Comparing Feed-In-Tariffs and Renewable Obligation Certificates - the Case of Wind Farming

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1 Introduction

Renewable energy is currently one of the top issues in the European energy policy debate. Many European policy makers see it as promising a solution to the energy problems of the 21st century. At the International Conference for Renewable Energies, held in Bonn in 2004, the German minister for the Environment, Jrgen Trittin identified global poverty and global warming as central challenges of our time and renewable energies as the "vital key" in their mastering. He said: "Renewable energies are inexhaustible. Renewable energies are available almost everywhere. Renewable energies represent multiple win-win options. They reduce dependence on oil and help save foreign currency. They create jobs - in Germany 120000 people now work in the renewables sector. They protect our climate and reduce air pollution - in Germany we save 53 million tonnes of CO2 per year with renewable energies. [...] For this reason the World Summit on Sustainable Development 2002 in Johannesburg advocated 'significantly increasing the share of renewable energies' ". Policy makers in Europe and around the world see renewable energy as a clean alternative to fossil fuels and as a promise of long term security of supply. Despite this consensus, the role of the government in promoting these energies remains controversial. Today energy generated from renewable sources is usually more expensive than conventional energy, rendering investment into it unprofitable under free market conditions. Some governments (such as the U.S. federal administration) have so far limited their efforts to subsidies for research and development in renewable energies aiming at speeding-up a technological breakthrough and thus their market maturity. In contrast, a number of European countries -as well as some U.S. states such as California- have introduced additional policy instruments to increase investments into renewable energy facilities, most notably for electricity generation. In their climate policy goals, EU governments have included a renewable energy target: By 2020, 20 % of all primary energy in the EU is to be produced from renewable sources. Figure 1 shows the respective goals for EU member states. These additional policy instruments fall into two categories: quotas and feed-in tariffs. A quota system has been introduced, for example, in the U.K. According to this system eligible renewable energy plants receive so called Renewables Obligation Certificates (ROC) corresponding to the amount of electricity they produce. Electricity supply companies are obliged to purchase ROCs from the producers up to a specified quota of their electricity sales. The government sets the quota (3Germany, instead, has opted for the introduction of feed-in-tariffs for renewable energy. Under this system, the electricity generated from renewable energy is sold to power supply companies at a fixed minimum price (e.g. for wind energy the price was set at 9.1 c/KWh in the first five years of operation and at 6.19 c/KWh for further 15 years). The additional costs for renewable electricity are covered by an additional per KWh charge on all consumers. Feed-in-tariffs decline over time to take account of technological progress. Introducing feed-in-tariffs in 2000, the German government declared that it wanted to raise the share of renewable energy in electricity production to 12% by 2010. Feed-in tariffs are also used in Spain, France, Austria, Denmark, Portugal and South Korea. Critics of quotas and feed-in tariffs for renewable energy usually point to the ineffectiveness of overlapping regulation. They argue that internalising the external costs (e.g. pollution) of non-renewable energy sources by taxation or by emission certificates would efficiently incorporate all environmental concerns. The market would then give a fair chance to renewable energy without further regulation. In our study we want to investigate the ex-ante relative effectiveness of quotas and feed-in-tariffs in promoting the use of renewable energy in electricity production. More specifically, we want to investigate how investors' incentives to commit to renewable energy technologies vary with the policy context in place. Because one major difference between quotas and feed-in-tariffs is the fact that the minimum price granted under feed-in-tariffs cuts the downside risk for investors by fixing the electricity price, our analysis follows a real option approach. Real option models, developed in the finance literature, are able to describe optimal investment strategies in the presence of irreversibility and uncertainty. Taking into account both the price dynamics for fossil fuels as well as (stochastic) technological progress in the renewable energy sector we ask which policy instrument is most likely to speed-up market maturity. This paper is structured as follows:

Section 2 discusses the economic background of support for renewable energy and the foundation of real option theory, that serves as a modelling framework to analyse our question. Section 3 introduces the model and formalizes the notion of the two policy regimes. The calibration is presented in section 4. Section 5 introduces the results of our numerical excercise.

2 Theoretical Background

Public support for renewable energy is motivated mainly by environmental concerns. Solar cells do not emit CO2, such as an electricity plant fired by coal. In economic theory, damages caused by emissions are classified as an externality. An externality exists when one party's utility or production function depends on (real) variables that are chosen by another party without regard of the impact of that choice on the first party. The concept was introduced by Pigou (1932) and further developed in the 60ies and 70ies (compare the seminal monograph by Baumol and Oates (1974)). Following the classical argument by Coase (1960), the introduction of property rights for a clean environment and subsequent trading of pollution rights will induce an efficient use of pollutants. When such property rights do not exists, government intervention is required. Such intervention may occur, for example, through the use of taxes, subsidies, or tradable emission permits. Economic theory warns against the use of subsidies that might induce excessive entry, against the use of more than one policy instruments to correct for a single externality and against setting constraints to the technology to be used in the production process (see for example Helfand, 1992). Yet some strong assumptions lie underneath these theoretically sound conclusions: transaction costs are negligible, there are no income effects associated with wealth transfers and information is perfect. The fact that in real life these assumptions are often violated, poses governments in front of the challenging tasks of building an incentive compatible policy context. A second argument in favour of government intervention to promote renewable energy relates to concerns about sustainable development. The use of renewable resources enables society to economise precious exhaustible raw material. Economic theory is less supportive of government intervention following this argument. In 1931, Hotelling argued that competitive markets for exhaustible goods guarantee an efficient dynamic allocation: the increasing scarcity of these resources should be reflected in increasing prices, leading to an optimal depletion path. The argument is elaborated and inserted into macroeconomic growth models in the seminal papers by Stiglitz (1975) and Dasgupta and Heal (1974) (compare the overview by Devarajan and Fisher (1981)). However, empirical evidence does not support the predictions of this theory (compare, e.g. Halvorsen and Smith (1991)). Solow (1974) and Hartwick (1978) challenge Hotelling's view. They argue that in a framework with finitely-lived, overlapping generations markets do not guarantee efficient intergenerational allocation of exhaustible goods. Present generations tend to over-consume the exhaustible good. According to Hartwick (1978), for reasons of intergenerational fairness, an (altruistic) government should invest into durable capital for later generations. The debate continues (recent contributions include Agnani, Betty et al. (2005) and Just, R. et al. (2005)). A third argument raised in favour of government intervention for renewable energy concerns its innovative character. An early adoption of renewable energy in the energy supply chain speeds up technological development, leading to an earlier market maturity. The cautious version of the argument favours subsidies to research and development in renewable energy technology. In a view of internal, but uncertain technological improvements and industrial innovation, direct subsidies to innovative industries are declared R & D subsidies. Classical economic theory is not in line with this view of the government's role in innovation activities. According to the traditional view, it is the scarcity of input factors rather than a government subsidy that drive invention and innovation efficiently. "A change in the relative prices of the factors of production is itself a spur to invention, and to invention of a particular kind - directed to economizing the use of a factor which has become relatively expensive." (Hicks, 1932). The empirical evidence for this "induced innovation hypothesis" in the energy sector is somewhat inconclusive: Newell et al. (1999) find the larger part of innovations to be autonomous, while Popp (2002) establishes a positive effect of energy prices on energy technology innovation. However, there is a widespread consensus among policy makers and economists today that the government has a role in research and development. These can take the form of a R & D subsidy, or direct subsidies to an innovative industry under the "Learning by Doing" paradigm (Arrow, 1962, Young, 1993). Economists have widely accepted the argument put forward by Griliches (1979): Innovation is risky and not fully appropriable, i.e. knowledge, which has been acquired at some cost, will spill-over from the innovative company to its competitors at a certain rate. These spill-over effects do not suppress innovation, but lead to inefficient under-investment. Subsidies to research and development can thus enhance welfare. Empirical evidence for spill-over effects is given by Griliches (1979, 1992). Another hypothesis about innovation in environmental technologies is controversial: Porter and van de Linde propose that environmental regulation fosters innovation in a way that leads to economic growth in the long-run (see Porter and van der Linde (1995)). This argument has become popular in the public policy debate, however, it lacks a sound theoretical foundation. Also, empirical studies have not found evidence in support of the argument (see Jaffe and Palmer (1997)). To summarize the discussion of government intervention to foster renewable energy, we can broadly say that there are two undisputed favorable arguments - environmental externalities and innovation spill-over - and two controversial arguments - economizing exhaustible resources and inducing economic growth (see Jaffe et al., 2005). As for the choice of policy instrument to be adopted, there is wide agreement in the economic literature about that market-based instruments (taxes, subsidies, permits and certificates) are more efficient than command-and-control instruments (quota, product and process standards) in achieving a given level of environmental protection. Market-based instruments, furthermore, provide dynamic incentives for an efficient green technological development (see Coase, 1960; Dales, 1968; Montgomery, 1972 and Weitzman, 1974). In the vintage capital theory, furthermore, from the early contributions by Johansen (1959) and Solow (1960) to the more recent work by Gilchrist and Williams (2000, 2001), and Laitner and Stolyarov (2002), new technologies, especially those subsidized by the government, should instantly dominate existing ones. Yet two empirical facts seem to be in contrast with these theoretical findings. First, policy makers seem to rely heavily on command-and control instruments when it comes to environmental protection rather than market-based instruments or a combination of the two. Examples are fuel standards in cars or the discussion on an "energy passport" for buildings in Germany. Second, as shown by Comin and Hobijn (2003) in a panel study considering 25 technologies, 23 countries and 215 years, investments in existing technologies continue to persist after new and better alternatives have become available, at least for some time. The latter phenomenon has been studied by several authors who propose different explanations: the development of technology specific human capital (for ex. Chari and Hopenhayn, 1991), the existence of innovator/imitator behaviour (for ex. Barro and Sala-i-Martin, 1997), endowment of factors that are complements or substitutes of the technology (Acemoglu, 2001), the existence of lobbying groups against the diffusion of particular technologies (for a theory of endogenous protection see Grossman and Helpman, 1994).

A further explanation, which we consider in this study, is the existence of uncertainty and irreversibility. In our work we will build on this latter hypothesis and on the work by Pizer (1997), who shows that ignoring uncertainty in policy decisions concerning stringency and instrument choice leads to inefficient policy recommendations, and of Dixit and Pindyck (1994), who model the decision to invest in a plant or a particular technology as a real option.

A real option is defined as the right, but not the obligation, to take an action. It differs from a financial option in that the action concerns a tangible or "real" asset instead of a financial security. Real option theory draws its foundations from financial option pricing theory as developed by Merton (1971, 1973, 1976, 1977 and 1990) and Myers (1977, 1984, and 1992). Real option theory has been developed in the last two decades to evaluate investments under uncertainty and irreversibility. Its application requires investments decision to be associated to irreversible effects (such as sunk costs associated to capital investments, irreversible effects on ecosystems etc.) to be characterized by uncertain future payoffs and by flexibility in the investment timing. If uncertainty totally, or partially, resolves over time, flexibility in the timing of the investment might become of value to the investors and this value should be taken into consideration in the decision making process. Real option theory offers a way to model the value of flexibility explicitly in the investment evaluation process. The investor decision making becomes a stochastic dynamic process that yields to an investment decision criteria which is stricter than the traditionally used expected net present value decision criteria. The basic difference between the two approaches is that in real options investors are not only given the possibility to choose the investment timing optimally, but they do so taking the value of timing flexibility explicitly into account. This procedure implies that different ENPVs are calculated and compared at different points in time. At each point in time the potential resolution of the uncertainty surrounding investment payoffs is taken into consideration.

Dixit and Pindyck show how this approach can help to explain why firms often do not invest until price rises substantially above long-run average costs, or why prices can fall substantially below average variable costs without inducing disinvestment or exit as standard theory would predict. The authors also show how price controls may actually discourage investments:

"Under price controls, firms wait to observe a greater pressure of demand before they act. This dynamic decrease of supply in turn implies that the pressure of demand will be high enough to keep the ceiling binding more often. In effect, the policy generates its own 'need'." (p. 301)

Real option theory has been applied to study liberalised electricity markets by a number of authors (e.g. Botterud, Ilic and Wangensteen (2005), Botterud and Korpas (2006), Madlener et al. 2005). The authors look at how uncertainty influences the optimal timing of investments in new power generation capacity. They use a discrete time approach, as we do in this paper.

We present a stylise model analysing the effect that the two support policies, feed-in-tariffs and renewable obligation certificates, have on the uncertainty faced by investors in renewable energy plants. In particular, we are interested to understand the effect the instruments have on innovation. In our empirical application we will focus on the case of wind energy power plants. In doing so we follow Butler and Neuhoff (2004), who use descriptive statistics combined to developers' interview to compare the effectiveness of renewable obligation certificates and feed-in-tariffs. The authors find that deployment of renewable energy is higher under feed-in-tariffs than under renewable obligation certificate and that suggest that the resource-adjusted cost to society of the feed in tariff is lower than the cost of the ROC. Kildegaard (2008), develops a theoretical framework showing that the failure of ROC may be due to the presence of low-fixed cost technology competing against high fixed-cost technologies in the certificate market. In our study we build on the work of Butler and Neuhoff using real option theory to advance a theoretically consistent explanation of their findings and suggestions, and extend Kildegaard line of arguments explaining ROC performance taking explicitly into consideration the role of uncertainty and irreversibility in shaping impacts of alternative policy instruments.

3 Model

Motivation In this section, we present our modelling framework for investment into a renewable energy plant. It is a discrete dynamic programming problem with infinite time horizon. There are four state variables, which are introduced below, and one (discrete) control variable depicting the investment decision. The model is set up to capture the decision of a single investor to renew his renewable energy plant under uncertainty about the electricity price and the price of capital. Our ultimate aim is to study the propensity to innovate under two stylized policy regimes: the feed-in-tariff (FIT) and the renewable obligation certificate (ROC). They are distinguished by the way they influence the price of electricity. Whereas the owner of a renewable plant faces a certain and foreseeable price path for his sales of electricity under FIT, the price is volatile under ROC. The notion of the policies will be formalized below. The second source of uncertainty in our model concerns the cost of capital. When deciding to invest into a new power plant, the owner has to take into consideration uncertainty about future revenues as well as opportunity costs (or benefits) that arise from price reductions (or increases) of capital.

State Variables To make the problem interesting, we model the two price uncertainties as Markov processes:

P_e is the current electricity price and a Markov state variable[1]

$$P_e' = \alpha_e + \beta_e P_e + \mu_e, \tag{1}$$

where μ is an i.i.d. stochastic shock variable with mean zero.

P_k is the current price of capital and also a Markov state variable

$$P_k' = \alpha_k + \beta_k P_k + \mu_k, \tag{2}$$

with ϵ being an i.i.d. stochastic shock variable with mean zero, too.

Since we intend to model the influence of technological progress on the investment decision, we introduce both the age A of the plant and the state of employed technology[2] T as two deterministic state variables. As we assume a

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[1] Here and in the sequel, we denote the forward time shift by a dash.

[2] By the term "employed technology" we refer to the technology installed as distinguished from available technology.

finite lifetime m of the plant, the value $m - A$ indicates the remaining time of operation. We set $A = 0$ and $T = 0$ when the lifetime is expired and the plant is out of operation; other than that age increases by 1 each period. The state of employed technology T translates into the technical efficiency of the plant with a function $f(T)$ such that $f(T)Q$ gives the electricity produced, where by Q we denote the primary energy input, e.g. wind or water flow. The function f is increasing, $f' > 0$, reflecting technological progress. Technological progress is deterministic in our model. We assume Q to be fix for simplicity's sake, a possible extension would allow for Q being stochastic. This setup yields the following current profit function of the investor

$$\pi = (P - c)f(T)Q,$$

where c denotes unit operational costs. We thus assume that the plant operates under a constant returns to scale technology, this assumption can, however, be modified easily.

Control Variable We now introduce the investment decision. The owner of a plant has to decide whether or not to adopt a new technology, incurring the cost of the new investment and renouncing profits with his current technology (note that the latter are limited to the remaining lifetime of the plant). His choice is captured by the discrete control variable u

$$u = \begin{cases} u = 1 & : \quad adopt \\ u = 0 & : \quad non - adopt \end{cases}$$

The control variable enters both into the objective function and the laws of motion of the deterministic state variables age A and technology T.

Objective function The objective function is the current profit minus the cost of an investment if it occurs. It thus mimicks the one period balance sheet of the investor:

$$\pi(P_e, P_k, T, u) = (P_e - c)f(T)Q - P_k u \tag{3}$$

Here T stands for the current state of technology. Any investment comes into effect with a time lag of one period, which is modelled by the effect of the choice $u = 1$ on T. The effect is captured by the laws of motion for A and T.

The law of motion for A is straightforward:

$$A' = \begin{cases} 1 & : \quad u = 1 \\ 0 & : \quad u = 0, \quad A = 0 \\ A + 1 \mod m & : \quad u = 0, \quad A \neq 0 \end{cases} \tag{4}$$

Any decision to invest sets the age of the plant to 1 - this explains the first case. Recall that $A = 0$ refers to the case where there is no plant. This state is left unchanged if there is no new investment and thus $u = 0$ - this explains the second case. If there is a plant and the owner decides against reinvestment, it grows older by 1 until the maximal age m is reached - this explains the third case.

The law of motion for T requires some more explanation.

$$T' = \begin{cases} T & : \quad u = 0 \\ T + m & : \quad u = 1, \;\; T = 0 \\ T + A & : \quad u = 1, \;\; T \neq 0 \end{cases} \tag{5}$$

The first case is simple - whenever the control variable is choosen to be $u = 0$, no investment occurs and the state of technology is left unchanged. The second and third case can be explained as follows: Technology advances each period, independent of the investment decision of the owner. The number of periods that passed since the last innovation is expressed by the age of the plant A. Thus, if the owner of a plant in technological state T and age A decides to renew his plant, the available state of technology is $T' = T + A$. This explains the third case[3]. A general problem of the dynamic programming approach is that in principle, technology T advances indefinitely - which would make the model intractable. The implementation requires boundaries for each state variable. Consequently, in the case of the plant being put down we limit the technological progress to the maximal age. This explains the second case in the law of motion for the state of technology.

Bellman equation We now have defined all ingredients for the Bellman equation of our model: The objective function (equ. 3), the law of motion $P'_e = P'_e(P_e)$ for the price of electricity (equ. 1), the law of motion $P'_k = P'_k(P_k)$ for the price of capital (equ. 2), the law of motion $A' = A'(A, T, u)$ for the age of the plant (equ. 4) and the law of motion $T' = T'(A, T, u)$ for the employed technology (equ. 5). We can thus formulate the Bellman equation (BM) with the value function Π that denotes the discounted sum of the stream of profits

$$\begin{aligned} \Pi(P_e, P_k, A, T) \quad &= \quad \max_{u \in \{0,1\}} \pi(P_e, P_k, T, u) + \beta E[\Pi(P'_e, P'_k, A', T') | P_e, P_k] \\ s.t. \quad & P'_e = P'_e(P_e) \\ & P'_k = P'_k(P_k) \\ & A' = A'(A, T, u) \\ & T' = T'(A, T, u) \end{aligned}$$

The expectation operator in (BM) calculates the expectated value Π with respect to the stochastic state variables P_e and P_k, taking into account their laws of motion and the distribution of the shock variables μ and ϵ. In section 4 we solve the calibrated version of (BM) for the value function

$$\Pi(P_e, P_k, A, T)$$

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[3] One implicit assumption we make in the model is that only current technology is available at one price level P_k.

and the policy function

$$u = u(P_e, P_k, A, T).$$

The policy function u indicates when innovative investment is optimal, for a given plant of age A and technology T and price levels P_e and P_k. It thus allows for a study of investment behaviour under price uncertainty.

4 Calibration

Whereas the -very stylized- model described in the previous section allows for a study of investment in any renewable plant - indeed in any electricity plant - we have to calibrate the model to obtain meaningful results. Consequently, in this section we describe the calibration of our model for investment into a wind plant. We use German data and refer to the legislation of the German feed-in-tariff (EEG).

Period length First, some choices have to be made. We start with period length which is set to two years - this seems resonably short given that we intend to study investment in wind energy. The average time to erect a wind mill is ... years. In accordance with the technical literature we set the lifetime of a wind plant to 20 years, i.e. 10 periods (cf. ECN 2007). Furthermore, we set the biannual real term interest rate to 5%, which corresponds to a time discount factor $\beta = 0.95$.

Technology As for technological progress, we calibrate it as growth in size. That is, wind energy plants become more productive as they become bigger. This choice is motivated by the technological development of the last decade, as depicted in Figure 2. The data provided by DEWI (2007) show an increase of average capacity between 1.02% and 1.49% for the years from 1993 to 2007. The average growth rate for that period is $t_{gr} = 1.16\%$ per year. To capture the development correctly, we modify the original profit function and use the following instead:

$$\pi(P_e, P_k, T, T', u) = (P_e Q - c)f(T) - P_k f(T')u,$$

where we specify technological growth by

$$f(T) = (1 + t_{gr})^T.$$

The new formulation of the profit function takes into account that replacing a small by a large wind plant requires higher investment: P_k is the unit price for wind power capacity, the growth in capacity is reflected in the cost of the new plant $P_k f(T')$. The second modification of the profit function is due to the fact that operating a wind plant entails fix rather than operational costs: the bulk of costs is O&M which has to be paid for independently of the actual output that is largerly determined by the weather. O&M costs roughly increase proportionally with the size of capacity - and so they enter with $cf(T)$ into the profit function. The value of c is taken from the study by ECN (2007). Given our choice of profit function, Q is calibrated as the binannual average output of electricity for a unit of installed capacity. To obtain the figure, we have evaluated tables of electricity output of wind plants published by the German Association of Wind Energy (BWE 2008). The average output for the years 1990 to 2007 is $Q = 160.38MWh$ for one Megawatt installed capcity.

Price Processes The publication BWE (2008) is also used to calibrate the price process P_k for capital. The collection of annualy published reports from 1990 to 2007 contains advertisements of wind plants, specifying capacity and price. From this information we calculate a time series of average prices of capacity[4]. The time series is then used to calibrate the Markov price process 2 for P_k. Assuming μ_k to be normally distributed we obtain $\alpha_k = 0.3562$, $\beta_k = 0.6067$ and variance $\sigma_k = 0.0281$ for the process

$$P_k' = \alpha_k + \beta_k P_k + \mu_k.$$

The case of the electricity price is more intricate, since we are going to study support programs for renewables. The decisive difference between FIT and ROC regulation is the allocation of risk: Under FIT, the owner of a renewable plant only bears the climatic risk associated with his particular technology (wind intensity in our case), which we do not model explicitly, but no price risk. In contrast, under ROC the owner bears both the price risk of the electricity price and the renewable obligation certificate, leading to a particularly volatile price process. Moreover, as discussed in the literature review, the ROCs are normally augmented with a price cap to avoid extreme price spikes in times of high demand for electricity and short supply of renewable energy (in Britain, this price cap was relatively low and usually binding). Both the construction of ROC regulation and the physical potential for electricity generation from renewable energy influence the likely price path for electricity faced by the owner of a renewable plant. As the concept has not been implemented in Germany, we can only calculate a stylized example for an ROC price process. Our main goal is to understand the reaction of the investor to the price volatility he faces under ROC in comparison to FIT.

For FIT, we implement the price scheme for wind energy from the German renewable-energy-feed-in-law (EEG) of 2000. As a comparison we implement a price process that has the same and higher volatility as the electricity price process actually to be found in Germany. To obtain this volatility, we estimate a time series of household electricity prices from OECD data. This estimation yields the coefficients $\alpha_e = -0.1446$, $\beta_e = 0.9188$ and variance $\sigma_e = 0.0605$ for the econometric specification of equation 1

$$P_e' = \alpha_e + \beta_e P_e + \mu_e.$$

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[4] Only wind plants with a capacity of more than 0.5 MW were taken into account.

The details of the policy analysis are discussed in the following section.

Boundaries Finally we set bounds on the state variables. As mentioned in the section "model", all state variables have to be bounded from above and below to allow for the numerical implementation. We have already justified our choice for the maximal age m of a plant. For the technology parameter, we allow a maximum of five steps - or ten years growth of average capacity. While putting a somewhat arbitrary cap on a possibly much larger increase in scale, the range chosen for T certainly allows for a study of the implication of renewable support policy. As for the price process, we have chosen the following ranges: Between 0% and 200% of the long-term average price of capital for P_k, and between 30% and 170% for the average price of electricity P_e. As the time series we have calculated show, these ranges chosen encompass the variation of data in our sample period.

5 Results

In this section, we present the (preliminary) results of our simulation exercise. Our model has been implemented in MATLAB. The price processes have been discretized - including the shock variables - and (BM) has been solved by value function iteration. The price grids have a length of 20. For our first analysis, we use an electricity price process with the mean equaling the tariff from the EEG and the variance the one of the electricity prices. As a numerical output, we obtain the value function $\Pi(P_e, P_k, A, T)$ and the policy function $u(P_e, P_k, A, T)$. These have the form of a 20x20x10x5 array - a rather large number of points. Fortunately, the function that is of most interest to us, $u(.,.,.,.)$, only takes the values in $\{0, 1\}$. Analysing this type of result requires a concept for the definition of diagrams and indicators. Plotting the price of capital P_e against P_k, Figure 2 shows the areas for which the the owner of a wind plant decides to invest (red) or not to invest (blue), given a certain age A of a plant and a state of technology T. A given price of electricity and capital means that the investor can form his expectation of the further development of that price, given the underlying Markov process.

A glance at the diagrams gives a first impression of the outcome: We see that in all diagrams the likeliness to invest increases with the price of electricity and decreases with capital costs. This is a plausible result: Higher electricity prices mean higher future revenues, lower capital prices mean lower capital costs. A comparison of diagrams shows that the likeliness to invest increases with the age of the plant and decreases with the advance of technology. This is plausible, too: An older plant is closer to the end of its lifetime, so the opportunity costs of investment are lower than for a new plant. And the gains from innovation are lower if the employed technology is already quite advanced.

This discussion of the results is based on a somewhat arbitrary selection of age-technology profiles for the wind plant. To allow for a more systematic analysis, we define an indicator: the "Propensity to Invest". It measures the red area of the diagram as percentage of the whole area and thus shows how likely the owner of the wind park is to renew his plant. With the help of the indicator, we compare the development of the investment behavior across states. Figure 4 and 5 show diagrams of the propensity to invest for the FIT and the ROC policy. The lines show the developement of the indicator with increasing age of the plant, they are ordered by the states of technology. The graphs confirm the first impressions drawn from Figure 3: the propensity to invest increases with age of the plant and decreases with the advance of technology.

Figure 4 and Figure 5 allow for a first comparison of the ROC and the FIT policy. The price process used here to distinguish the two policies have been detrended, the difference between the two policies is the variation around the mean. First, we note that the difference is not very strong - price variation has an influence, but not much. The astonishing fact is that ROC makes investors more, not less likely to innovate in comparison to FIT. This is somewhat counterintuitive: One would expect the certainty ensured by the feed-in-tariff to make investments more likely. This is how Mitchell et al. (2006) argue in their -informal- comparison of the German EEG and the British ROC. Clearly, our results tend into the opposite direction. Note, however, that there is one striking difference between the intuition and real option models like ours: we neglect risk aversion, focussing exclusively on the opportunities offered by the interaction of risk parameters.

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A Figures

Figure 1: Renewable Energy Targets in the EU

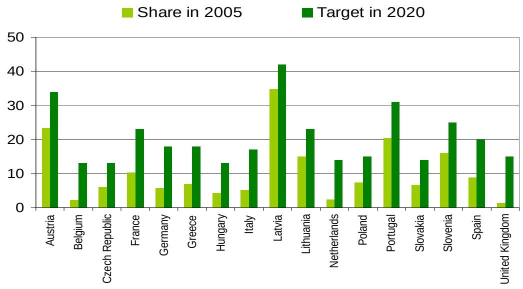
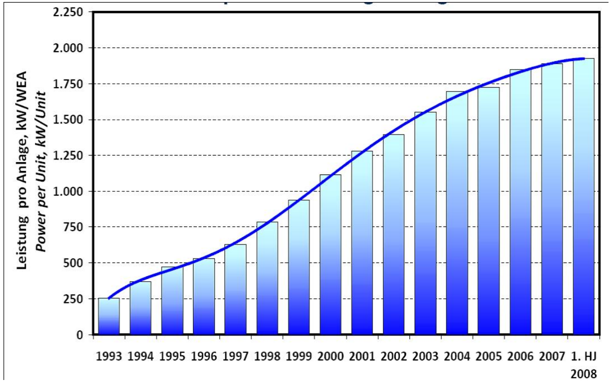
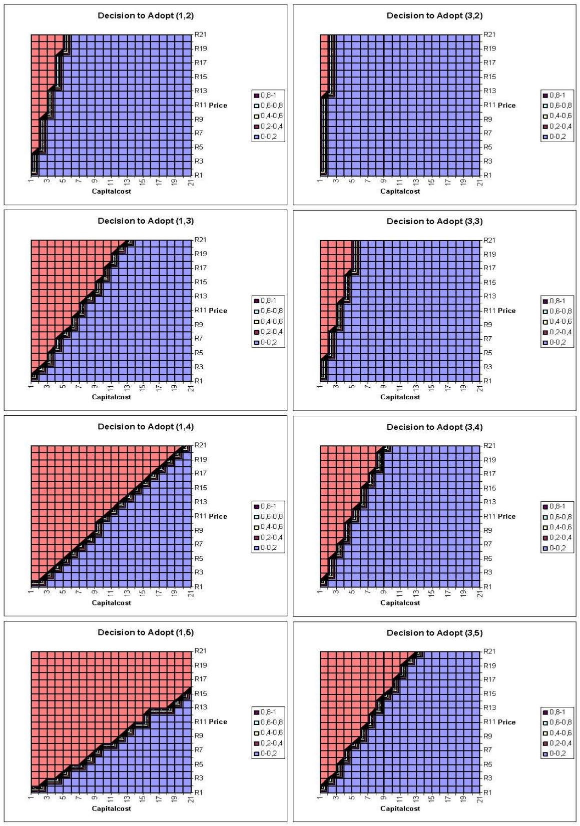


Figure 2: Development of Average Wind Capacity



Source: DEWI (2007)

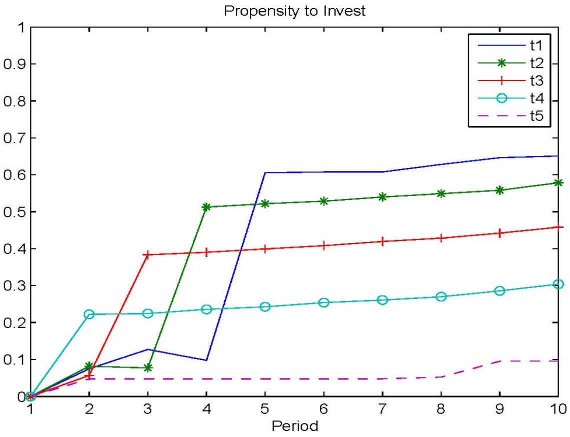
Figure 3: Decision to Adopt New Technology



Red – Adopt, Blue – Non-Adopt

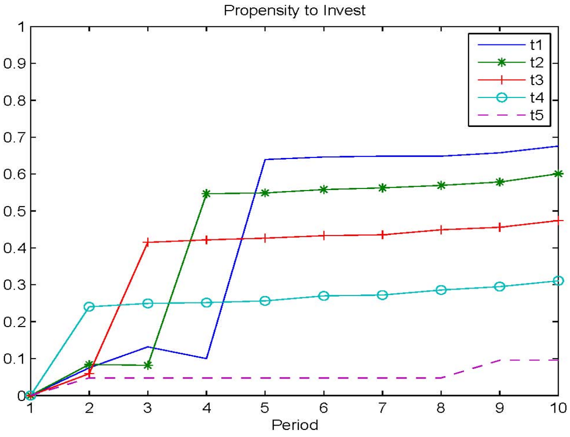
For (T,A) with T - state of technology and A - age

Figure 4: Propensity to Invest



under the FIT price process

Figure 5: Propensity to Invest



under the ROC price process