliers associated with those constraints. All primal (decision) variables of this problem are also constrained to be non-negative.

2.1.2 Market clearing conditions

The market clearing conditions that combine each of the firms' problems are

$$\begin{aligned} \sum_{f,t} B_{f,t,s} * gen_{f,t,p,s} &= Z_p - E * \gamma_{p,s}, \ \forall p, s(\gamma_{p,s}), & (5) \\ POT &= cp\Big(\sum_{f,t} inv_{f,t} + CAP_{f,t} - exit_{f,t}\Big), \quad (cp), & (6) \end{aligned}$$

where Z_p is the intercept of the demand curve for period p and E is a parameter representing the elasticity of demand. In this way, total generation is constructed in equation (5) as a linear function of demand and its elasticity, which follows the approach of Khalfallah (2011). Equation (6) specifies that the capacity pot, which is set administratively and so is exogenous to the problem, should be divided evenly between all installed generation. The prices $\gamma_{p,s}$ and cp are the free Lagrange multipliers associated with these constraints.

As each firm's problem is convex, the Karush-Khun-Tucker conditions are both necessary and sufficient conditions for optimality. The overall model is thus a mixed complementarity problem (MCP) given by the KKT equations for each firm, along with the market clearing conditions (5) and (6). The full model is outlined in the appendix.

2.2 Reliability options mechanism

In the second mechanism, the firms receive capacity revenues from a quantity-based reliability options mechanism. The reliability options are allocated to firms at a price determined by a competitive auction. The objective function and constraints for each firm are similar to the pot without reliability mechanism above, with the addition that generators offer capacity into an auction and some of their capacity wins a reliability option. There is thus a new variable, $cap\_ro_{f,t}$, which denotes the generation capacity owned by each firm and technology that wins a reliability option. Firms holding reliability options must also repay the difference between the spot price and a predetermined strike price when spot prices are higher than the strike price.

2.2.1 Firm f's problem

As in Section 2.1, firm f maximises its profits by choosing the amount of generation, refurbishment of existing capacity, investment in new capacity and decommissioning of existing capacity. Additionally it now also chooses how much capacity to offer in a reliability options auction as follows:

$$\begin{aligned}\max_{\substack{inv_{f,t},\\ gen_{f,t,p},\\ exit_{f,t}\\ refurb_{f,t}\\ cap\_ro_{f,t}}} \Pi_f = \max_{\substack{inv_{f,t},\\ gen_{f,t,p},\\ exit_{f,t}\\ refurb_{f,t}\\ cap\_ro_{f,t}}} & \sum_t \Bigg(cap\_ro_{f,t}cp - inv_{f,t}ICOST_t \\ & - (CAP_{f,t} - exit_{f,t})MCOST_t - refurb_{f,t}RCOST_t \Bigg) \\ & + \sum_{t,p,s} pr_s \Bigg((B_{f,t,s}gen_{f,t,p,s}(\gamma_{p,s} - MC_t)) - cap\_ro_{f,t}rebate_{p,s} \Bigg)\end{aligned} \tag{7}$$

subject to:

$$gen_{f,t,p,s} \leq inv_{f,t} + CAP_{f,t} - exit_{f,t}, \ \forall t,p,s \ (\lambda^1_{f,t,p,s}), \tag{8}$$

$$R_{f,t} + refurb_{f,t} \leq \overline{R_{f,t}} \ \forall t, (\lambda^2_{f,t}), \tag{9}$$

$$cap\_ro_{f,t} \leq inv_{f,t} + CAP_{f,t} - exit_{f,t}, \ \forall t, \ (\lambda^3_{f,t}), \tag{10}$$

where all previously mentioned indices, decision variables and parameters are as described in Section 2.1. The variable $rebate_{p,s}$ represents the unit price rebate that each firm f pays in period p for scenario s for the capacity for which they hold a reliability option. This price is exogenous to firm f's problem but is a variable of the overall mixed-complementarity problem. In addition to the extra decision variable ($cap\_ro_{f,t}$) being constrained to being non-negative, the reliability options mechanism problem also has an extra constraint which ensures that capacity offered in the reliability options auction by firm f for technology t cannot exceed its installed capacity (see equation (10)). The variable $\lambda^3_{f,t}$ is the Lagrange multiplier associated with this constraint.

2.2.2 Market clearing conditions

The market clearing conditions include the condition that all elastic demand must be met, as in the first problem, along with a constraint that the total number of reliability options awarded must reach the predetermined target set by the regulator. The Lagrange multipliers associated with these constraints are $\gamma_{p,s}$ and cp, respectively. The rebate paid by firms holding reliability options also acts as a market clearing condition. The rebate is paid when the electricity price, $gamma_{p,s}$, rises above a strike price, SP, which is determined administratively and is known to the firms in advance. The market clearing conditions are:

$$\begin{aligned} \sum_{f,t} B_{f,t,s} gen_{f,t,p,s} &= Z_p - E * \gamma_{p,s}, \;\; \forall p, s(\gamma_{p,s}), & (11) \\ TARGET &= \sum_{f,t} cap\_ro_{f,t}, \quad (cp), & (12) \\ rebate_{p,s} &= max(\gamma_{p,s} - SP, 0) \;\; (rebate_{p,s}). & (13) \end{aligned}$$

As previously each firm's problem is convex. Hence, the Karush-Khun-Tucker conditions are both necessary and sufficient conditions for optimality. The overall model is thus a MCP given by the KKT equations for each firm, along with the market clearing conditions (11) - (13). The full model is outlined in the appendix.

3 Input data

We solve the model for a simplified system with three generation technologies, five time periods and four generation firms. The five time periods represent summer low demand, summer high demand, winter low demand, winter high demand and winter peak demand. Intertemporal constraints are not considered and so the sequence of the demand periods is not relevant; for simplicity we show the demand intercept in each period in ascending order:

Period	1	2	3	4	5
Demand (MW)	300	500	750	900	1500

Table 1: Demand intercept (Z_p) in each period

We consider three generation technologies which we denote as baseload, midmerit and peaking capacity. We consider pulverised coal to be roughly representative of baseload units, combined cycle gas plants as representing midmerit units and open cycle gas turbines as the peaking technology for this study. We consider the investment and maintenance costs to be fixed, as per Shortt et al. (2013) and Hirth (2013) respectively, and use the marginal costs of production from Shortt et al. (2013). Sensitivities were conducted using different marginal costs and they did not impact on the final results. The cost characteristics are given in table 2.

Technology t	Investment ($ICOST$) (âĆň/MW)	Maintenance ($MCOST$) (âĆň/MW)	Marginal cost (MC) (âĆň/MWh)
Baseload	100000	25	65
Mid merit	65000	12	40
Peaking	45000	7	83

Table 2: Generation cost characteristics

Firm one is an integrated firm, with investments in all three generation technologies. Firm two has baseload capacity only, firm three has midmerit capacity only and firm four has peaking capacity only. The quantities of each are given in table 3.

t	$f = 1$	$f = 2$	$f = 3$	$f = 4$
Baseload	300	300	0	0
Mid merit	200	0	200	0
Peaking	200	0	0	200

Table 3: Initial capacities ($CAP_{f,t}$) of each firm (MW)

The total generation capacity is 1400MW, which falls 100MW short of peak demand in period 5. Thus at least 100MW of investment will be required.

The strike price (SP) in the reliability options mechanism is set equal to the marginal cost of the most expensive unit, in this case the peaking units. The recommendation in Vázquez et al. (2002) (in which reliability options were originally proposed) is that the strike price should be 25% above the incremental cost of the most expensive unit, while Cramton and Stoft (2005) recommends setting the strike price at the cost of the most expensive unit. However, the strike price can be set at a higher (or indeed a lower) level if desired.

The initial levels of reliability ($R_{f,t}$)of installed capacity are considered fixed for each technology and firm. These reliability levels can be thought of as the forced outage rates of the units and are based on forced outage rates of units found on the Irish system as per the regulators' validated model for studying the Irish system (CER and NIAUR, 2013). The forced outage rate takes a value between zero and one, where zero indicates no reliability (i.e. the unit will be continually on forced outage) and one indicates guaranteed reliability (the unit will always be available when required). In other words, $R_{f,t}$ is the probability of being available to generate at each period[4]. These initial levels are given in table 4. Midmerit units tend to have slightly lower levels of reliability than baseload units as they are cycled more frequently (Troy et al., 2010), which adds to wear and tear on the units, and lower reliability than peaking units, as midmerit plants are online more frequently. Peaking units are used least often and so have higher reliability.

	Baseload	Midmerit	Peaking
Reliability	0.965	0.955	0.985

Table 4: Initial levels of reliability for each technology and firm

Given these initial levels of reliability for baseload and midmerit units, there are six units with reliability of less than one. Hence, there are $2^6 = 64$ scenarios which must be considered, representing each possible combination of units available for generation. The probability associated with each of these scenarios is a function of the units' reliability.

The cost of refurbishment ($RCOST_{f,t}$) is a continuous variable given as a proportion of the investment cost. Thus to increase a unit's reliability from 0.4 to 0.5 costs one tenth of the investment cost. While this is a simplification, the rationale for this is that no increase in reliability should cost nothing, and to raise the reliability of a unit from zero to one entails building a new unit[5]. The reliability of new investments is assumed to be equal to one, i.e., a new build is as reliable as any unit can be expected to be.

The elasticity of demand on the island of Ireland is calculated in Di Cosmo and Hyland (2013) as -0.16, which is in line with international estimates. Following the methodology in Walsh and Malaguzzi Valeri (2014) we use the elasticity of demand (E) for the wholesale electricity market of -0.11.

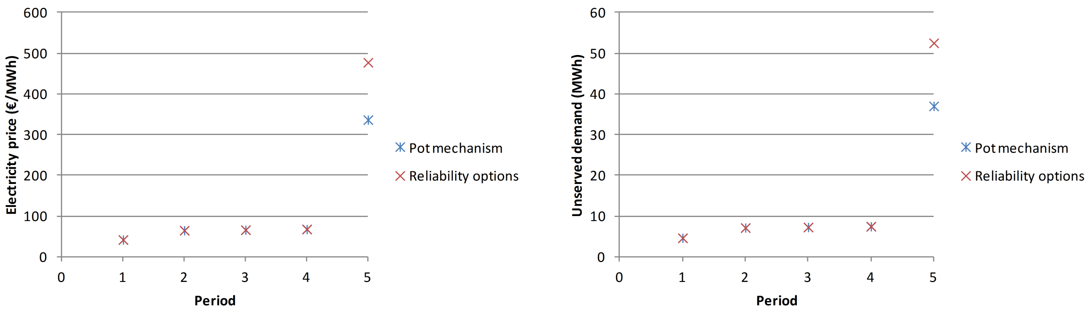
4 Results

The model is solved for both capacity payment mechanisms with and without the possibility of investing in refurbishment. The generic algebraic modelling system (GAMS) was used to solve the models, employing the PATH solver.

---

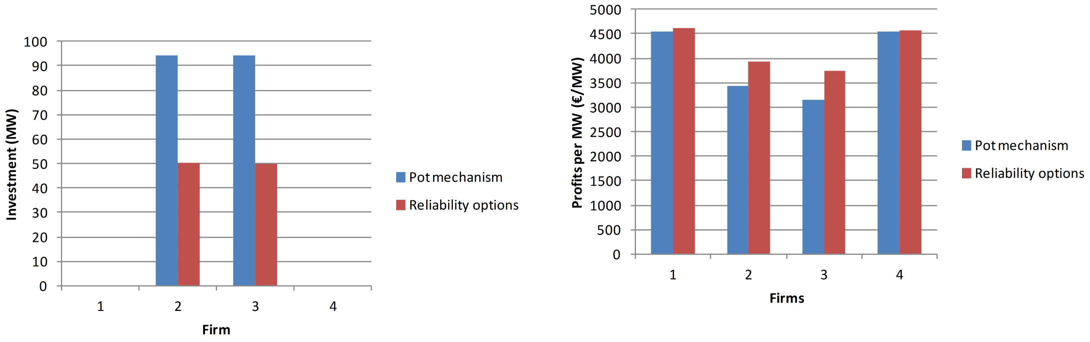
[4] Note that the reliability of each unit in independent of the period; i.e. the probability of being available to generate in a given period is independent of its availability in the previous period

[5] Future work will examine this assumption in more detail



(a) Expected electricity prices in each period

(b) Expected total generation each period



(c) Investment in new capacity by each firm

(d) Expected profits per megawatt installed capacity

Figure 1: Results under both capacity payment mechanisms with no refurbishment

4.1 Results without refurbishment

The pot mechanism and reliability options models are first run without taking consideration of potential refurbishments, i.e., they are run with the variable $refurb_{f,t}$ set equal to zero for all firms and technologies.

4.1.1 Base case

Figure 1 depicts the electricity prices, investment, generation, market shares and profits per megawatt installed capacity arising under both capacity payment mechanisms.

Figure 1a shows the expected electricity price at each period, i.e. the price at each scenario weighted by the probability of the scenario ($\sum_s prob_s * \gamma_{p,s}$). There is little difference in the electricity prices arising under the two models with the exception of period 5. In this period the market price is higher under reliability options, but due to the rebate mechanism consumers are not exposed to this high price. The weighted average of unserved demand in each period again only diverges in period 5, where there is slightly higher generation (i.e. slightly lower unserved demand) under the pot mechanism.

The reason for this difference in unserved demand in period 5 may be explained by figure 1c, which shows the total generation investments by each firm[6]. Given the initial

---

[6] All firms invest in peaking capacity only. A multi-period analysis may see investment in baseload or

1400MW of installed generation capacity, and the 1500MW of reliability options available, there is only 100MW of investment under the reliability options model. Given the fact that units do not have 100% reliability, this brings about scenarios where there is insufficient generation available to meet all demand. Under the pot mechanism, however, there is a higher level of investment, leading to a more reliable system overall and thus less unserved demand. This is in spite of the fact that the pot was chosen to induce the same amount of total investment - indeed, the capacity price arising from the reliability options model is equal to the cost of peaking units, and so the total payout from consumers for capacity is equal to the size of the pot under the pot mechanism. Thus, a pot mechanism may lead to overcapacity relative to the reliability options model.

No exit of existing generation takes place under this scenario and so the generation capacity market shares are determined on the basis of the existing capacity and the 100MW of new generation. As firms two and three are the only firms to invest the dominant position of firm one is lessened somewhat under both models. This is because firm one can earn the same revenues without incurring the cost of investment, and so by not investing, firm one earns higher profits per MW installed capacity than the firms that do invest. The profits of firm four are equal to those of firm one, as firm four also does not invest and so has no investment cost.

In terms of the cost to consumers, the prices and the capacity pots are similar. However, the rebate mechanism under reliability options leads to lower final costs, as the difference between the cost of the most expensive unit (€83 per MWh) and the price in period 5 is repaid to the consumer. Thus from our initial position of slight underinvestment, the reliability options model leads to a lower consumer cost, but the pot mechanism induces higher investment, which brings about more reliability and lower levels of unserved demand, while reducing profits for the firms in question.

4.1.2 Varying market concentration

The simulation was repeated with the same amount of total installed capacity, but changing the proportions of capacity held by each firm as per tables 6 and 5. The results are shown in figure 2.

The results in this scenario exhibit the same patterns as the base case and concentration in the market does not appear to have an impact on the arising prices and generation

---

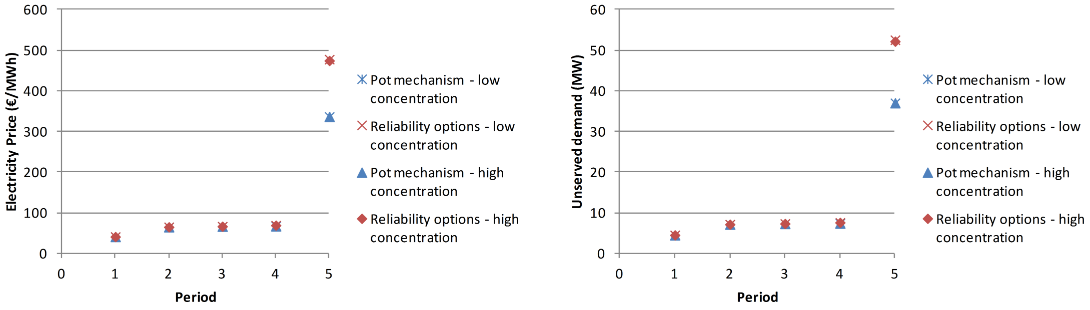
midmerit technologies

	Firm 1	Firm 2	Firm 3	Firm 4
Baseload	200	400	0	0
Mid merit	100	0	300	0
Peaking	100	0	0	300

Table 5: Initial capacity endowments ($CAP_{f,t}$) with low market concentration (MW)

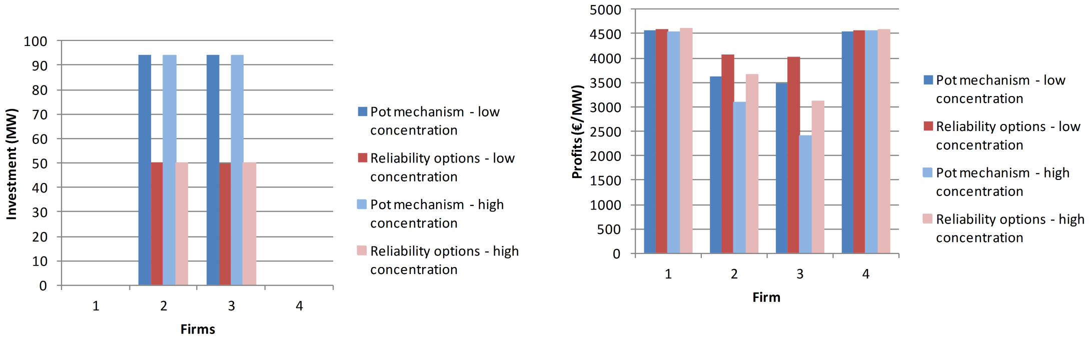
	Firm 1	Firm 2	Firm 3	Firm 4
Baseload	400	200	0	0
Mid merit	300	0	100	0
Peaking	300	0	0	100

Table 6: Initial capacity endowments ($CAP_{f,t}$) with high market concentration (MW)



(a) Expected electricity prices in each period

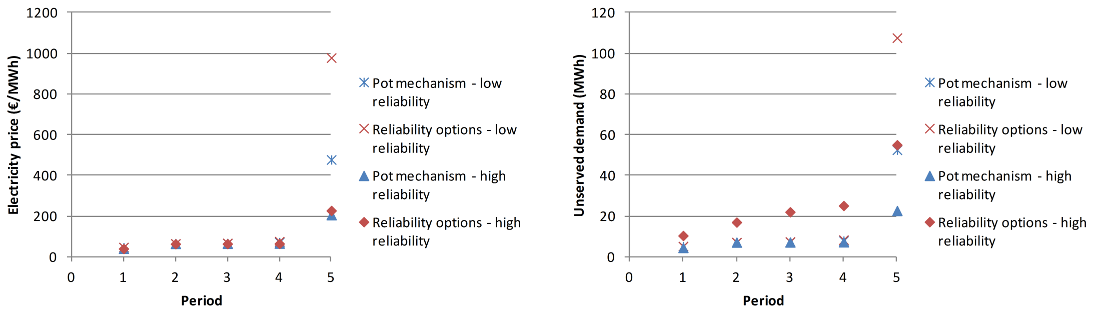
(b) Expected total generation each period



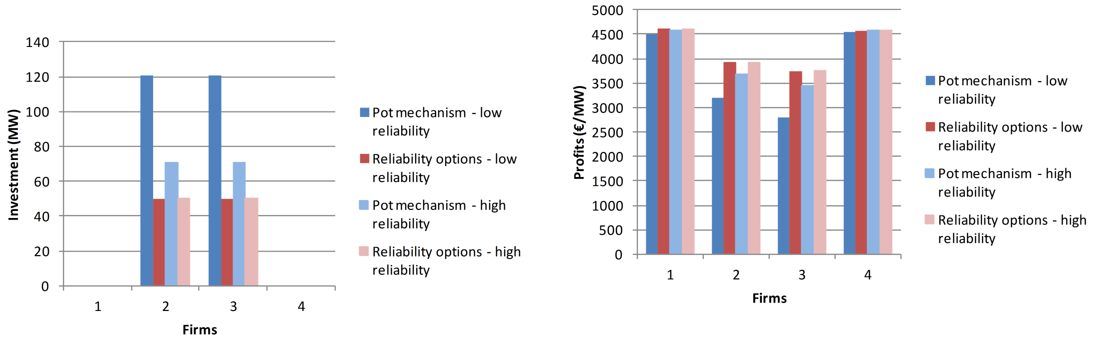
(c) Investment in new capacity by each firm

(d) Expected profits per megawatt installed capacity

Figure 2: Results under both capacity payment mechanisms with varying levels of initial concentration



(a) Expected electricity prices in each period (b) Expected total generation each period



(c) Investment in new capacity by each firm (d) Expected profits per megawatt installed capacity

Figure 3: Results under both capacity payment mechanisms with varying levels of initial reliability

levels. This is due to the fact that entry is not restricted, and so the possibility of new entry mitigates against the incumbants' opportunity to exercise market power.

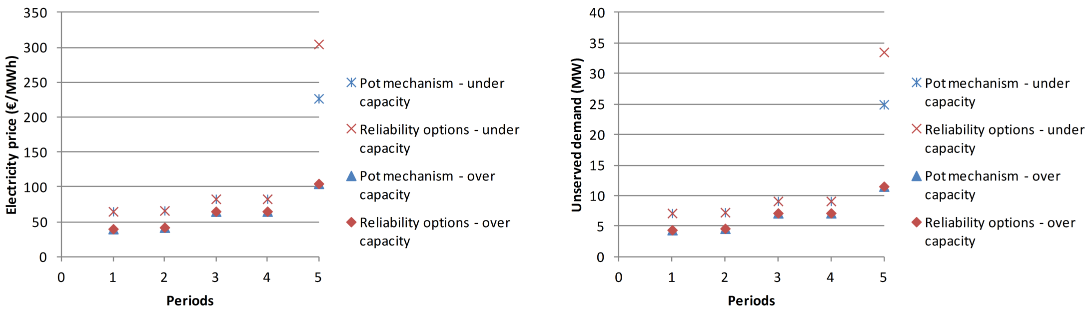
4.1.3 Varying reliability

The analysis is repeated varying the initial levels of reliability according to table 7. The results are shown in figure 3.

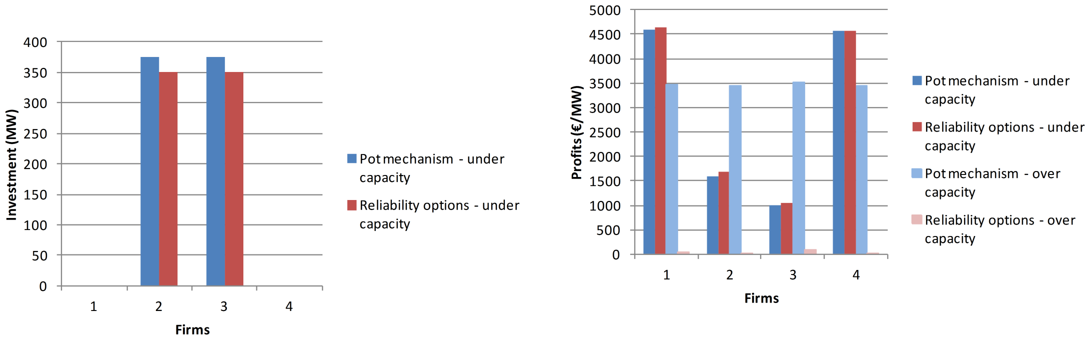
Reliability ($R_{f,t}$)	Baseload	Midmerit	Peaking
Low	0.95	0.84	0.98
High	0.985	0.98	0.1

Table 7: Sensitivity analysis on the initial levels of reliability for each technology and firm

Unsurprisingly, expected market prices in period 5 rise under decreased reliability, as the probability of a unit being unavailable, and hence the probability of the associated scenarios arising, is increased. The expected unserved energy also increases, particularly in the case of reliability options. The investments undertaken under the reliability options model are the same in both cases (100MW in total), but there is increased investment by the pot mechanism under low reliability. This again shows that, as argued in the base case, higher levels of investment prove optimal in order to allow generators to provide



(a) Expected electricity prices in each period (b) Expected total generation each period



(c) Investment in new capacity by each firm (d) Expected profits per megawatt installed capacity

Figure 4: Results under both capacity payment mechanisms with initial over and under capacity

generation in spite of the unreliability of their generators. Thus the increased investment improves the reliability of the system without imposing extra costs on consumers. This again leads to lower profits for firms two and three under the pot mechanism relative to the reliability options model.

4.1.4 Varying initial capacities

The analysis is repeated for initial levels of over and under capacity according to tables 8 and 9. The resuls are shown in figure 4.

	Firm 1	Firm 2	Firm 3	Firm 4
Baseload	200	200	0	0
Mid merit	100	0	100	0
Peaking	100	0	0	100

Table 8: Initial capacity endowments ($CAP_{f,t}$) with undercapacity (MW)

	Firm 1	Firm 2	Firm 3	Firm 4
Baseload	400	400	0	0
Mid merit	300	0	300	0
Peaking	300	0	0	300

Table 9: Initial capacity endowments ($CAP_{f,t}$) with overcapacity (MW)

The effect of under and overcapacity on prices and unserved demand is as one would expect. Interestingly, the unserved demand does not fall to zero even with significant overcapacity. There is no new investment in the case with overcapacity and the pot mechanism sees slightly more investment relative to reliability options with undercapacity, in keeping with the pattern observed above. In the undercapacity scenario, the capacity price falls to €22 per MW, leading to much lower costs for consumers and much lower profits for generators. Generators' profits per MW installed capacity fall under overcapacity relative to undercapacity with the pot mechanism, as the same pot must be spread over a smaller number of generators. However this was not enough to induce market exit by firms, either under the pot model or the reliability options model, as firms were still making a positive profit per MW of installed generation.

A further sensitivity with an extremely high level of overcapacity (ten times the initial amount) was performed. There was still no exit under the pot mechanism, as the payment per MW installed was still higher than the maintenance cost. However exit did take place under the reliability options model, leaving a total of 2703MW installed. Thus initial overcapacities of more than this amount would see exit (depending on the initial reliability of the units).

The reliability options were distributed evenly across the technology types and firms according to figure 5. The rebate mechanism operates such that a generator holding an option must repay the rebate to the system operator regardless of whether the unit was scheduled. Thus it is in firms' interest to hold both reliability options and back-up generation, to reduce the probability of their being called on to repay the difference between the strike price and the reference price while being unable to generate due to being on forced outage. This may explain the lack of exit by firms under the reliability options model.

4.1.5 Varying elasticities

Finally the analysis is repeated for different levels of price elasticity of demand of 0.05 and 0.2. The results are presented in figure 6.

The results under varying elasticities follow the same patterns as above, with prices and unserved demand rising as elasticity decreases. The investment decisions again see the reliability options model investing only in the generation necessary to reach the total target amount of capacity.

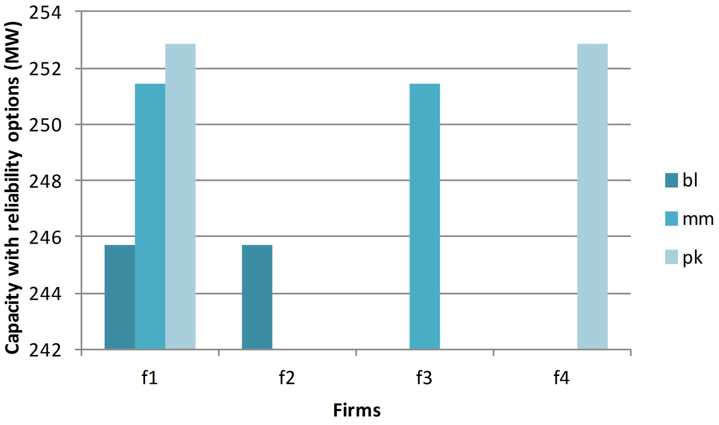
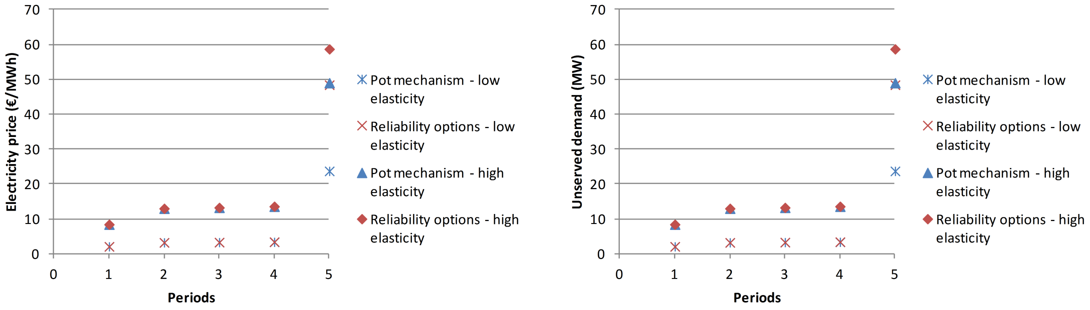
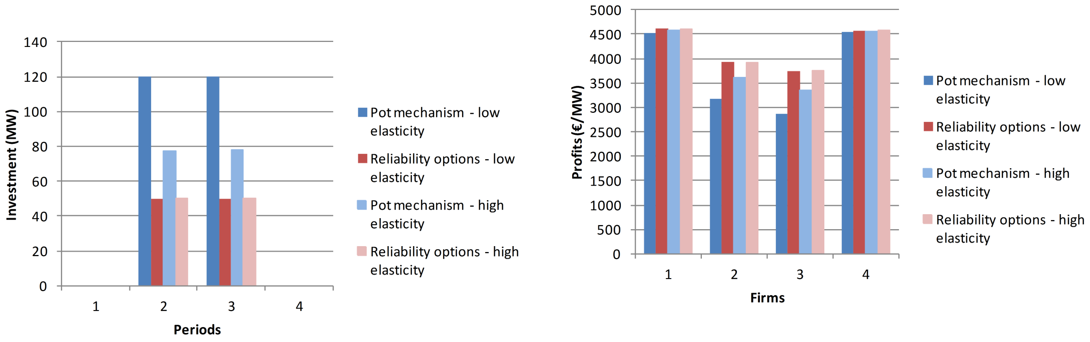


Figure 5: Reliability options held by each firm with over-capacity

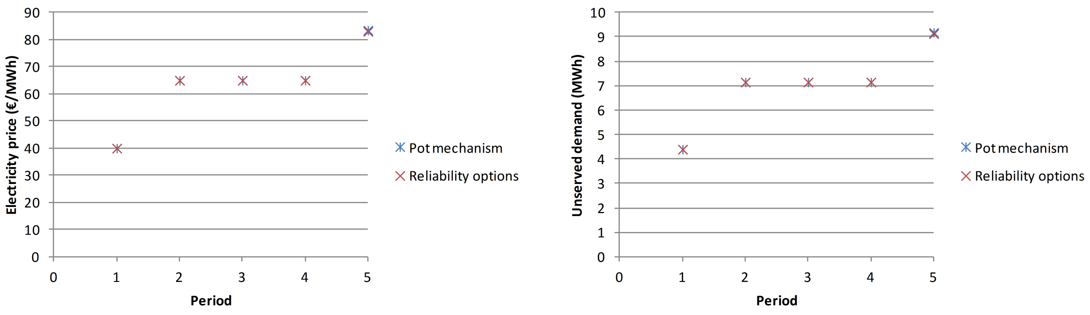


(a) Expected electricity prices in each period (b) Expected total generation each period

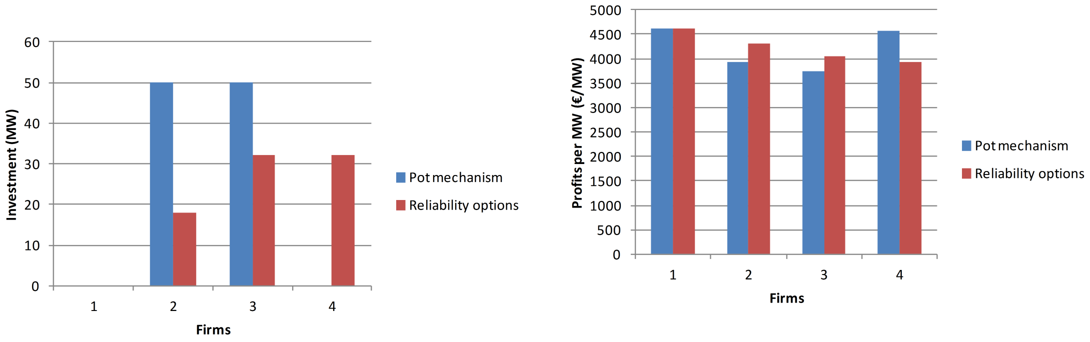


(c) Investment in new capacity by each firm (d) Expected profits per megawatt installed capacity

Figure 6: Results under both capacity payment mechanisms with varying levels of elasticity



(a) Expected electricity prices in each period (b) Expected total generation each period



(c) Investment in new capacity by each firm (d) Expected profits per megawatt installed capacity

Figure 7: Results under both capacity payment mechanisms with refurbishment

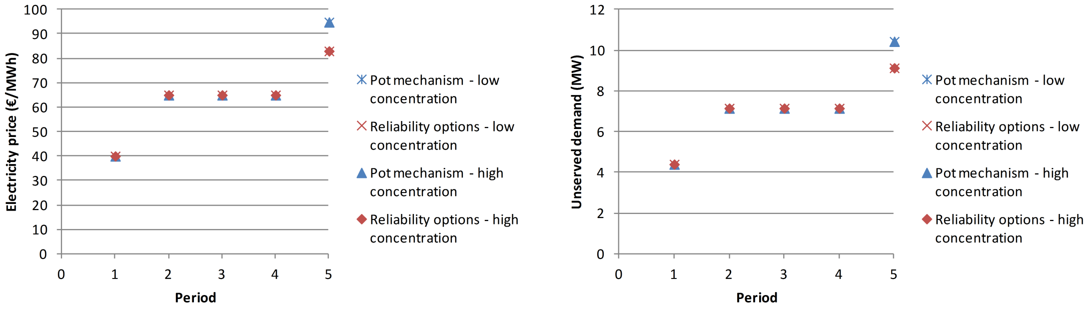
In general it seems that in the absence of refurbishment options, a pot mechanism leads to lower costs to consumers along with a slightly lower level of unserved demand and a more reliable system. Even in the case of overcapacity, no market exit takes place.

4.2 Results with refurbishment

We repeat the analysis including the $refurb$ variable and equations; all other inputs are as per section 4.1.1 above.

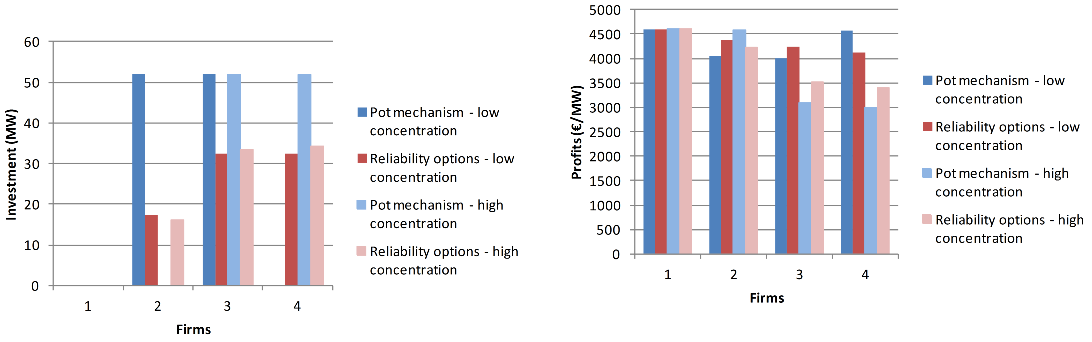
4.2.1 Base case

The results under the base case are shown in figure 7. All firms invest in refurbishment of midmerit and baseload units to the maximum extent possible, bringing their reliability levels to one. Refurbishment does not take place of firm one's existing peaking capacity under the pot mechanism; however firm 4, the firm with investments in peaking capacity, does refurbish its units. Under reliability options, maximum refurbishment takes place. The increased reliability of the units on the system reduces the peak prices seen in period 5, which were being influenced by the capacity investment cost in the previous models without refurbishment. This lowers costs to consumers under the pot mechanism (as consumers were not exposed to the costs under the reliability options mechanism in any



(a) Expected electricity prices in each period

(b) Expected total generation each period



(c) Investment in new capacity by each firm

(d) Expected profits per megawatt installed capacity

Figure 8: Results under both capacity payment mechanisms with refurbishment and varying initial levels of concentration

case) relative to the non-refurbishment model. This decrease in prices in period 5 means that the total costs to the consumer is equal under the two mechanisms, as the capacity price in the reliability options model again clears at the cost of investment in peaking capacity.

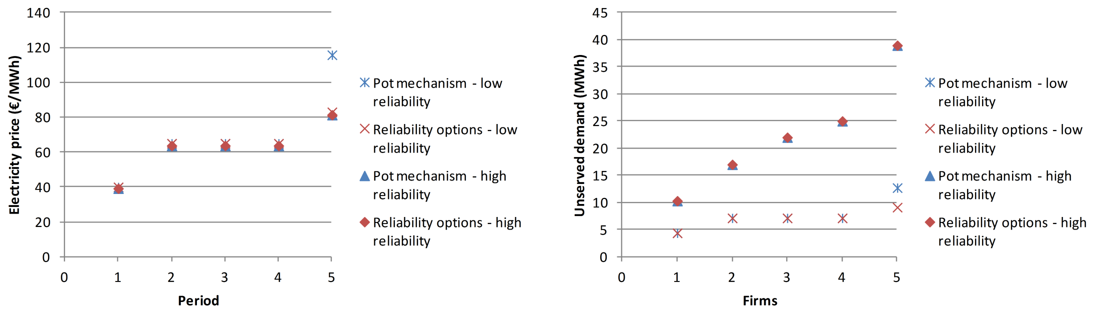
The levels of unserved demand have also fallen, confirming that the forced outage of units was to some degree responsible for unserved demand. Given the refurbishment of all baseload and midmerit units, the unserved demand in periods 1-4 is not due to forced outage, and is instead the firms' optimal level of output given the elasticity of demand.

Investment under each model is now 100MW, as the refurbishment reduced the need for surplus investment to meet demand. The profits for each firm reflect their investment decisions.

4.2.2 Varying market concentration

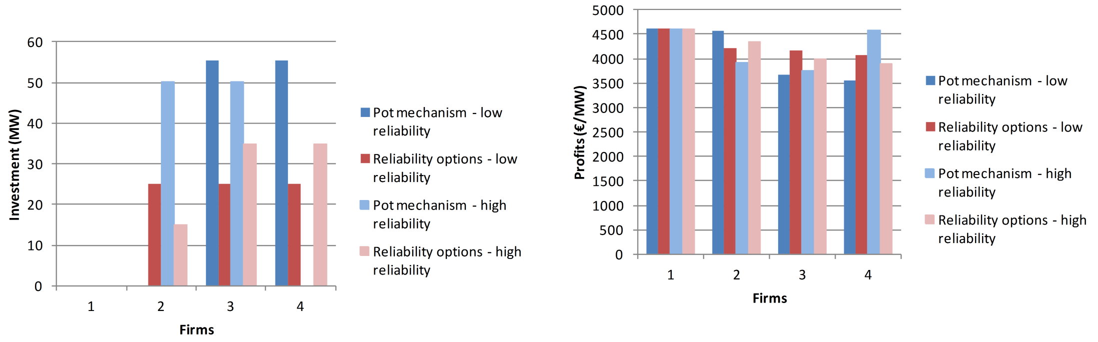
The analysis is repeated with a higher level of concentration in the market, as per section 4.1.2 above. The results are shown in figure 8.

The investments in refurbishment are the same as the base case for baseload and midmerit units. However, in the case of peaking units, firm one does not invest in refur-



(a) Expected electricity prices in each period

(b) Expected total generation each period



(c) Investment in new capacity by each firm

(d) Expected profits per megawatt installed capacity

Figure 9: Results under both capacity payment mechanisms with refurbishment and varying initial levels of reliability

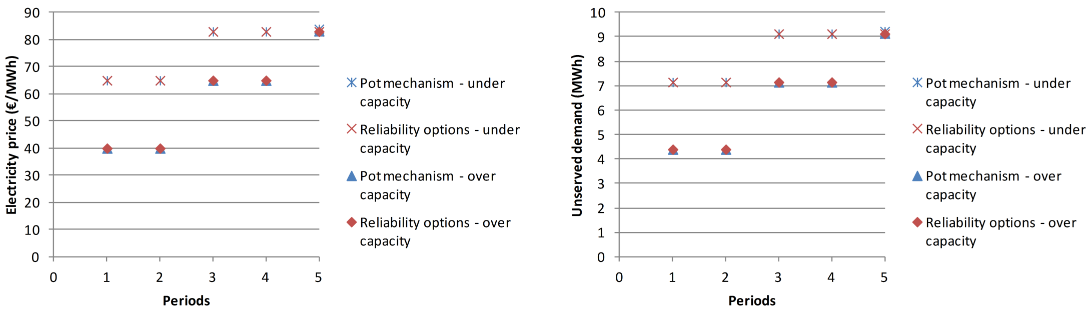
bishment in the low-concentration input set, while firm four does not refurbish its peaking units in the high-concentration input set. The unserved energy is therefore about 1MW higher in period five under the pot mechanism. The energy prices in period five under the pot mechanism are slightly higher for both higher and lower concentration than that seen under the base case. However the total increase in costs to consumers relative to the reliability options scenario, is less than 0.3% (while in the basecase the difference in costs to consumers was 0.06%).

The integrated firm does not invest in new capacity under either sensitivity, and so earns highest profits in both cases. The profits of other firms reflect their investment decisions.

4.2.3 Varying reliability

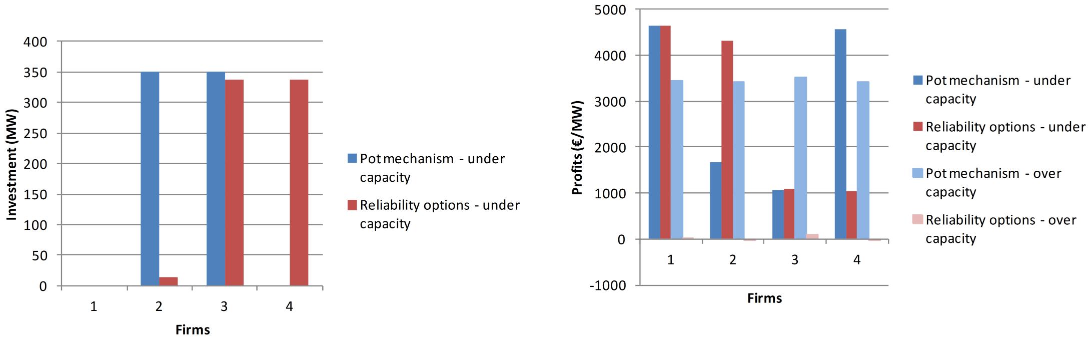
The analysis is repeated with a higher level of initial reliability, as per section 4.1.3 above. The results are shown in figure 9.

Maximum refurbishment once again takes place in all technologies, as in case 4.1.3 above. The prices seen under the pot mechanism are higher than those under the reliability options model for low initial levels of reliability. The increase in costs to consumers is still



(a) Expected electricity prices in each period

(b) Expected total generation each period



(c) Investment in new capacity by each firm

(d) Expected profits per megawatt installed capacity

Figure 10: Results under both capacity payment mechanisms with refurbishment and initial over and undercapacity

low however, less than 0.8% of total costs compared to the reliability options case.

The unserved demand is the same for the pot and the reliability options mechanism under both input sets, although the unserved demand is much higher under the input set with high initial reliability.

There is slightly higher investment under the pot mechanism with low reliability, with 110MW of investment overall. Thus, we again see higher levels of new investment to compensate for low reliability, and this gives rise to the increase in prices in period 5. The reliability options mechanism and the pot mechanism with high reliability see 100MW investment each. The investments under reliability options are spread over firms 2-4 while the investment under the pot mechanism is by firms 2 and 3 only, leading to different investment costs and thus profits.

4.2.4 Varying initial capacity

The analysis is repeated using initial over and undercapacity, as in 4.1.4. The refurbishment decisions are the same as under previous input sets.

Under the reliability options model, market exit takes place according to figure 11, leaving only 1500MW of installed capacity. There is no exit under the pot mechanism.

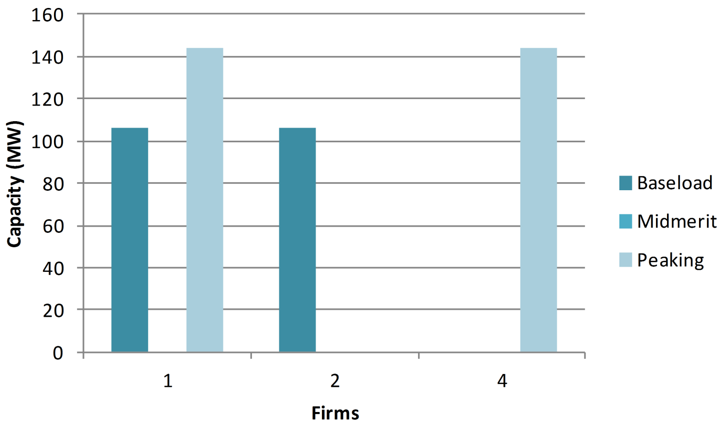


Figure 11: Market exit with initial overcapacity

Under the overcapacity input set, the capacity price in the reliability options model collapses to €7 per MW. For the first time with refurbishment, there is a different final resulting cost to consumers under the two models, with the reliability options model resulting in a 25% decrease in costs to consumers. This also leads to significantly reduced profits for generators with the reliability options model and overcapacity. The price and unserved demand follow the same patterns as observed in previous input sets.

4.2.5 Varying elasticity

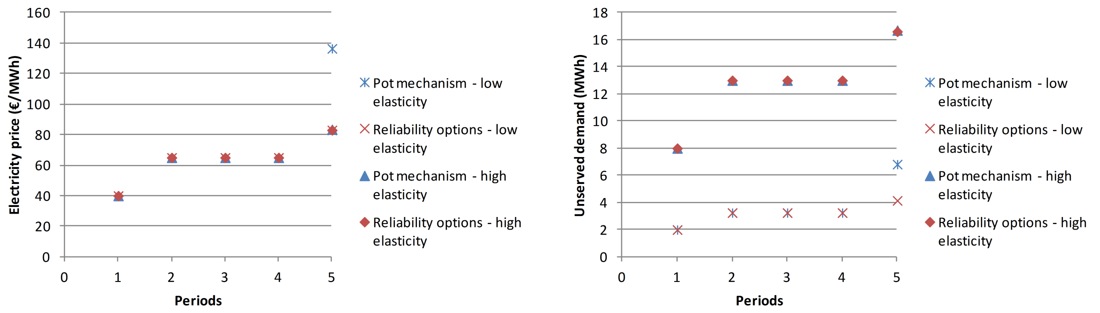
Finally the analysis is repeated for varying levels of elasticity, as per section 4.1.5.

The refurbishment decisions follow the same pattern as before. Under the lower elasticity of demand of 0.05, the probability-weighted price in period 5 increases from €83 per MWh to €136 per MWh under the pot mechanism. Consumers are exposed to this increase in price, and so total consumer payments under the pot mechanism increase by approximately 1% compared to the reliability options mechanism (the cost of the reliability options mechanism again clears at the same cost of the pot). The unserved demand is also slightly higher under this input set.

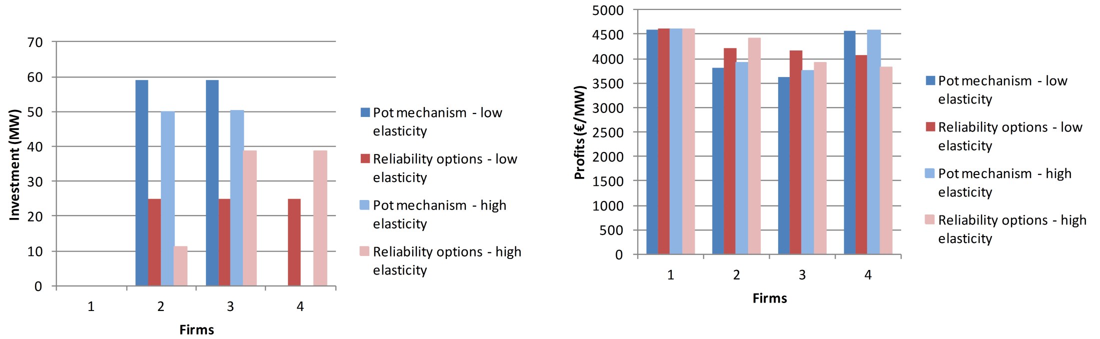
Low elasticity of demand induced higher overall investment under the pot mechanism. As before, reliability options lead to exactly 100MW of investment under both models. The integrated firm again fails to invest, and so sees higher profits than its competitors.

5 Discussion

In the models that omit refurbishment, the higher levels of prices seen in peak periods mean that the pot mechanism imposes a higher cost on consumers relative to the reliability



(a) Expected electricity prices in each period (b) Expected total generation each period



(c) Investment in new capacity by each firm (d) Expected profits per megawatt installed capacity

Figure 12: Results under both capacity payment mechanisms with refurbishment and varying initial levels of elasticity

options mechanism - between 2% and 7%, depending on the input set. This is due to the forced outages of units increasing the price in the peak period, and under the pot mechanism this increase in price is passed on to the consumer. However, the pot mechanism also induces higher levels of investment, and therefore lower levels of unserved energy. Thus it appears that the rebate penalty used here is not sufficient to induce investment in new capacity to ensure security of supply in the case of reliability options, and only the target level of investment occurs. This is in spite of the fact that the strike price is set at the marginal cost of the most expensive unit, while the literature recommends setting the strike price at up to 25% above this level. There may therefore be a case for introducing extra penalties during period of non-delivery in order to encourage refurbishment of units.

In the case of over-capacity, however, market exit does not take place under the reliability options mechanism, and unserved energy declines. Therefore a system with overcapacity will see higher levels of reliability and lower prices. However, the reliability options mechanism clears at a very low price, reducing total costs for consumers by 20%, indicating that if a system has overcapacity a reliability options framework may lower costs.

In summary, when considering the case of nonrefurbishment, there is a tradeoff between higher costs to consumers and higher levels of unserved demand in choosing the capacity payment mechanism.

When refurbishment is included, high levels of refurbishment take place, reducing the need for overinvestment. The total capacity on the system is therefore 1500MW for all scenarios (apart from the case of overcapacity under the pot payment), electricity prices are equal to the marginal costs of production in most periods and the payouts from consumers under reliablity options and the pot mechanism in general are the same.

The two exceptions regarding the costs to consumers are in the case of low elasticity of demand, where prices rise in period five, increasing costs to consumers in the pot case only, and again in the case of overcapacity, where the reliability options payment clears at a low level. In these cases the consumer payment under reliability options is 1% and 25% lower than in the case of the pot mechanism, respectively.

If policy makers place a high premium on having sufficient capacity to meet demand but no more, and if a system has significant overcapacity, reliability options may be the best choice for the system in question. However, the results suggest that, when refurbishment of units is possible, there is no reason as to why overcapacity would occur in the first place as overinvestment does not take place in equilibrium under either mechanism. Overcapacity may arise due to generators earning extra rent from energy markets through some other mechanism which is leading to overcompensation and therefore excess capacity. It is not clear that choosing a capacity payment mechanism to induce exit, correcting for overcompensation in some other market mechanism, would bring about the optimal solution.

It should be noted that the assumed maximum reliability level of 1 may be unrealistic; however the relevant point is to assume that refurbishment can raise the reliability of a unit to that of a new build. The relevant result is that maximum investment in refurbishment takes place, which suggests that there is an incentive for generators to ensure their units are as reliable as possible under both capacity payment mechanisms.

There are several potential extensions for this work. The first is to refine the assumptions surrounding refurbishment costs. Another possibility is to relax the assumption around unlimited competition from new entrants, either by imposing extra costs on new entrants or by employing a repeated game framework which we anticipate would alter the results presented here. Finally a dynamic analysis, wherein we model multiple years, would see the investment decisions change. We anticipate investment in baseload units rather than peaking units would take place, as the extra hours of operation earning higher inframarginal rents would justify their capacity costs. We also anticipate investment by firm one rather than seeing investment restricted to smaller firms.

6 Conclusion

This paper presents a stochastic mixed complementarity model with endogenous probabilities to investigate the impacts of two different capacity payment mechanisms in electricity markets. We compare a capacity payment on the basis of a fixed central pot with a market-based reliability options method. We consider one integrated firm, holding baseload, midmerit and peaking capacity, and three firms specialising in one technology each. Generators are subject to forced outages and can refurbish their units to reduce the probability of same.

We find with no refurbishment decisions allowed, total costs to consumers are lower under a reliability options mechanism. However, both investment and generation are higher under the pot mechanism. When refurbishment is allowed, consumer costs are equal under both mechanisms. The exception is the case of initial levels of overcapacity and low elasticity of demand, where consumer costs are slightly and significantly higher, respectively.

Reliability options may reduce costs to consumers in the case of overcapacity in the short run. However once the target level of capacity is achieved, they are likely to arrive at a similar cost to consumers but with lower levels of generation. The pot mechanism does not induce overinvestment, nor does it induce exit with overcapacity. Therefore the reasons for overcapacity in a given system cannot be attributed to a pot mechanism alone but rather a conflation of factors, of which a pot mechanism may be one. We leave the identification of these factors for further research.

Acknowledgements

Lynch acknowledges funding from the Programme for Research in Third Level Institutions and is co-funded by the European Regional Development Fund (ERDF). Devine is funded under Science Foundation Ireland award 09/SRC/E1780. We are grateful to Seán Lyons and participants at the Mannheim Energy Conference for helpful comments and suggestions. All omissions and errors are our own.

Appendix

6.1 Capacity pot mechanism

The Karush-Kuhn-Tucker optimality conditions for all firms are given below using “perb” notation, where $0 \leq a \perp b \geq 0$ is equivalent to $a \geq 0$, $b \geq 0$ and $a.b = 0$.

$$
\begin{aligned}
0 \leq inv_{f,t} \quad &\perp \quad -cp + ICOST_t - \sum_{p,s} \lambda^1_{f,t,p,s} \geq 0, \ \forall f,t, && (14)\\
0 \leq gen_{f,t,p,s} \quad &\perp \quad -pr_s B_{f,t,s}(\gamma_p - MC_t) + \lambda^1_{f,t,p,s} \geq 0, \ \forall f,t,p,s, && (15)\\
0 \leq exit_{f,t} \quad &\perp \quad cp - MCOST_t + \sum_{p,s} \lambda^1_{f,t,p,s} \geq 0, \ \forall f,t, && (16)\\
0 \leq refurb_{f,t} \quad &\perp \quad -\sum_s \frac{\partial pr_s}{\partial refurb_{f,t}} (B_{f,t,s} gen_{f,t,p,s}(\gamma_{p,s} - MC_t)) + RCOST_t + \lambda^2_{f,t,p,s} \geq 0, \ \forall f,t, && (17)\\
0 \leq \lambda^1_{f,t,p,s} \quad &\perp \quad -gen_{f,t,p,s} + inv_{f,t} + CAP_t - exit_{f,t} \geq 0, \ \forall f,t,p,s, && (18)\\
0 \leq \lambda^2_{f,t} \quad &\perp \quad -R_{f,t} - refurb_{f,t} + \overline{R_{f,t}} \geq 0, \ \forall f,t, && (19)
\end{aligned}
$$

where

$$
\frac{\partial pr_s}{\partial refurb_{f,t}} = (-1)^{1-B_{f,t,s}} \prod_{\substack{\hat{f},\hat{t} \\ \hat{f} \neq f \\ \hat{t} \neq t}} (R_{\hat{f},\hat{t}} + refurb_{\hat{f},\hat{t}})^{B_{\hat{f},\hat{t},s}} (1 - R_{\hat{f},\hat{t}} - refurb_{\hat{f},\hat{t}})^{1-B_{\hat{f},\hat{t},s}}, \quad (20)
$$

where $\hat{f}$ and $\hat{t}$ are dummy indices representing each firm and technology respectively except firm f and technology t. Equations (14)-(19), along with market clearing conditions (5) and (6), represent the full mixed complementarity problem for the capacity pot mechanism problem.

6.2 Reliability options mechanism

The Karush-Kuhn-Tucker optimality conditions for all firms in the reliability options mechanism are

$$0 \leq inv_{f,t} \quad \perp \quad ICOST_t - \sum_{p,s} \lambda^1_{f,t,p,s} - \lambda^3_{f,t} \geq 0, \;\; \forall f, t, \tag{21}$$

$$0 \leq gen_{f,t,p,s} \quad \perp \quad -pr_s B_{f,t,s}(\gamma_p - MC_t) + \lambda^1_{f,t,p,s} \geq 0, \;\; \forall f, t, p, s, \tag{22}$$

$$0 \leq exit_{f,t} \quad \perp \quad -MCOST_t + \sum_{p,s} \lambda^1_{f,t,p,s} + \lambda^3_{f,t} \geq 0, \;\; \forall f, t, \tag{23}$$

$$0 \leq refurb_{f,t} \quad \perp \quad -\sum_s \frac{\partial pr_s}{\partial refurb_{f,t}} (B_{f,t,s} gen_{f,t,p,s}(\gamma_{p,s} - MC_t) - cap\_ro_{f,t} rebate_{p,s}) + RCOST_t + \lambda^2_{f,t,p,s} \geq 0, \;\; \forall f, t, \tag{24}$$

$$0 \leq cap\_ro_{f,t} \quad \perp \quad -cp + \sum_{p,s} pr_s rebate_{p,s} + \lambda^3_{f,t} \geq 0, \;\; \forall f, t, \tag{25}$$

$$0 \leq \lambda^1_{f,t,p,s} \quad \perp \quad -gen_{f,t,p,s} + inv_{f,t} + CAP_{f,t} - exit_{f,t} \geq 0, \;\; \forall f, t, p, s, \tag{26}$$

$$0 \leq \lambda^2_{f,t} \quad \perp \quad -R_{f,t} - refurb_{f,t} + \overline{R_{f,t}} \geq 0, \;\; \forall f, t, \tag{27}$$

$$0 \leq \lambda^3_{f,t} \quad \perp \quad -cap\_ro_{f,t} + inv_{f,t} + CAP_{f,t} - exit_{f,t} \geq 0, \;\; \forall f, t. \tag{28}$$

Equations (21)-(28), along with market clearing conditions (11) - (13), represent the full mixed complementarity problem for the reliability options mechanism problem.

References

Abbott, M. (2001). Is the security of electricity supply a public good? *The Electricity Journal*, 14(7):31–33.

ACER (2013). Capacity remuneration mechanisms and the internal market for electricity. Available online: `http://www.acer.europa.eu/Official_documents/Acts_of_the_Agency/Publication/CRMs%20and%20the%20IEM%20Report%20130730.pdf`.

Botterud, A. and Doorman, G. (2008). Generation investment and capacity adequacy in electricity markets. *International Association for Energy Economics Energy Forum second quarter 2008*. Available online: `http://www.iaee.org/documents/newsletterarticles/208Botterud.pdf?origin=publication_detail`.

Caldecott, B. and McDaniels, J. (2014). Stranded generation assets: Implications for european capacity mechanisms, energy markets and climate policy. Technical report, Working Paper. Smith School of Enterprise and the Environment, University of Oxford (Oxford, UK).

CER and NIAUR (2013). Round 5 (r5) sem plexos forecast model 2013-14. Available online: `http://www.allislandproject.org/en/market_decision_documents.aspx?article=a440f19a-dc21-4d5b-82f1-743c7d082bd6`.

CER and NIAUR (2006). Decision documents relating to the Single Electricity Market capacity payment mechanism. Available online: `http://www.allislandproject.org/en/capacity-payments-decision.aspx`.

Cramton, P. and Ockenfels, A. (2012). Economics and design of capacity markets for the power sector. *Zeitschrift für Energiewirtschaft*, 36(2):113–134.

Cramton, P. and Stoft, S. (2005). A capacity market that makes sense. *The Electricity Journal*, 18(7):43–54.

Cramton, P. and Stoft, S. (2008). Forward reliability markets: Less risk, less market power, more efficiency. *Utilities Policy*, 16(3):194–201.

CREG (2012). Study on capacity remuneration mechanisms. Available online: `http://www.creg.info/pdf/Etudes/F1182EN.pdf`.

De Vries, L. J. (2007). Generation adequacy: Helping the market do its job. *Utilities Policy*, 15(1):20–35.

Di Cosmo, V. and Hyland, M. (2013). Carbon tax scenarios and their effects on the irish energy sector. *Energy Policy*, 59:404–414.

European Commission (2013). Delivering the internal electricity market and making the most of public intervention. Available online: `https://ec.europa.eu/energy/sites/ener/files/documents/com_2013_public_intervention_en.pdf`.

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

Grigorjeva, J. (2015). Capacity mechanisms in the EU: Nationalizing energy security? Available online: `http://www.delorsinstitute.eu/011-21313-Capacity-mechanisms-in-the-EU-nationalizing-energy-security.html`.

Hirth, L. (2013). The market value of variable renewables: The effect of solar wind power variability on their relative price. *Energy economics*, 38:218–236.

Hobbs, B. F., Hu, M.-C., Iñón, J. G., Stoft, S. E., and Bhavaraju, M. P. (2007). A dynamic analysis of a demand curve-based capacity market proposal: the pjm reliability pricing model. *Power Systems, IEEE Transactions on*, 22(1):3–14.

Khalfallah, H. (2011). A game theoretic model for generation capacity adequacy: Comparison between investment incentive mechanisms in electricity markets. *Energy Journal*, 32(4):117–157.

Meyer, R. and Gore, O. (2014). Cross-border effects of capacity mechanisms: Do uncoordinated market design policies countervail the goals of european market integration? Technical report, Bremen Energy Working Papers.

Shortt, A., Kiviluoma, J., and O'Malley, M. (2013). Accommodating variability in generation planning. *Power Systems, IEEE Transactions on*, 28(1):158–169.

Stoft, S. (2002). *Power system economics.* IEEE Press & Wiley-InterScience.

Troy, N., Denny, E., and O'Malley, M. (2010). Base-load cycling on a system with significant wind penetration. *Power Systems, IEEE Transactions on*, 25(2):1088–1097.

Vázquez, C., Rivier, M., and Pérez-Arriaga, I. J. (2002). A market approach to long-term security of supply. *Power Systems, IEEE Transactions on*, 17(2):349–357.

Walsh, D. and Malaguzzi Valeri, L. (2014). Gaming in the irish single electricity market and potential effects on wholesale prices. *ESRI working paper No. 488.* Available online: `http://www.esri.ie/UserFiles/publications/WP488/WP488.pdf`.

Year	Number	Title/Author(s) ESRI Authors/Co-authors *Italicised*
2015		
	506	Returns to Education and the Demand for Labour in Vietnam *Seamus McGuinness, Elish Kelly, Pham Thi Thu Phuong , Ha Thi Thu Thuyd*
	505	Analysing Residential Energy Demand: An Error Correction Demand System Approach for Ireland *John Curtis and Brian Stanley*
	504	Restructuring European Electricity Markets – A Panel Data Analysis *Marie Hyland*
	503	Assessing the Sustainable Nature of Housing - Related Taxation Receipts: The Case of Ireland Diarmaid Addison-Smyth and *Kieran McQuinn*
	502	Perceived Group Discrimination among Polish Migrants to Western Europe: Comparing Germany, the Netherlands, the UK and Ireland *Frances McGinnity* and Merove Gijsberts
	501	Europe's Long-Term Growth Prospects: With and Without Structural Reforms *Kieran McQuinn and* Karl Whelan
	500	Macroprudential Policy in a Recovering Market: Too Much too Soon? *David Duffy, Niall Mc Inerney and Kieran McQuinn*
	499	The Great Recession, Austerity and Inequality: Evidence from Ireland *Michael Savage, Tim Callan,* Brian Nolan *and Brian Colgan*
	498	Investment Efficiency, State-Owned Enterprises and Privatisation: Evidence from Vietnam in Transition *Conor M. O'Toole, Edgar Morgenroth* and Ha Thi Thu Thuy
	497	Competition and the Single Electricity Market: Which Lessons for Ireland? *Valeria Di Cosmo and Muireann Á. Lynch*
	496	Modelling the Impact of Direct and Indirect Taxes Using Complementary Datasets *Michael Savage and Tim Callan*
	495	The Role of Credit in the Housing Market Petra Gerlach-Kristen and *Niall Mc Inerney*

For earlier *Working Papers* see http://www.esri.ie/publications/latest_working_papers/