Modelling the Investment and Innovation Decision of a Grid Operator

Francisca Bremberger [*]   Dénes Kucsera [†]

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Abstract

After deregulation, the European Energy market necessitates adequate regulatory frameworks to achieve allocative and dynamic efficiency. Especially innovative investments will gain importance in the light of future challenges faced by electricity grids. In this paper we develop a model that enables us to analyse the effect of different regulatory regimes on investment and innovation decisions separately. We find that the regulatory lag in cost–based regulation may lead to inefficient investment strategies. Under incentive regulation the innovation incentives are likely to be outweighed by the cost risk of innovation leading to lower investment in risky process innovations. Mixture regulation as suggested by Bauknecht (2010) could potentially solve both problems, where firms would not bear the entire cost risk of innovations and they would partially profit from subsequent efficiency improvements.

Keywords: Regulation, Investments, Price Cap vs Cost–Plus, Dynamic Optimisation

JEL classification: C 61, G 11, G 18, L 51

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[*]Institute for Regulatory Economics, **WU** Vienna University of Economics and Business, E-mail: francisca.bremberger@wu.ac.at, postal address: Heiligenstaedter Strasse 46-48, A - 1190 Vienna.

[†]Institute for Regulatory Economics, **WU** Vienna University of Economics and Business, E-mail: denes.kucsera@wu.ac.at, postal address: Heiligenstaedter Strasse 46-48, A - 1190 Vienna.

1 Introduction

The European Energy market has undergone substantial changes since Directive 96/92/EC, which was the first movement towards an integrated liberalised European energy market. Privatisation and liberalisation triggered basic developments. With respect to the legal entity of enterprises engaging in the electricity sector, various unbundling activities were undertaken in order to split the competitive sectors of electricity production and retail from the natural monopoly of grid operation. According to the latest directive (Directive 2009/72/EC) member states can choose between three possible unbundling models: ownership unbundling, an independent system operator or an independent transmission operator.

Beside unbundling, setting appropriate grid tariffs is the main task for regulators in energy markets (Brunekreeft and Bauknecht (2009)). Adequate regulatory frameworks are essential to achieve allocative and dynamic efficiency. In theory, first–best pricing actually refers to marginal cost pricing, which maximises total welfare and guarantees allocative efficiency. But marginal cost pricing is not cost–covering in industries with increasing returns to scale, like energy markets, and thus would prevent investments and distort dynamic efficiency. This illustrates the trade–off between allocative and dynamic efficiency in regulation[1], which has to be taken into account by the regulatory authority when deciding in favour of a certain design.

"The key determinant of welfare is the firm's investment behavior" (Guthrie (2006)). This statement emphasises the importance of examining the impact of regulation on investment decisions in detail. It is widely acknowledged that different regulatory regimes have different effects on the individual investment decisions of a grid operator. The two most famous regulatory frameworks in practice are traditional cost–based regulation and incentive regulation. Most of the European countries initially started with a cost–based regulation[2]. Under this regime full cost recovery for the grid operator is guaranteed, whereby the risk of underinvestment in grid capacity vanishes and security of supply is greatly improved.

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[1] See e.g. Armstrong et al. (1994), Borrmann and Finsinger (1999) or Growitsch et al. (2010) for a more detailed description.

[2] E.g. rate–of–return or cost–plus regulation.

The recently dominant regulatory regime in Europe is incentive regulation[3]. The main argument for this regulatory regime switch is the regulator's ability to set incentives for cost–reducing investments and thus for more efficient grid provision. While the grid operator gets full cost recovery under cost–based regulation, incentive regulation works with predetermined regulatory periods wherein regulated tariffs and real costs are detached from each other. Precisely this separation between regulated prices and costs induces the profit–maximising grid operator to undertake cost–decreasing investments.

Innovative investments will gain special importance in the light of future challenges faced by electricity grids. Increasing renewable electricity production, e.g. because of wind turbines, will cause more volatility in loads. Moreover, renewable production tends to be more decentralised (e.g. photovoltaic stations on roofs) which influences the classical consumer–supplier relation with distinct load directions. Therefore, electricity grids need to be adapted and improved as subsumed under the keyword smart grids. The effect of the regulatory regime on innovative investments has been rarely studied in literature so far (see e.g. Bauknecht (2010) and Growitsch et al. (2010)). Especially the effect of different types of regulatory regimes on innovations is rather ambiguous. Hence, our paper contributes to this field by explicit modelling of innovative investments within the dynamic investment decision of an electricity grid operator. We develop a discrete–state–space simulation model in Matlab, which can be used to analyse the effects of different regulatory regimes on the investment and innovation decisions of an electricity grid operator. Within the analysis we assume that higher innovative investments are better for overall welfare, because of the necessity to develop smart grid solutions.

The remaining paper is structured as follows. After an overview of relevant literature in Section 2, Section 3 carefully presents the dynamic optimisation model including investment and innovation decisions. Section 4 explains the numerical modelling approach. The effect of cost–based and fixed–price regulation, as one example for incentive regulation, is discussed by means of a sensitivity analysis in Section 5. Finally, Section 6 summarises our main findings and provides ideas for further research

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[3]E.g. price–cap, revenue–cap or yardstick regulation.

options using our dynamic investment and innovation model.

2 Literature Review

In order to achieve dynamic efficiency, in the sense of optimal investment levels to guarantee security of supply and to cope with future challenges, awareness of different investment types is essential. Brunekreeft and Bauknecht (2009) distinguish different investment opportunities for electricity grid operators. In addition to classical replacement and grid expansion investment, they highlight process and product innovations.

Process innovations as well as replacement investments influence the level of marginal costs. Due to wear and tear marginal costs are increasing in each period. Replacement investment is conducted in order to lower the marginal costs, e.g. through new machines. Risky process innovations also exhibit the potential to lower marginal costs but not necessarily. Therefore, it is not sure with which marginal cost level the grid operator will end up after conducting a process innovation investment. A similar relation holds for grid expansion investment and product innovations. Both are connected to demand fluctuations and influence the level of grid capacity, but the product innovation result is risky.

Several articles, using a variety of different methods, treated the impact of different regulatory regimes on investments. The first one to be mentioned is the seminal paper from Averch and Johnson (1962). The authors showed that a profit–maximising firm under a rate–of–return regulation overinvests in capital in comparison to an unregulated firm. Concerning the impact of price–cap regulation on capacity investments in comparison to unregulated markets, Roques and Savva (2009) described two counteracting effects from introducing price–cap regulation in a Nash–Cournot game. On the one hand, a price cap will prevent strategic underinvestment in capacity in order to increase prices in the long run. On the other hand, incentives to defer investments, in order to circumvent risks in next cost hearings, increase. Based on this, the authors were able to determine an optimal price cap independent of market concentration. Using a real option approach, Nagel and Rammerstorfer (2009) found underinvestment in grid expansion under a price–cap regulation in comparison to an

unregulated market. They showed that a larger price cap reduces underinvestment at a decreasing rate and thus emphasised the importance of adequate mechanisms to guarantee revelation of true costs in order to implement non–distorting price–caps. In line with this, several other authors also highlighted the importance of a sensitive setting of the price cap, because too low caps rather tend to destroy investment incentives, see e.g. Cabral and Riordan (1989) and Roques and Savva (2009). Guthrie (2006) surveyed the relationship between regulation and investments and dealt with the question which regulatory system is more encouraging for investments. He identified investment flexibility and the credibility of the regulatory regime as decisive components and concluded the more risk the customers bear, the more encouraging the regulatory regime is for investments. Therefore, cost–based regulation can be assumed to generate higher grid expansion investment than incentive regulation.[4]

In contrast to that, Cambini and Rondi (2010) found in an empirical investigation of investment behaviour of EU energy utilities between 1997 and 2007, that the ratio of capital expenditure to total assets is higher under incentive than rate–of–return regulation. This finding need not exclusively be driven by grid expansion investment, but can for instance refer to replacement investment. This would be intuitive as Cabral and Riordan (1989) showed that the level of cost–reducing investments (replacement investment) is "the same or lower under cost–based regulation than under price–cap regulation." Pint (1992) concluded by means of a stochastic cost model, that price–cap as well as cost–based regulation lead to overinvestment in replacement[5] investment, in comparison to an unregulated monopoly.

Most of the articles discussed above refer to grid expansion and replacement investment. The overall conclusion is that grid expansion investment tends to be higher under a cost–based regulation, whereas replacement investment is thought to be higher under incentive regulation.

In the light of smart grids and future challenges of electricity grids, especially innovative investments are gaining importance. The well–known Arrow Theorem states

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[4]This is because the grid operator bears less risk under cost–based regulation than under price–cap regulation, as all costs are recovered.

[5]Pint (1992) describes that "firms can invest in capital in order to reduce costs". These investments can be classified as replacement investment in the definition of Brunekreeft and Bauknecht (2009).

that less incentives for innovations are existing in monopolistic than competitive markets (Arrow (1962)). But what impact does the regulatory regime in monopolistic markets have on innovations? Using uncertain cost distributions, Cabral and Riordan (1989) and Pint (1992) introduced risk in the replacement investment decisions of regulated monopolists. This did not change their main results described above. Nevertheless, the overall effect of investing — namely a reduction in costs — was assumed to be certain in their models. Future smart grid solutions for electricity grids still need to be developed, constructed and tested. Therefore, uncertainty plays a decisive role for recent innovations in electricity grids, and the overall outcome of investments in process innovations may not be certain in advance. Which regulatory system, incentive or cost–based regulation, is more stimulating for process innovations was discussed in Growitsch et al. (2010) and Bauknecht (2010). The authors argued that in a cost–based regime, grid operators do not bear any cost risk of innovations, but will not profit from resulting efficiency gains. Whether incentives for innovations arise in practice depends on the impact of the regulatory lag, as grid operators benefit from innovation–driven efficiency gains during these lags. Growitsch et al. (2010) concluded that incentive regulation, due to the pre-determined efficiency aims and longer periods between regulatory hearings, has a higher potential to generate incentives for process innovations than cost–based regulation. Bauknecht (2010) additionally mentioned that under incentive regulation the costs of innovation "in principle need to be recoverd through resuling efficiency improvments", consequently the grid operator bears the cost risk of innovation. To summarise, the analysis of the impact of single regulatory regimes on innovations is not fully developed yet and more research in this area is needed.

To contribute to the recent discussion about innovative investments, we explicitly model uncertainty in the investment decision of a grid operator. This allows us to examine the impact of different regulatory regimes on risky process innovations. Our modelling approach is for instance in line with Borrmann and Brunekreeft (2010), whose theoretical analysis examines the effects of price– and cost–based regulation on the timing of monopoly investment. We find that the choice of the regulatory regime matters for risky process innovations. In our simulations, innovative investments tend to decrease the more fixed–price the regulatory regime gets and firms operating under a fixed–price regime stop choosing minimal marginal costs if costs of innovative

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investments approach the cost–level of grid expansion investments.

3   Model Description

In the following section we introduce our basic model framework that allows a joint implementation of grid expansion investment, influencing installed transmission capacity, and risky process innovations, affecting marginal costs of transmission. This setup enables us to analyse the effect of different regulatory regimes on investment and innovation decisions separately.

We consider a grid operator that faces a stochastic demand for transmission and distribution capacity. Based on the actual level of demand, the grid operator decides on the optimal investment into transmission and distribution capacity that is subject to depreciation. An insufficient capacity level is sanctioned by a penalty payment, which can be considered as congestion or system-balancing costs[6].

The stochastic demand for transmission capacity (D) is given as an n–state Markov process:

$$D_{t+1} = \rho_D \cdot D_t + \sigma_D. \tag{1}$$

With this formulation the logarithmic demand approximates an AR(1) process with persistence ρ_D and shock variance σ_D. The Markov approximation assures a discrete state space of realisable demand levels. Herein, electricity demand is naturally bounded by an upper and lower level as only n states are possible.

Based on the realised level of demand, the grid operator decides on grid expansion investment. In order to take the demand uncertainty into account, the grid operator can only choose the capacity level for the subsequent period, i.e. $t + 1$[7]. Similarly, for capacity level (K) we choose a discrete state space, which can differ from the demand state space. The transmission and distribution capacity level is subject to

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[6]Note that we use a simplified version of reality as we combine required capacity levels and the supply and demand balancing duty of the grid operator.

[7]This can also be interpreted as building time. In case the grid operator is able to choose its capacity level for the current period, it would choose it on the level of demand in order to avoid penalty.

depreciation δ_{K_t} and exhibits the following law of motion:

$$K_{t+1} = (1 - \delta_{K_t}) \cdot K_t + I_t^{Exp}, \tag{2}$$

where the next–period capacity K_{t+1} is equal to the sum of depreciated capacity from the actual period K_t and the level of capacity expansion investment I_t^{Exp}. Consequently, the level of grid expansion investment in period t is determined by the level of capacity expansion I_t^{Exp} multiplied by a unit price for grid expansion investment (u_E).

When demand turns out to exceed the installed capacity level $(D_t > K_t)$ the grid operator gets penalised for increasing congestion costs in the network as introduced in Grande and Wangesteen (2000) and Léautier (2001). These costs can be considered as congestion costs or as costs arising from system balance[8]. In our setup, penalty costs are related to the level of the capacity shortfall, i.e. actual level of demand net of the installed capacity level $(D_t - K_t)$. Hence, the penalty level the system operator faces is determined by the product of the capacity shortfall level multiplied by a unit penalty payment for deviation (u_P). If capacity is sufficient to serve demand $(D_t \leq K_t)$, penalty payment is set to zero.

$$Pen_t = \begin{cases} 0 & \text{if } D_t \leq K_t \\ D_t - K_t & \text{if } D_t > K_t. \end{cases} \tag{3}$$

Efficient electricity transmission and distribution also belongs to the regulator's main objectives. Hence, in practice the regulatory rule should also motivate innovative investments into system efficiency improvement and into transmission cost reduction. Innovative investments especially gain importance with respect to recent developments like increasing decentralised production and the growing share of renewable energy sources with high production volatility which will establish the need for smart distribution grids.[9] Therefore, we explicitly include an innovation decision variable, introduced in (4). This decision variable indicates whether the grid operator decided in favor of an innovation $(d = 1)$ or not $(d = 0)$. The process

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[8]The system operator has to sell energy at unit costs, in order to match the demand level.
[9]See e.g. European Commission (2006).

innovation acts like replacement investment and thus modifies the marginal costs. Herein, the real effect of process innovations on marginal costs is uncertain in order to model the risky character of innovations.

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d = \begin{cases} 1 & \text{adoption of innovation} \\ 0 & \text{non–adoption of innovation.} \end{cases} \tag{4}
$$

Next period's marginal cost level (M_{t+1}) is affected by the level of the grid operator's decision on process innovations. We do not model innovations according to the learning curve framework dating back to Ebbinghaus (1885), Bryan and Harter (1897) and Wright (1939). First, because the learning curve also has its critics[10] and second, because we wanted to illustrate that smart–grid innovations will persistently enter new fields. Therefore, if an innovation is adopted, marginal costs are determined through a stochastic process which is modeled as an m–state Markov process with persistence ρ_M and shock variance σ_M. Herein, the realised marginal costs in the next period fluctuate around the chosen optimal marginal costs (M_t^*). The Markov approximation again assures a discrete state space of realisable levels for marginal costs with natural upper and lower bounds. Within this discrete state space risk is described by ρ_M $(0 < \rho_M < 1)$. The closer ρ_M to one, the more likely it is to achieve M_t^* through the innovation. The more ρ_M approaches zero, the less likely it becomes to achieve M_t^*, which means the more risky the innovation gets. If no innovation takes place, marginal costs increase gradually to the maximum level (upper bound) due to wear and tear. Hence marginal costs are determined as:

$$
M_{t+1} = \begin{cases} \rho_M \cdot M_t^* + \sigma_M & \text{if } d = 1 \\ (1 + \delta_t^M)M_t & \text{if } d = 0 \ \ \& \ \ M_t < M_{max} \\ M_t & \text{if } d = 0 \ \ \& \ \ M_t = M_{max}. \end{cases} \tag{5}
$$

As mentioned above, the process–innovation cost level depends on the desired level of optimal marginal costs. Hence, costs of process innovations are determined as product of the chosen level of marginal cost reduction (I_t^{Innov}), namely the difference between the actual level of marginal costs $((1 + \delta_t^M)M_t$, that is increased due to

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[10]See e.g. Nordhaus (2011) who states that "the learning model is a poor way to model endogenous technological change because of statistical bias in estimating the learning coefficient and because it gives an upward bias in estimating the value of new (learning) technologies".

wear and tear) and the desired optimal marginal costs (M_t^*), and the unit price for innovations (u_I).

$$I_t^{Innov} = \begin{cases} (1 + \delta_t^M)M_t - M_t^* & \text{if } M_t < M_{max} \\ M_t - M^* & \text{if } M_t = M_{max}. \end{cases} \quad (6)$$

The pricing rule (P_t) for transmission and distribution tariffs can be adapted to different regulatory regimes, in order to compare the effects on investment and innovation decisions. In the current formulation we implement simultaneously a fixed price (a), representing optimal unit costs, and the realised unit costs of electricity transmission and distribution with the sharing parameter (b). This enables us to implement regulatory regimes with various degrees of cost–based and fixed–price elements and is related to Newbery (1998).[11] If b is equal to one, the price follows a regulatory fixed–price regime, as one example of incentive regulation, and is exclusively determined by optimal unit costs a. If b is equal to zero, the regulatory regime is cost–based and the fixed price component a drops out whereas the realised unit costs are fully accounted. Therefore, parameter b determines the underlying regulatory system. The closer b gets to one, the more fixed–price oriented the regulatory regime is. The more b approaches zero, the more cost–based the regulatory system is.

$$P_t = b \cdot a + (1 - b) \cdot [M_{t-1} + \frac{(wacc \cdot K_{t-1} + d \cdot u_I \cdot I_t^{Innov} + u_E \cdot I_t^{Exp})}{S_t}] \quad (7)$$

The unit costs of electricity transmission and distribution include lagged marginal costs (M_{t-1}) as well as financing costs approximated by lagged capacity (K_{t-1}) multiplied by weighted costs of capital $(wacc)$, innovation costs $(d \cdot u_I \cdot I_t^{innov})$ and grid expansion investment $(u_E \cdot I_t^{Exp})$ divided by current supply. The level of the current supply (S_t) is determined by demand (D_t) as long as demand is smaller or equal to installed capacity. Only if demand exceeds installed capacity, supply is given by lagged installed capacity (K_{t-1}). Consequently, demand and supply are always balanced if possible.

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[11] Following Newbery (1998), incentive and cost–based regulation can be combined in one rule to determine allowed revenues, as both are second–best pricing rules under imperfect information of the regulator. Both mechanisms will constitute extremes for intermediate regulatory mechanisms.

$$S_t = \begin{cases} D_t & \text{if } D_t \leq K_t \\ K_t & \text{if } D_t > K_t. \end{cases} \tag{8}$$

We also analyse a mixture regulation, as recently suggested by Bauknecht (2010) under the heading pass–through of R&D costs:

$$P_t = a + \left[\frac{d \cdot u_I \cdot I_t^{Innov}}{S_t}\right] \tag{9}$$

Herein, the price in period t is determined according to the fixed–price a[12] with cost–based elements for innovative investments $\left[\frac{d \cdot u_I \cdot I_t^{Innov}}{S_t}\right]$.

Given the above–described background framework, the grid operator seeks to max-imise its profits over capacity and marginal costs next period:

$$\Pi = \max_{K_{t+1}, M_{t+1}} \sum_{t=0}^{\infty} \beta^t \cdot [(P_t(M_{t-1}, K_{t-1}, I_t^{Exp}, I_t^{Innov}) - M_t) \cdot S_t - d \cdot u_I \cdot I_t^{Innov} - u_E \cdot I_t^{Exp} - u_P \cdot Pen_t] \tag{10}$$

The problem can be transformed into a Bellman equation:

$$V(K, M, D) = \sup_{K' \in G(K), M' \in G(M), d \in \{0,1\}} \Pi(K, M, D, P, K_t^{exp}, M_t^I, Pen, d) + \beta \cdot E[V(K', M', D')], \tag{11}$$

where capacity (K), marginal costs (M) and demand (D) can be considered as state variables and next period's capacity (K') and marginal costs (M') and d as decision variables. The whole model is summarised in the Appendix.

4 Numerical Approach

Modelling the full dynamics of the model described above is analytically not pos-sible, hence it requires numerical procedures. As we are more interested in the absolute levels of innovative investments than the concrete timing, we use a recur-sive dynamic programming approach, namely iterating over the value space, instead of a real option approach to solve the problem. We derive the optimal strategies for investments and innovations for each possible state. Due to the time–independence

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[12]Note, that a is the same parameter as in Equation 7.

of the profit function and the transition probabilities (the profit flow depends only on the actual state and the actions taken), the iterative approach described below will result in a convergence of the optimal strategies. The procedure is based on the contraction mapping theorem that guarantees convergence of both, the value function and the optimal control rule. In practice the program continues iterating until the value function improves not more than an predefined criterion in one iteration. The whole algorithm can be summarised as follows:

1. We start with an initial guess for the value function (V) at each possible state (we use zero for all states). Since we have n possible realisations for the demand (D'), k possibilities for capacity choice (K') and m realisations for marginal costs (M'), the dimension for this value function guess V is $n * k * m$.

2. Next we update the value function by considering the future value as initial guess:

$$V(K, M, D) = \Pi(K, M, D, P, Exp, Innov, Pen, d) + \beta \cdot E[V(K', M', D')] \quad (12)$$

The new value consists of the current payoff and the discounted expected future payoff (for the first iteration we use the initial value function containing only zeros). This new value function is used as the future value function in the next iteration.

3. We continue the iteration until the value function change will be lower than a predefined value (ϵ). If $\|V(K, M, D) - V(K', M', D')\| < \epsilon$ the optimal value function is reached, else additional iteration is needed and we go back to step 2.

4. Having the optimal strategy of the firm, we simulate investment and innovation decisions running Monte Carlo simulations of the demand and marginal–cost processes.

5 Simulation Results

Using the above–described dynamic optimisation model, we examine grid expansion investment and risky process innovations under different regulatory regimes over

a period of 50 years. For numerical simulations, we refer to the benchmark values of the parameters given in Table 1, which often refer to Austria. Nevertheless, our modelling approach is quite general and results should be valid for typical grid operators in Europe. The value of the risk-free rate is chosen at 5% level, while the weighted average cost of capital, based on Energie–Control Kommission (2010) p.27, is chosen at 7.03%. The initial electricity supply that corresponds to demand for transmission capacity in our model is set at 68.85 TWh. This is the electricity supply in TWh for Austria in 2009, reported by E–Control. The penalty payment is determined by the regulator. For modelling purposes we set it at 50,000€. In our simulation the firms decide on two different investment opportunities. Following Brakelmann (2004) and DENA (2005), we approximate grid expansion investment costs with $100\frac{€}{kmMW}$. These investment costs correspond to $11,415\frac{€}{kmTWh}$.[13] Since the average line length (based on Platts database) is 14.15 km in Austria, the unit investment costs for electricity grid expansion can be approximated by $161,522\frac{€}{TWh}$. We have set the unit investment costs for innovative investment at 100,000€. For simplicity, the unit investment costs for both capacity expansion and innovative investments are constant in each period. Based on these parameter values, our results show that the choice of the regulatory regime, in particular the choice between a fixed–price and a cost–based regime, matters for the different investment decisions.

Table 1: Benchmark Parameter Values

Parameters	Unit	Value
Risk–free interest rate, r	[%]	5
Weighted average cost of capital, $WACC$	[%]	7.03
Electricity demand, D	[TWh/yr]	68.85
Penalty, Pen	[€]	50,000
Investment costs for grid expansion, u_E	[€/TWh]	161,522
Unit investment costs for innovative investment, u_I	[€]	100,000

The grid expansion investment in our dynamic optimisation setup is shown in Figure 1. Firms under cost–based regulation always invest as much as possible in grid

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[13]$100\frac{€}{kmMW} \cdot 1,000,000 = 100,000,000\frac{€}{kmTW}$; $\frac{100,000,000\frac{€}{kmTW}}{24 \text{ hours} \cdot 365} = 11,415\frac{€}{kmTWh}$.

expansion and ensure maximal possible grid capacity in each period, independent of demand development. In contrast to that, firms under incentive and mixture regulation take demand developments into account and ensure that they are able to serve demand requirements, without maximal possible grid capacities in each period. In that way, some evidence for the well–known over–capitalisation under cost–based regulation can be found in our analysis and we are in line with the literature presented in Section 2.

Figure 1: Optimal Grid Capacity
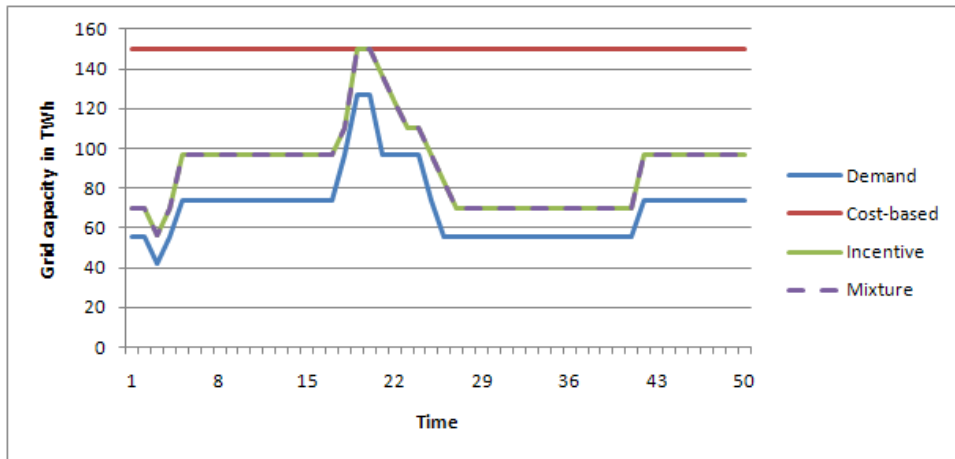
Under incentive regulation, managerial effort is incentivised and governed with stimuli[14] for cost–reducing investments. In line with this, we find in our simulations that firms under incentive regulation always invest as much as necessary in non–risky replacement investment to ensure minimal possible marginal costs in each period.[15] This picture changes when risk is introduced in order to treat risky process innovations instead of non–risky replacement investment to affect the level of marginal costs.

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[14]These stimuli arise from a separation of prices and costs within a predetermined regulatory period.

[15]In order to analyse common replacement investment, we replaced the Markov Process for marginal costs by a similar choice rule as for capacity and grid expansion investment.
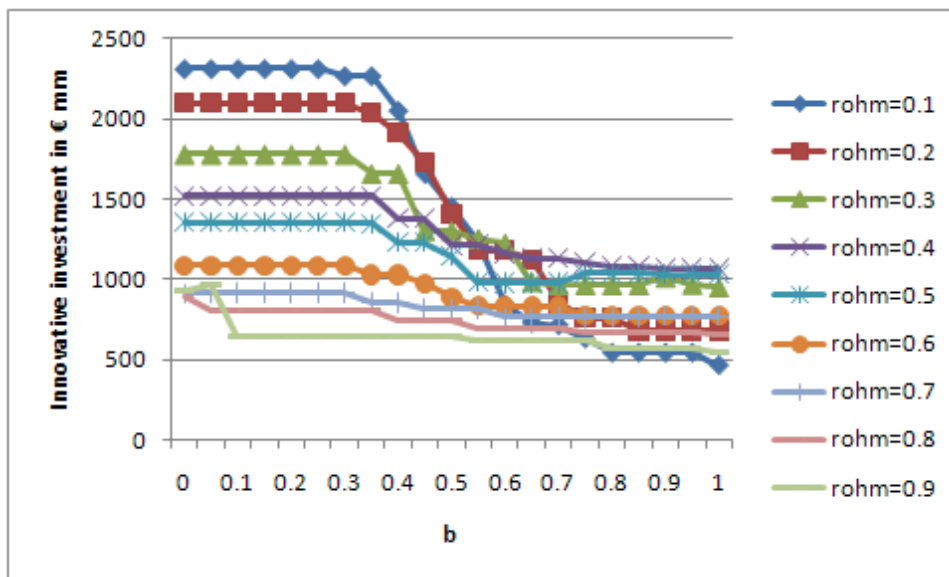
Figure 2: Innovative Investment Behaviour

Figure 2 illustrates cumulative innovative investments over 50 periods in variation of the sharing parameter b between zero and one. If b is equal to zero, firms face a cost–based regulation. If b is equal to one a fixed–price rule representing incentive regulation is assumed. Values between zero and one indicate hybrid regulatory regimes with different degrees of cost–based and fixed–price elements.

Several aspects can be seen in Figure 2. First of all, it becomes obvious that the higher the assumed degree of incentive regulation is, the lower are cumulative innovative investments, indicating a negative correlation. Second, the lower rohm (persistence of the marginal costs ρ_M) gets, the more distinct the difference between different regulatory regimes is. This is intuitive, as ρ_M describes the risk of the innovation. The lower ρ_M gets, the more risky[16] the innovation is, which affects the behaviour of grid operators under incentive regulation as they bear the risk of innovation on their own. Consequently, differences between the regulatory regimes increase. Finally, in the range of ρ_M between 0.3 and 0.9, lower values of ρ_M are in both regulatory regimes accompanied by higher absolute levels of cumulative innovative investments. This increase in absolute cumulative innovative investments is exclusively due to the increased risk, which makes it necessary to invest more in order to obtain the same level of marginal costs.

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[16]Risky in the following sense: The lower ρ_M $(0 < \rho_M < 1)$, the less likely it is to achieve the optimal marginal costs M_t^* intended by the innovation.

Due to the fundamental changes in electricity grids and the necessity to develop smart grid solutions, we assume that higher innovative investments are more flourishing for overall welfare. Especially regulatory regimes which motivate firms to achieve the lowest possible marginal costs are better for overall welfare, as lower marginal costs will translate into lower consumer prices.

For a more detailed look on innovative investment behaviour, Figures 3 and 4 present average optimal marginal costs[17] over 50 periods for high[18] and low[19] innovative investment costs, respectively. The average optimal marginal costs are presented in variation of the persistence of marginal costs (ρ_M). Due to possible shocks, incentives for cost–reduction are not sufficient under incentive regulation to motivate firms to innovate as much as necessary to obtain minimal marginal costs. This result depends on the assumed costs of innovative investments.
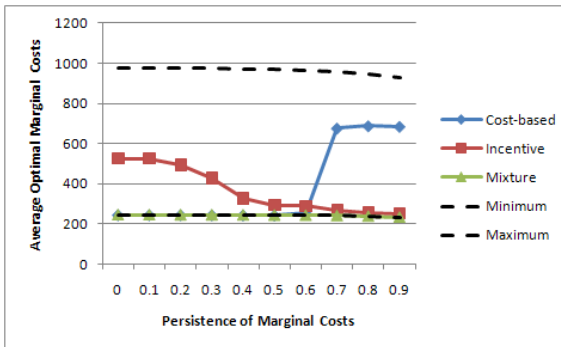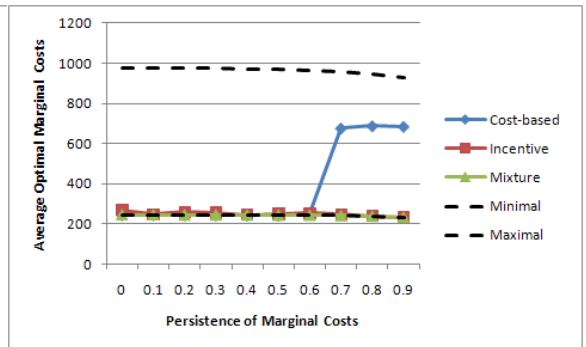
Figure 3: High Innovation Costs	Figure 4: Low Innovation Costs

We distinguish between cost–based and incentive regulation (represented by a fixed–price rule) as well as mixture regulation. The black dashed lines represent minimal and maximal possible marginal costs in our discrete space. As can be seen in Figure 3, firms under cost–based regulation nearly always choose lowest possible marginal costs. Only for higher values of ρ_M (the persistence in the Markov process describing marginal costs) an increase in average optimal marginal costs is observable. This is

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[17]Realised and optimal marginal costs can deviate in our model setup. As realised marginal costs are subject to possible shocks which cannot be influenced by the grid operator, we concentrate the discussion here on optimal marginal costs.

[18]We define the high cost scenario by unit innovation costs of 100,000€. This means a firm has to pay 100,000€ if it intends to decrease its marginal costs one step in our discrete state space for marginal costs.

[19]The low costs scenario is referred to unit innovation costs of 50,000€.

driven by a distinct business strategy, which is explained in Figure 5 in more detail. Consequently, incentives arising through the regulatory lag in combination with no cost risks seem to be sufficient to motivate process innovations with a certain level of risk under cost–based regulation. In contrast to the behaviour of cost–based regulated firms, firms operating under incentive regulation rather tend to choose optimal marginal costs above the minimum. Here, chosen average optimal marginal costs are decreasing with increasing persistence of marginal costs.[20] Consequently, it seems that the higher the risk of process innovations is, the more likely it is that investment incentives, arising through the isolation of regulated prices and costs within the predetermined regulatory periods, are outweighed by the cost risk of process innovations which is exclusively born by the grid operator. A kind of mixture regulation as suggested by Bauknecht (2010) would potentially solve both problems (no business strategies and no cost constraints for innovations), as grid operators could profit longer from innovations and pass the cost risk of innovation to consumers. In line with this, firms operating under mixture regulation always choose the minimal optimal marginal costs in our simulations.

Figure 4 is added to demonstrate that this result depends on the assumed level of unit costs of innovative investments. The cheaper process innovations are, the lower the cost risk and the lower the likelihood for innovation incentives to be outweighed by the cost risk. Assuming lower unit costs of innovation, grid operators under incentive regulation as well as under mixture regulation would always choose minimal marginal costs as optimal.

Concerning firms under cost–based regulation, our simulations detect an interesting business strategy. Above a distinct level of persistence in marginal costs ($\rho_M = 0.7$), cost–based regulated firms do no longer attempt to achieve lowest marginal costs in each period. Instead, firms accept wear and tear until they reach the highest marginal costs in the discrete state space. Innovations are undertaken in the subsequent period.

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[20]Recall that lower persistence ρ_M means that it is less likely to achieve optimal marginal costs M_t^* intended by the innovation. Therefore, lower persistence ρ_M means higher risk.

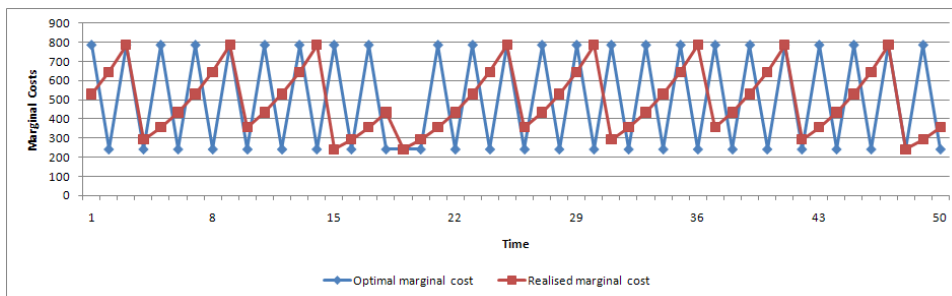Figure 5: Business Strategy of Firms under Cost–based Regulation

Figure 5 illustrates this strategy. For the illustration we assume a persistence of 0.7 for marginal costs and high unit costs of innovative investments; marginal costs vary between 240 and 900€ per TWh. The blue line represents optimal marginal costs for the firm — the costs a firm would choose if it would be allowed to choose marginal costs freely. The striking strategy is that firms would alternatingly choose lowest and second highest marginal costs. Due to the regulatory lag[21] and wear and tear, firms would benefit more from decreased marginal costs in every second period than they lose in the periods with increased marginal costs. Therefore, we eliminated this business strategy in our simulations. The red line represents resulting realised marginal costs. As the firms are no longer able to alternatingly choose lowest and highest marginal costs, they wait until marginal costs due to wear and tear reach one level before their maximum and invest in the subsequent period. Due to the persistence of 0.7, it is not guaranteed that the firm will reach the lowest marginal costs when investing. Consequently, the minimums of the blue and red line are sometimes deviating.

Finally, the break in the business strategy from period 18 to 20 is driven by an extraordinarily high demand for electricity. If demand reaches extremely large values, the strategy does not pay off for firms any longer. Instead it is rather profitable for them to ensure the lowest possible marginal costs.

Beside the above–described results, we find that average prices under cost–based regulation are much higher than under incentive regulation (in the high cost scenario even by a factor of 10). The bigger part of the price increases is driven by grid

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[21]The regulatory lag comprises one period in our simulations, which means that in period t, marginal costs from period $t-1$, increased due to wear and tear, enter the regulated prices.

expansion investment, additionally supporting mixture regulation where prices are only slightly higher than under pure incentive regulation.

6 Summary and Concluding Remarks

Following Guthrie (2006) the "key determinant of welfare is the firm's investment behavior". Electricity grids, as natural monopolies, are subject to regulation which affects the firm's investment decisions. It is widely acknowledged that different regulatory regimes have different effects on the individual investment decisions of a grid operator. Therefore, it is especially interesting to examine the impact of regulation on investment decisions in detail. The two most famous regulatory frameworks in practice are traditional cost–based regulation and incentive regulation. Existing literature showed that cost–based regulation rather stimulates grid expansion investment, whereas incentive regulation generates higher replacement investments and consequently a more efficient grid provision.

Innovative investments in particular will gain importance in the light of future challenges faced by electricity grids, like increasing renewable and decentralised electricity production. Smart grid solutions for electricity grids need to be developed, constructed and tested which involves distinct innovative investments. The effect of the regulatory regime on innovative investments has been rarely studied in literature so far (see e.g. Bauknecht (2010) and Growitsch et al. (2010)). The authors argued that on the one hand in a cost–based regime, grid operators do not bear any cost risk of innovations, but will only slightly profit from resulting efficiency gains. On the other hand, under incentive regulation the grid operator bears the cost risk of innovation, but can profit longer from innovations. Consequently, it is still ambiguous which regulatory regime is superior in stimulating process innovations in electricity markets.

Uncertainty plays a decisive role for recent innovations in electricity grids, and the overall outcome of investments in process innovations may not be clear in advance. Therefore, we want to contribute to the recent discussion concerning innovative investments by explicit modelling of investment and innovation decisions of an elec-

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tricity grid operator. Our framework allows us to analyse the impact of cost–based versus fixed–price regulation on grid expansion investment, affecting demand, and risky process innovations, affecting the level of marginal costs. Due to the necessity for the development of smart grid solutions, we assume that higher innovative investments are better for overall welfare.

On the one hand, we find that due to the regulatory lag, cost–based regulation may reward strange business strategies and create incentives to conceal true marginal costs resulting from innovations. This finding suggests that the regulatory authority should have a close look on the success of process innovations in a market under cost–based regulation. On the other hand, under incentive regulation incorporating a fixed–price rule, innovation incentives, arising from the efficiency gains of successful process innovations, are likely to be outweighed by the cost risk of innovation. Thus, grid operators tend to invest less in risky process innovations as would be necessary to achieve minimal marginal costs. In other words, with increasing risk of innovations they choose higher optimal marginal costs.

Mixture regulation as suggested by Bauknecht (2010), i.e. a fixed–price rule with cost–based elements for innovative investments, could potentially solve both problems. First, firms would not bear the entire cost risk of innovations and second, they would partially profit from subsequent efficiency improvements via the fixed–price rule. This holds for all assumed risk characteristics.

The simulation model developed in this paper provides a general tool for analysing investment and innovation decisions of grid operators. The present analysis of advantages of cost–based versus fixed–price regulation for innovative investments is only a starting point. Further research could examine the impact of various other regulatory regimes on the investment and innovation decisions of a grid operator. This could help regulatory authorities to evaluate the effect of future changes in regulatory regimes on dynamic efficiency in advance.

7 Appendix

The grid operator seeks to maximise its profits over capacity and marginal costs next period:

$$\Pi = \max_{K_{t+1}, M_{t+1}} \sum_{t=0}^{\infty} \beta^t \cdot [P_t(M_{t-1}, K_{t-1}, I_t^{Exp}, I_t^{Innov}) \cdot S_t - d \cdot u_I \cdot I_t^{Innov} - u_E \cdot I_t^{Exp} - u_P \cdot Pen_t]$$

such that:

$$K_{t+1} = (1 - \delta_t^K) \cdot K_t + I_t^{Exp}$$

$$S_t = \begin{cases} D_t & \text{if } D_t \leq K_t \\ K_t & \text{if } D_t > K_t \end{cases}$$

$$Pen_t = \begin{cases} 0 & \text{if } D_t \leq K_t \\ D_t - K_t & \text{if } D_t > K_t \end{cases}$$

$$d = \begin{cases} 1 & \text{adoption of innovation} \\ 0 & \text{non--adoption of innovation} \end{cases}$$

$$M_{t+1} = \begin{cases} \rho_M \cdot M_t^* + \sigma_M & \text{if } d = 1 \\ (1 + \delta_t^M) M_t & \text{if } d = 0 \ \& \ M_t < M_{max} \\ M_t & \text{if } d = 0 \ \& \ M_t = M_{max} \end{cases}$$

$$I_t^{Innov} = \begin{cases} (1 + \delta_t^M) M_t - M_t^* & \text{if } M_t < M_{max} \\ M_t - M^* & \text{if } M_t = M_{max} \end{cases}$$

$$P_t = b \cdot a + (1 - b) \cdot [M_{t-1} + \frac{(wacc \cdot K_{t-1} + d \cdot u_I \cdot I_t^{Innov} + u_E \cdot I_t^{Exp})}{S_t}]$$

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