Working Paper No. 518

November 2015

A Menu Approach to Revealing Generator Reliability Using a Stochastic Bilevel Mathematical Program

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Subsequently published in "Inducing truthful revelation of generator reliability", *Energy Economics,* Volume 64, May 2017, Pages 186–195, https://doi.org/10.1016/j.eneco.2017.03.017

Abstract: Liberalised electricity markets often include a capacity remuneration mechanism to allow generation firms recover their fixed costs. Various de-rating factors and/or penalties have been incorporated into such mechanisms in order to award the unit based on the contribution they make to system security, which in turn depends on the unit's reliability. However, this reliability is known to the firm but not to the regulator. We propose an adaptation of menu regulation to design capacity payments based on a declaration by the firm of their reliability. We scale payments and penalties according to this declared reliability such that the firm's profit-maximising strategy is to truthfully reveal their reliability. We apply the methodology to an illustrative test system. Truth-telling is induced, increasing the efficiency of capacity payments while eliminating the requirement for the regulator to allocate resources to discovering reliability.

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Acknowledgements:Devine acknowledges the ESRI Energy Policy Research Centre and Science Foundation Ireland award 09/SRC/E1780. Lynch acknowledges funding from the Programme for Research in Third Level Institutions and is co-funded by the European Regional Development Fund (ERDF). We are grateful to Peter Wibberley of YellowWood Energy for inspiring this project and to Seán Lyons for helpful comments and suggestions. All omissions and errors are our own.

1 Introduction

Electricity markets have undergone a process of liberalisation in recent years. The absence of an active demand-side in electricity generation markets, along with the shared nature of the network, means 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 compensating generators for providing capacity, over and above the energy they provide, the market mechanism must differentiate between the rated capacity of the unit and the capacity they can be expected to reliably provide. No generation unit is completely reliable, in that there is always a non-zero probability that the unit will be on either scheduled or forced outage when required. In the case of variable renewable generators, such as wind or photovoltaic generators, their availability is obviously weather-dependent, as well as being subject to forced or scheduled outage for maintenance. An efficient capacity payment mechanism will take this inherent unreliability into account.

Several capacity remuneration mechanisms include different ways of 'de-rating' the unit's capacity to account for unreliability. For example, the Electricity Market Reforms (EMR) in Great Britain have included a new capacity market incorporating a de-rating factor. The de-rating factor of thermal generators is determined for each technology, based on their historic availability during the last seven winters (National Grid, 2015b). In the electricity market of Pennysylvania-New Jersey-Maryland (PJM) conventional generators are de-rated according to their forced outage rates, while wind is de-rated to 13% of its installed capacity and solar generation is de-rated to 38% of installed capacity (Bowring et al., 2013). The Single Electricity Market (SEM) of the island of Ireland is currently undergoing a redesign, including a new capacity remuneration mechanism. The regulators envisage that a capacity offered in the capacity market shall be de-rated, and explicitly state that the method of de-rating capacity should be "...reflective of its [the unit's] ability to deliver capacity at times of system stress." (CER and NIAUR, 2015).

These examples are not exhaustive and do not cover all possible capacity mechanisms or de-rating methodologies. However, the principle that installed capacity should be de-rated when considering appropriate revenues from capacity remuneration mechanisms has been established in general. The methods currently used in, for example, Great Britain and PJM to determine the de-rating can be viewed as somewhat *ad hoc*. They are based on historical data, which may have been determined partly as a result of strategic withholding of capacity by firms. They are calculated on a technology-basis, rather than on the basis of the individual units and/or the firms that own them. For this reason, a firm that owns a unit with higher reliability than the average unit of that particular technology (i.e. a lower than average forced outage rate) has a diminished incentive to ensure the continuing reliability of that unit, while a firm with a unit of less than average reliability (i.e. a higher than average forced outage rate) has a diminished incentive to refurbish their unit and improve its forced outage rate. Finally the interaction between units is not taken into account (*ex ante*, at least).

The issue of the appropriate de-rating factor to apply can be viewed as a problem of imperfect information. The firm possesses the best information regarding the reliability of their particular unit. Instead of estimating de-rating factors for entire technologies, the regulator may instead wish to induce the firm to reveal their (best estimate of their) true reliability. Simply scaling capacity payments according to a firm's declared reliability will not induce firms to be truthful, as they will declare the highest possible reliability and claim the highest possible capacity payment. However, if the energy market includes a penalty that generators must pay for those periods when they are unavailable for generation, it is possible to scale both the capacity payment and the penalty by the firm's declared level of reliability. If these payment and penalty factors are well-chosen, the firm's profit-maximising strategy will be that of truthful declaration of their reliability.

The challenges arising from informational asymmetries are a feature of many regulated industries. One proposed solution is that of menu regulation, whereby firms are presented with a choice of regulatory contracts. The firm picks the contract that will maximise their expected revenue, and in so doing reveals information about their cost structures to the regulatory body (see Laffont and Tirole (1993) for a more detailed discussion). In the case of the electricity sector, Cossent and Gómez (2013) propose menu regulation for electricity distribution networks, while Ajodhia and Hakvoort (2005) and Léautier (2000) consider other examples of regulatory incentives for electricity network expansion. Menu regulation is currently employed by various regulators including in the UK for sectors such as water, gas and electricity distribution (Oxera, 2007). To the best of our knowledge, however, menu regulation has not been applied to the case of electricity generation capacity as a means of determining the reliability of same.

In this paper, we propose a methodology for determining the scaling and penalty formulas that will induce truth-telling by generation firms. The methodology draws on menu regulation and is a means by which a regulator can construct an appropriate menu which will, in turn, induce truth-telling. We do not address the related question of the optimal level of reliability for the system, or how to incentivise generators to provide this optimal level. Rather we concentrate instead on addressing the informational asymmetry between the regulator/market operator and the firms regarding the reliability of each unit, and therefore the appropriate level of capacity compensation for each firm. We apply the methodology to a stylised test system based on the SEM of Ireland, but the method is readily applicable to any system. We demonstrate that the profit-maximising strategy of firms is indeed to declare their best estimate of their true reliability, relieving the regulator of any responsibility in this regard. We also examine the impact of refurbishment of existing units, allowing firms to improve the reliability of their generation portfolio, as well as investing in new generation or retiring old units.

We model the problem as a stochastic mathematical programme with equilibrium constraints. The stochasticity arises from the inherent unreliability of the units, each of which has a probability of being unavailable (i.e. on forced outage) during any given period. Given that refurbishing a unit will render a unit less likely to be on forced outage, the probabilities of the scenarios in the stochastic problem are endogenous to the problem itself (in the case where refurbishment is permitted).

2 Methodology

We formulate the problem as a bi-level game with n generation firms and a regulator. The regulator, the Stackelberg leader, firstly chooses the policy that induces truth telling knowing how the generation firms (followers) will react, i.e., the regulator chooses the policy that minimises the distance between the declared and actual reliabilities subject to the optimality conditions of the generators. The firms' objectives is to maximise expected profits, which they earn in both energy and capacity markets. The capacity mechanism is a price-based mechanism, whereby a fixed sum of money to remunerate generators for capacity provision is determined administratively. We propose that sum be divided among generators on the basis of their declared reliability as well as their installed capacities. In order to induce truth-telling by the generators, the capacity payment mechanism must be a function both of the reliability declared by the generator, and of the actual level of reliability. We therefore include a penalty term whereby the generator is penalised for periods of unavailability. This is a standard feature of many capacity payment mechanisms, including the new mechanism in Great Britain. The generators' capacity payments are given by an exponential function and include a linear penalty function. The firms are assumed to have the best knowledge of their units' reliability and so the capacity pot is divided on the basis of a declaration of reliability made by each firm.

The regulator's objective function is to minimise the deviation of declared reliability from actual reliability by choosing the penalty for being offline, subject to the firms' expected profits being maximised.

2.1 Firm f's problem (lower level problem)

Generator f wishes to maximise the revenue they receive from the capacity and energy markets less the cost of investment, refurbishment and maintenance as well as the penalty they must pay in scenarios where their units are offline. Their problem is as follows:

$$\begin{aligned}
\max_{\substack{inv_{f,t},\\ gen_{f,t,p},\\ \hat{R}_{f,t},\\ refurb_{f,t}}} \Pi_f = \max_{\substack{inv_{f,t},\\ gen_{f,t,p},\\ \hat{R}_{f,t},\\ refurb_{f,t}}} & \sum_t (inv_{f,t} + CAP_{f,t} - exit_{f,t})\big(\alpha(1 - e^{-\hat{R}_{f,t}})\big) \\
& - (inv_{f,t} ICOST_t) \\
& - refurb_{f,t} RCOST_t (CAP_{f,t} - exit_{f,t}) \\
& - (CAP_{f,t} - exit_{f,t}) MCOST_t \\
& - \sum_s \Big(pr_s (1 - B_{f,t,s})(inv_{f,t} + CAP_{f,t} - exit_{f,t}) \tau_t \hat{R_{f,t}} \Big) \\
& + \sum_{p,s} \Big(pr_s B_{f,t,s} gen_{f,t,p,s} (\gamma_p - MC_{f,t}) \Big)
\end{aligned} \tag{1}$$

subject to:

$$\begin{aligned} gen_{f,t,p,s} &\leq inv_{f,t} + CAP_{f,t} - exit_{f,t}, \ \forall t,p,s \ (\lambda^1_{f,t,p,s}), &(2)\\ \hat{R}_{f,t} &\leq \overline{R_{f,t}} \ \forall \ t \ (\lambda^2_{f,t}) &(3)\\ R_{f,t} + refurb_{f,t} &\leq \overline{R_{f,t}} \ \forall \ t \ (\lambda^3_{f,t}) &(4)\end{aligned}$$

where t represents different energy technologies and p represents different time periods. The decision variables for firm f are $\hat{R}_{f,t}$, $inv_{f,t}$, $exit_{f,t}$, $gen_{f,t,p,s}$ and $refurb_{f,t}$ representing declared reliability, market investment, market exit, generation and refurbishment decisions respectively. Each scenario s represents a different combination of units being on/offline. The energy price at each period for scenario s is $(\gamma_{p,s})$ while α is the capacity price paid for each unit of installed capacity. The prices $\gamma_{p,s}$ and α are exogenous to firm f's problem but are variables of the overall lower level problem. The parameters $RCOST_t$, $ICOST_{f,t}$, $MCOST_t$ are the firm's costs of refurbishment, investment in new generation and the maintenance cost of existing generation[1] for each technology respectively while $CAP_{f,t}$ and $MC_{f,t}$ 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 online ($B_{f,t,s} = 1$) or offline ($B_{f,t,s} = 0$) in scenario s. The reliability (or probability of being online) for firm f with technology t is $R_{f,t} + refurb_{f,t}$ where $R_{f,t}$ is a parameter representing initial reliability before refurbishment. Hence the probability associated with scenario s is:

$$pr_s = \prod_{f,t} (R_{f,t} + refurb_{f,t})^{B_{f,t,s}} (1 - R_{f,t} - refurb_{f,t})^{1-B_{f,t,s}}. \quad (5)$$

Constraint (2) ensures that generation for a given unit and time period cannot exceed the amount of installed capacity while constraints (3) and (4) provide upper bounds for the declared and actual reliability of each unit. The variables in brackets alongside constraints (2) - (4) are the Lagrange multipliers associated with those constraints. All primal (decision) variables of this problem are also constrained to be non-negative.

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

2.1.1 Market clearing conditions

The Market Clearing Conditions that combine each of the firms' problems are

$$\sum_{f,t} B_{f,t,s} * gen_{f,t,p,s} = DEMAND_p + ELAS\gamma_{p,s}, \;\; \forall p, s(\gamma_{p,s}), \tag{6}$$

$$POT = \alpha\Big(\sum_{f,t}(1 - e^{-\hat{R}_{f,t}})(inv_{f,t} + CAP_{f,t} - exit_{f,t})\Big), \quad (\alpha), \tag{7}$$

where $DEMAND_p$ is the demand intercept for period p and $ELAS$ is a parameter representing the elasticity of demand. Equation (6) specifies that total generation in each period p and scenario s must match demand, while equation (7) 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 α are the free Lagrange multipliers associated with these constraints.

The lower level problem is given by the KKT equations for each firm, along with the market clearing conditions (6) and (7).

2.2 Regulator's problem (Upper level problem)

In addition to the generation firms, there is a regulator, whose actions determine the parameters of the capacity payment mechanism. The regulator's objective is to minimise the deviation of declared reliability from actual reliability. In order to do so the regulator chooses the penalty (τ_t) for each technology, which is imposed on the firms in each period that their technology is offline. The regulator's objective function is

$$\min_{\tau_t} = \min_{\tau_t} \sum_{f,t} (\hat{R}_{f,t} - R_{f,t} - refurb_{f,t})^2 \; \forall \; f, t, \tag{8}$$

subject to the KKT conditions of the generators plus the market clearing conditions, i.e., subject to the firms' profits being maximised. Note that in order for the regulator to solve their problem, we assume prior knowledge of the firms' true levels of reliability, which we in fact require the firms to provide. However, the regulator could in practice solve this problem for a full set of reliability inputs within a realistic range, for example between 0.5 and 1. The values of τ_t obtained from this optimisation ensure that the best response of a firm whose reliability takes any of these values will be to declare their true value of reliability. The regulator can thus solve the problem without prior knowledge of the firms' levels of reliability. The full model takes the form of a Mathematical Program with Equilibrium Constraints (MPEC).

3 Input data

To illustrate the methodology, we solve the model for a simplified market with three generation technologies, five time periods and four generation firms. We construct the case study as a stylised example not intended to replicate any particular market, and use generic or internationally-applicable data when possible. In the case of the reliability of the units and the elasticity of demand, we use data from the Irish electricity market, as it was publicly available, and in the case of elasticity, is in line with international estimates. Using alternative reliability/de-rating data from Great Britain (National Grid, 2015a) produces similar results. The five time periods represent summer low demand, summer high demand, winter low demand, winter high demand and winter peak demand. Inter-temporal constraints are not considered and so the sequence of the demand periods is not relevant; for simplicity we show the demand in each period in ascending order:

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

Table 1: Demand level 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 assume that the investment and maintenance costs are 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 significantly affect the final results. The cost characteristics are given in table 2.

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.

The total generation capacity is 1400MW, which falls 100MW short of peak demand in

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

Table 2: Generation cost characteristics

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

Table 3: Initial capacities of each firm (MW)

period 5. Thus 100MW of investment will be required.

The initial levels of reliability 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). These initial levels are given in table 4. Midmerit units have slightly lower levels of reliability than baseload units as they are cycled more frequently (Troy et al., 2010), adding 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 lower wear and tear and higher reliability.

	Baseload	Midmerit	Peaking
Reliability	0.965	0.955	0.985

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

The cost of refurbishment is a continuous variable assumed to be the same as 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. This assumption is sufficient for our illustrative model but can of course be updated with information relevant to the system in question should this methodology be employed by a regulator. 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 for the wholesale electricity market of −0.11.

4 Results

4.1 Without refurbishment

In this subsection we solve the model without the variable $refurb_{f,t}$, i.e., refurbishment of units is not included. The declared reliability for each technology and firm are given in table 5 while the costs, total profits and investment are shown in table 6 (note: any investment that takes place is in peaking capacity).

	Firm 1	Firm 2	Firm 3	Firm 4
Baseload	0.965	0.965		
Midmerit	0.955		0.955	
Peak	0.985			0.985

Table 5: Declared reliability for each technology and firm without refurbishment.

	Firm 1	Firm 2	Firm 3	Firm 4	Total
Profit (€)	1356000	565000	398000	397000	2716000
Cost (€)	1883000	1260000	1060000	523000	4726000
Investment (MW)	0	95	110	0	215

Table 6: Profits, costs and investment for each technology and firm without refurbishment.

	τ_t
Baseload	75014
Midmerit	58930
Peak	171567

Table 7: Penalty for being offline for each technology.

The firms were induced to reveal their true reliability for each technology. This led to a very low value for the regulator's objective solution ($< 10^{-6}$), which suggests that the solution is a global optimum as the regulator's objective function cannot be negative. The total investment across all firms was higher than the 100MW shortfall seen on the system; however given the imperfect reliability of the existing units a margin of excess capacity is optimal. No firms retired generation units.

Table 7 displays the penalty (τ_t) for each technology. These figures show that the optimal values for τ_t are larger for higher values of initial relabilities. In fact, assuming the initial reliability is neither zero nor one, the value for τ_t^* that ensures declared and actual reliability are the same is:

$$\tau_t^* = \frac{\alpha e^{-R_{f,t}}}{1 - R_{f,t}}. \tag{9}$$

This relationship was obtained using optimality condition (13). Figure 1 displays the relationship[2] and shows that for units with low reliability, a relatively small penalty is needed in order to incentivise truth-telling. For units with high reliability, much larger penalties are needed in order to ensure firms declare their actual reliability. This is because these units are much less likely to be offline and without a large penalty they would only be encouraged to overestimate their reliability in order to increase the proportion of the pot they receive.

4.2 With refurbishment

In this subsection we solve the model with the variable $refurb_{f,t}$, i.e., refurbishment of units is included. The declared reliability for each technology and firm are given in table 8 while the costs, total profits and investment are shown in table 9 (investment again takes place in peaking capacity only).

	Firm 1	Firm 2	Firm 3	Firm 4	Total
Profit (€)	3171000	1343000	919000	909000	6342000
Cost (€)	295000	370000	361000	32000	1058000
Investment (MW)	0	44	56	0	100

Table 8: Profits, costs and investment for each technology and firm with refurbishment.

	Firm 1	Firm 2	Firm 3	Firm 4
Baseload	1	1		
Midmerit	1		1	
Peak	1	1	1	1

Table 9: Delared reliability for each technology and firm with refurbishment.

[2]For Figure 1, $\alpha = 6891.39$ which was the optimal value obtained for the results shown in Table 6.

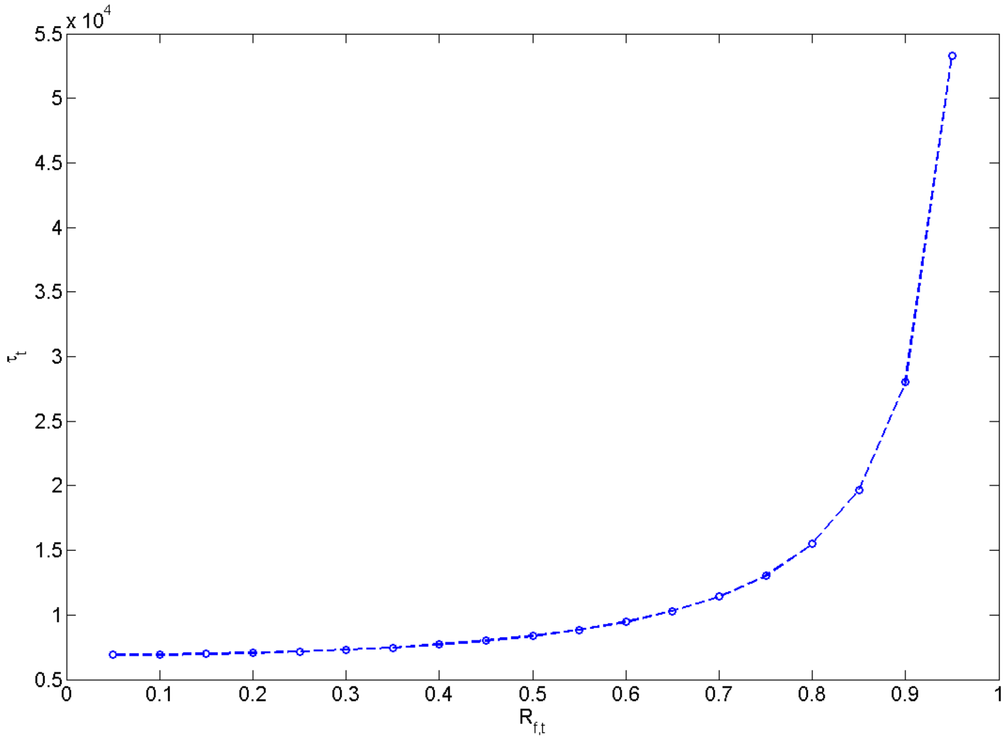

Figure 1: Values for the penalty (τ_t^*) that ensures declared and actual reliability are the same for varying levels of initial reliability.

When refurbishment is allowed, firms take full advantage, as shown in table 10.

	Firm 1	Firm 2	Firm 3	Firm 4
Baseload	0.035	0.035		
Midmerit	0.045		0.045	
Peak	0.015			0.015

Table 10: Refurbishment for each technology and firm.

Truth-telling is again induced, with a similarly low level for the regulator's objective solution ($< 10^{-6}$). This again suggests that this model arrived at a global optimum. The firms invest to the maximum extent possible in refurbishment to make their units as reliable as possible, and the market-clearing level of investment sees a corresponding drop relative to the case with no refurbishment. All firms earn higher profits when refurbishment is allowed. This is due to the decrease in penalty payments incurred by the firms due to their increased reliability, which outweighs the refurbishment costs incurred.

5 Discussion and conclusions

This paper used stochastic mathematical programming with equilibrium constraints and endogenous probabilities to demonstrate that it is possible to induce electricity generation firms to truthfully declare the reliability of their units. This removes the need for the regulator to dedicate resources to calculating appropriate de-rating factors for capacity markets, and optimises the scaling of capacity payments at the level of the individual firm, rather than at technology-level. The results above show that for this simplified stylised system, it is possible to induce firms to declare their best estimate of their true reliability by choosing an appropriate method of scaling both capacity payments and penalties for non-delivery.

One obvious drawback that may occur to the reader is that our method assumes the regulator has prior knowledge of the reliability of the units, and uses this knowledge in determining the optimal levels of α and τ_t. However, this difficulty may be overcome by the regulator solving the model for many different levels of reliability, and thereby obtaining values for α and τ_t that will induce truth-telling for all initial levels of reliability. Given these values, the generators' profit-maximising strategies are those of truth-telling, regardless of their actual reliability. Sensitivity testing performed on this model yielded an objective function very close to zero for any set of initial reliabilities, inducing truth-telling for any initial levels of reliability chosen.

Further work will consider the impact of multiple time scales, which may induce investment in generation units other than peaking plants. A more sophisticated treatment of renewable generation may also be required if this method of declaration of reliability for wind and solar generation is to be included.

Acknowledgements

Devine acknowledges the ESRI Energy Policy Research Center and Science Foundation Ireland award 09/SRC/E1780. Lynch acknowledges funding from the Programme for Research in Third Level Institutions and is co-funded by the European Regional Development Fund (ERDF). We are grateful to Peter Wibberley of YellowWood Energy for inspiring this project and to Seán Lyons for helpful comments and suggestions. All omissions and errors are our own.

Appendix

5.1 KKT conditions for lower level problem

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 $a.b = 0$.

$$0 \leq inv_{f,t} \perp -\alpha(1 - e^{-\hat{R}_{f,t}}) + ICOST_t + \sum_s pr_s(1 - B_{f,t,s})\tau_t \hat{R_{f,t}} - \sum_{p,s} \lambda^1_{f,t,p,s} \geq 0, \ \forall f, t, \tag{10}$$

$$0 \leq gen_{f,t,p,s} \perp -pr_s B_{f,t,s}(\gamma_p - MC_t) + \lambda^1_{f,t,p,s} \geq 0, \ \forall f, t, p, s, \tag{11}$$

$$0 \leq exit_{f,t} \perp \alpha(1 - e^{-\hat{R}_{f,t}}) - MCOST_t - refurb_{f,t}RCOST_t - \sum_s pr_s(1 - B_{f,t,s})\tau_t \hat{R_{f,t}} + \sum_{p,s} \lambda^1_{f,t,p,s} \geq 0, \ \forall f, t, \tag{12}$$

$$\begin{aligned} 0 \leq \hat{R_{f,t}} \perp & -(inv_{f,t} + CAP_{f,t} - exit_{f,t})\alpha e^{-\hat{R}_{f,t}} + \\ & \sum_s (pr_s(1 - B_{f,t,s})(inv_{f,t} + CAP_{f,t} - exit_{f,t})\tau_t) + \lambda^2_{f,t} \geq 0, \ \forall f, t, \end{aligned} \tag{13}$$

$$\begin{aligned} 0 \leq refurb_{f,t} \perp & RCOST_t(CAP_{f,t} - exit_{f,t}) + \lambda^3_{f,t} + \\ & \sum_s \frac{\partial pr_s}{\partial refurb_{f,t}} \Big((1 - B_{f,t,s})(inv_{f,t} + CAP_{f,t} - exit_{f,t})\tau_t \hat{R_{f,t}} - B_{f,t,s} gen_{f,t,p,s}(\gamma_{p,s} - MC_t) \Big) \geq 0, \ \forall f, t, \end{aligned} \tag{14}$$

$$0 \leq \lambda^1_{f,t,p,s} \perp -gen_{f,t,p,s} + inv_{f,t} + CAP_t - exit_{f,t} \geq 0, \ \forall f, t, p, s, \tag{15}$$

$$0 \leq \lambda^2_{f,t} \perp -\hat{R_{f,t}} + \overline{R_{f,t}} \geq 0, \ \forall f, t, \tag{16}$$

$$0 \leq \lambda^3_{f,t} \perp -R_{f,t} - refurb_{f,t} + \overline{R_{f,t}} \geq 0, \ \forall f, t, \tag{17}$$

where

$$\frac{\partial pr_s}{\partial refurb_{f,t}} = (-1)^{1-B_{f,t,s}} \prod_{\substack{\hat{f},\hat{t} \\ \hat{f} \neq f \\ \hat{t} \neq t}} (R_{\hat{f},\hat{t}} + refurb_{\hat{f},\hat{t}})^{B_{\hat{f},\hat{t},s}} (1 - R_{\hat{f},\hat{t}} - refurb_{\hat{f},\hat{t}})^{1-B_{\hat{f},\hat{t},s}}, \tag{18}$$

where $\hat{f}$ and $\hat{t}$ are dummy indices representing each firm and technology respectively except firm f and technology t. Equations (10)-(17), along with market clearing conditions (6) and (7), represent the full mixed complementarity problem for the lower level problem.

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