

Mennel, Tim; Scatasta, Sara

**Conference Paper**

## Comparing Feed-In-Tariffs and Renewable Obligation Certificates - a Real Option Approach

Beiträge zur Jahrestagung des Vereins für Socialpolitik 2010: Ökonomie der Familie - Session: Environmental Policy: Incentives and Instruments, No. F18-V3

**Provided in Cooperation with:**

Verein für Socialpolitik / German Economic Association

*Suggested Citation:* Mennel, Tim; Scatasta, Sara (2010) : Comparing Feed-In-Tariffs and Renewable Obligation Certificates - a Real Option Approach, Beiträge zur Jahrestagung des Vereins für Socialpolitik 2010: Ökonomie der Familie - Session: Environmental Policy: Incentives and Instruments, No. F18-V3, Verein für Socialpolitik, Frankfurt a. M.

This Version is available at:

<https://hdl.handle.net/10419/37153>

**Standard-Nutzungsbedingungen:**

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

**Terms of use:**

*Documents in EconStor may be saved and copied for your personal and scholarly purposes.*

*You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.*

*If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.*

# Comparing Feed-In-Tariffs and Renewable Obligation Certificates - a Real Option Approach

Tim Mennel\*  
Sara Scatasta†

January 29, 2010

*Preliminary version - do not quote!*

## Abstract

The increase of the share of renewable energy in total energy production is a stated goal of environmental and industrial policy in many developed countries. Governments adopt regulation to support the investment into renewable energy infrastructure, in particular in power generation. Two main policy instruments emerge: renewable quotas and feed-in-tariffs. Quota systems, such as the British ROCs, oblige an electricity producer to certify that a fixed share of his electricity is 'green', i.e. generated from renewable sources. Feed-in-tariffs, such as the German EEG tariffs, guarantee a certain, fixed price for 'green' electricity, depending on the technology. The decisive difference between the instruments is the allocation of price risk. The paper presents a real option framework to study the effect the instruments on investment and innovation of renewable energy plants. The modelled is calibrated on data for German Wind power plants. We find that the propensity to invest is higher under a quota system. So the presence of price risk spurs technological innovation.

JEL classification: Q28, Q48, H23

Keywords: Renewable Energy, Investment support policy, Real Options

---

\*Corresponding Author, e-mail: mennel@zew.de. Department of Environmental Economics, Center for European Economic Research (ZEW), P.O. Box 103443, D-68034 Mannheim, Germany

†Chair of Development Policy, University of Hohenheim, Wollgrasweg 43, D-70599 Stuttgart, Germany.

# 1 Introduction

Renewable energy is one of the core issues in the European energy policy debate. There is today broad support among policy makers for the goal of increasing the share of renewable energy in the European energy mix. Most visibly, European leaders have included a renewable target in their climate policy goals: They are supposed to cover 20% of primary energy consumption by 2020. While there is near-consensus on this goal in the policy arena<sup>1</sup>, opinions differ on how to achieve it. Consequently, a recent EU directive on renewable energy (2009/28/EC) calls for national renewable energy action plans and sets national targets rather than introducing a uniform renewable policy across the EU. In this paper, we will focus on electricity generation.

Clearly, at current costs, electricity generation from renewable sources is not competitive, and so market intervention is necessary to achieve the renewable quotas (a notable exception is hydro power, which has, however, little potential for further development). Governments across the EU have thus introduced different policy instruments to increase installed capacity and speed up market maturity of renewable energy.

These policy instruments fall into two categories: quota systems and feed-in-tariffs. A quota system has been introduced, for example, in the U.K.<sup>2</sup>. Under the rules of this system, electricity companies have to ensure that a fixed quota of the electricity they sell is generated from renewable sources. They are not obliged, though, to produce this electricity themselves: Eligible renewable energy plants receive so called Renewables Obligation Certificates (ROC) corresponding to the amount of electricity they produce. The ROCs are then sold in a certificate market so that any electricity supply company can fulfill its quota. For renewable energy plants, there are thus two sources of revenue, stemming from the sale of electricity and the sale of certificates.

Other countries, such as Germany, have opted for feed-in-tariffs instead<sup>3</sup>. Under this system, the electricity generated from renewable energy is sold to power supply companies at a fixed minimum price (e.g. in the case of on-shore wind energy, 9.1 c/KWh in the first five years of operation and at 6.19 c/KWh for further 15 years). The additional cost for renewable energy is covered by a proportional charge on electricity consumption.

While ROCs represent a market based instrument that at least in theory should be able to achieve its goals more efficiently than command-and-control instruments such as feed-in-tariffs, in practice ROCs quotas often fail to be met and companies prefer to pay a fine than buying ROCs. Butler and Neuhoff (2004) suggest that judging from the size of installed and generating capacity for on-shore wind energy in Germany and the UK, feed-in-tariffs seem to have

---

<sup>1</sup>Some economists have criticized the goal, e.g. Frondel et al. (2008).

<sup>2</sup>Quota systems for the promotion of renewable electricity has been established in thirteen U.S. states, as well as in Japan, Italy and Australia (cf. the overview by Sawin, 2004, as well as Butler and Neuhoff, 2004).

<sup>3</sup>Feed-in-Tariffs are also used in Spain, France, Austria, Denmark, Portugal and South Korea.

been more effective than ROCs in increasing the proportion of renewable energy in the energy mix. One of the hypotheses advanced in the literature supporting Butler and Neuhoff suggestion is the different impact these systems have on the amount of uncertainty surrounding investor decisions in the renewable energy sector. Mitchell et al. (2006) argue, for example, that the German feed-in-tariff system is "ore effective at increasing the share of renewables than the England and Wales RO because it reduces risk", in particular the downside risk of investment in renewable energy generators more effectively. In their line of argument Mitchell et al. assume that reducing risk is a key factor in the effectiveness of a policy instrument trying to increase investments in a particular sector.

In this paper we present a model to compare quota systems and feed-in-tariffs and to study the argument by Mitchell et al. (2006). Our focus is on investment and innovation. While a number of environmental concerns are brought forward in the political debate on renewable energy, the major economic argument in favor of renewable energy support is the promotion of innovation: An early adoption of renewable energy in the energy supply chain speeds up technological development, so the argument goes, leading to earlier market maturity. While classical economic theory is not in line with this view of the government's role in innovation activities<sup>4</sup>, many economists today see some role of the government in research and development, and some in subsequent innovation. Since benefits from inventions and innovations are not fully appropriable due to spill-over effects (Griliches 1979), private R&D expenditures are likely to be insufficient in welfare terms and should therefore be complemented by an R&D policy. Direct subsidies to an innovative industry can be justified under the "Learning by Doing" paradigm (Arrow, 1962, Young, 1993).

As pointed out by Mitchell et al. (2006), the central difference between a quota system and a feed-in-tariff is the allocation of (price) risk. Under a quota system, the owner of a renewable energy plant is exposed to price risks on electricity wholesale markets and on the market for green certificates. Under a feed-in-tariff, the price risk is eliminated. In this paper, we present a real option model to study the effect of QS and FiT on investment in innovation in a renewable energy plant. 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 (cf. Dixit and Pindyk 1994). Our model focusses on the innovation decision problem by the owner of a renewable energy plant given the price risk he faces under the alternative policies.

In our empirical application we will focus on the case of wind energy power

---

<sup>4</sup>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)

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. However, their calculation is based on available data and does not capture the impact of regulation on innovation. Their suggestion to adapt the feed-in-tariff regularly to (reported) lower production costs ignores the possibly detrimental feed-back effect on the implementation of new technological kit. Kildegaard (2008) develops a theoretical framework showing that the liquidity problems of ROC markets may be due to the presence of low-fixed cost technology competing against high fixed-cost technologies in the certificate market. In contrast our study focusses on the role of price uncertainty and irreversibility on innovation in renewable energy plants under different regulatory regimes.

Our results are in some contrast to the view put forward by Mitchell et al. (2006). We show that the propensity of a wind plant owner to renew his plant is actually higher under a quota system. This is due to a lock-in effect: Given the security of fixed prices, there is less pressure to adopt the latest technology. Wind plant owners that face the price risk are more likely to innovate to capture the extra rents.

The rest of the paper is structured as follows: Section 2 introduces the model and formalizes the notion of the two policy regimes. The calibration is presented in section 3. Section 4 describes the results of the numerical exercise, section 5 concludes.

## 2 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 quota system (QS). 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<sup>5</sup>

$$P'_e = \alpha_e + \beta_e P_e + \mu_e, \quad (1)$$

where  $\mu$  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

$$P'_k = \alpha_k + \beta_k P_k + \mu_k, \quad (2)$$

with  $\epsilon$  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<sup>6</sup>  $T$  as two deterministic state variables. As we assume a 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  $u$

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

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

<sup>5</sup>Here and in the sequel, we denote the forward time shift by a dash.

<sup>6</sup>By the term "employed technology" we refer to the technology installed as distinguished from available technology.

**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:

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

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:

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

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.

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

The first case is simple - whenever the control variable is chosen 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<sup>7</sup>. 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

<sup>7</sup>One implicit assumption we make in the model is that only current technology is available at one price level  $P_k$ .

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  $\Pi$  that denotes the discounted sum of the stream of profits

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

The expectation operator in (BM) calculates the expected value  $\Pi$  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  $\mu$  and  $\epsilon$ . In section 4 we solve the calibrated version of (BM) for the value function

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

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.

### 3 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 reasonably short given that we intend to study investment in wind energy. The time to erect a wind mill varies between a few days and a few months - depending on the geographical site. 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 largely 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  $Q = 160.38 MWh$  for one Megawatt installed capacity.

**Price Processes** The publication BWE (2008) is also used to calibrate the price process  $P_k$  for capital. The collection of annually 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<sup>8</sup>. The time series is then used to calibrate the Markov price process  $2$  for  $P_k$ . Assuming  $\mu_k$  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 QS 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 QS the owner bears both the price risk of the electricity price

<sup>8</sup>Only wind plants with a capacity of more than 0.5 MW were taken into account.

and the renewable obligation certificate, leading to a particularly volatile price process. Moreover, as discussed in the literature review, the QSS 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 QS 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 QS price process. Our main goal is to understand the reaction of the investor to the price volatility he faces under QS 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

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

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.

## 4 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 QS policy. The lines show the development 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 QS 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. Figure 6 and 7 show the full picture with trend. First, we note that the difference is not very strong - price variation has an influence, but not much. The astonishing fact is that QS 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.

## 5 Conclusion

We have developed a model of investment into innovation in a wind electricity plant. It shows the propensity to invest of a wind plant owner under different renewable support schemes for a given plant, characterized by its age and state of technology. Surprisingly, a wind park owner is more likely to adopt a new technology under a quota system. We interpret the result as a lock-in effect of the alternative system, feed-in-tariffs. In contrast, under quota systems, it is paying off to capture the extra rents from renewing the plant. Of course the framework chosen is very stylized: As we do not know the extend of likely extend of variation in the price of a quota system in the German market, we have to assume that they are at least as high as electricity price volatility. Also, the model does not incorporate potential liquidity problems. However, our results suggest that uncertainty can enhance innovation rather than slow it down. In policy aimed at promoting market maturity, that should count as an argument.

## References

- [1] Arrow, K. (1962), "The Economic Implications of Learning by Doing", *Review of Economic Studies*, 29
- [2] Barro, R. J. and X. Sala-i-Martin (1995), "Technological Diffusion, Convergence, and Growth", Department of Economics and Business, Universitat Pompeu Fabra, Economics Working Papers
- [3] Böhringer, C. and T. Hoffmann and T. F. Rutherford (2007), "Alternative Strategies for Promoting Renewable Energy in EU Electricity Markets", *Applied Economics Quarterly* 58 Supplement, 9-26
- [4] Botterud, A. and M. Korps (2004), "Modelling of Power Generation Investment Incentives under Uncertainty in Liberalised Electricity Markets", 6th IAEE European Conference, 1-3
- [5] Butler, L. and K. Neuhoff (2004), "Comparison of feed-in-tariff, quota and action mechanisms to support wind power development", *Renewable Energy* 33 (8), 1854-1867
- [6] Dixit, A.K. and R. S. Pindyck (1994), "Investment under uncertainty", Princeton: Princeton University Press, 468
- [7] Frondel, M., N. Ritter, and Ch.M. Schmidt (2008), "Germany's Solar Cell Promotion: Dark Clouds on the Horizon", *Energy Policy* 36
- [8] Griliches, Z. (1979), "Issues in assessing the contribution of research and development to productivity growth", *Bell Journal of Economics* 10 (1)
- [9] Griliches, Z. (1992), "The search for R&D spillovers", *Scandinavian Journal of Economics* 94 (S)

- [10] Hicks, J. (1932), "The Theory of Wages", London
- [11] Jaffe, A. and R. Newell and R. Stavins (2005), "A tale of two market failures: Technology and environmental policy", *Ecological Economics*
- [12] Kildegaard, A. (2008), "Green certificate markets, the risk of over-investment and the role of long-term contracts", *Energy Policy* 36, 3413-3421
- [13] Kühn, I. and G. J. Schaeffer and M. Voogt and C. Crookall-Fallon (1999), "How to improve the framework and design of national policies for the promotion of renewable electricity. Observations on Germany, the Netherlands and the UK", Final Paper of REALM Working Group III
- [14] Kühn, I. (2001), "Renewable Energies & Green Certificate Trading in the EU", *WorldPower 2001 Vol.2*, Isherwood Production Ltd., 84-86
- [15] Mitchell, C. and Bauknecht, D. and P. M. Connor (2006), "Effectiveness through risk reduction: a comparison of the renewable obligation in England and Wales and the feed-in-tariff system in Germany", *Energy Policy* 34, 297-305
- [16] Popp D. (2002), "Induced Innovation and Energy Prices", *American Economic Review* 92 (1)
- [17] Sawin, J. L. (2004), "National Policy Instruments - Policy Lessons for the Advancement and Diffusion of Renewable Energy Technologies around the World", Worldwatch Institute
- [18] Young, A. (1993), "Invention and Bounded Learning by Doing", *Journal of Political Economy* 101(3)

## A Figures

Figure 1: Renewable Energy Targets in the EU

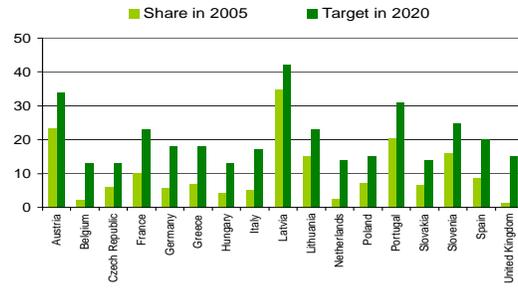
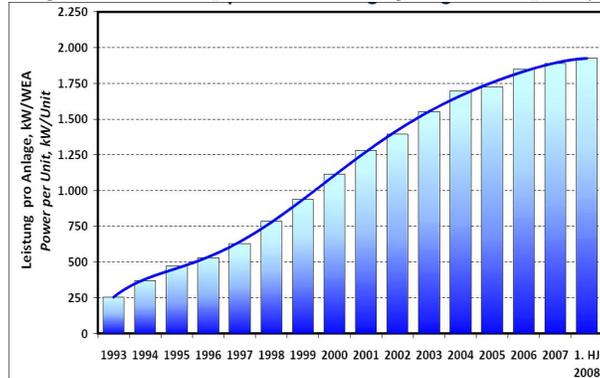
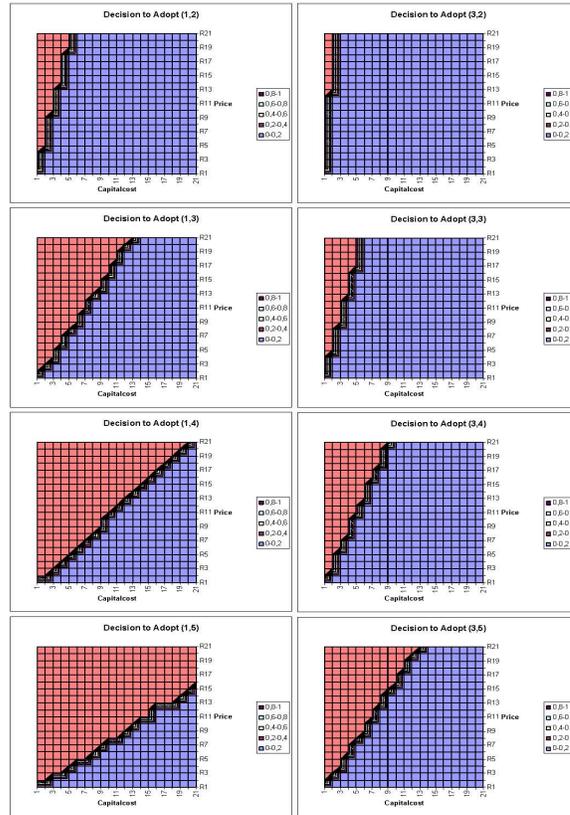


Figure 2: Development of Average Wind Capacity



Source: DEWI (2007)

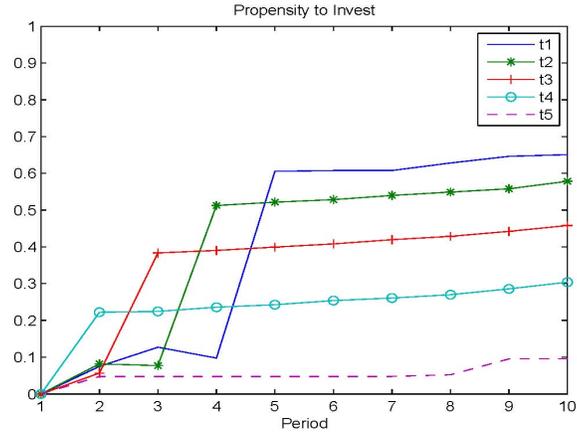
Figure 3: Decision to Adopt New Technology



*Red – Adopt, Blue – Non-Adopt*

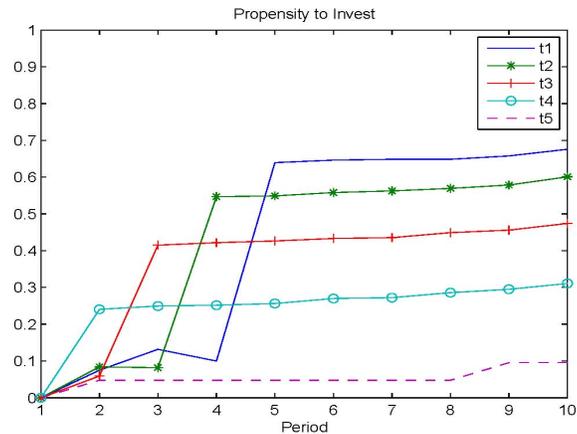
For (T,A) with T - state of technology and A - age

Figure 4: Propensity to Invest



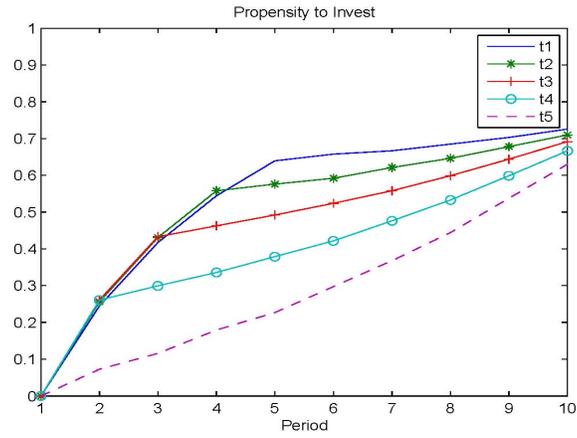
under the FiT price process (detrended)

Figure 5: Propensity to Invest



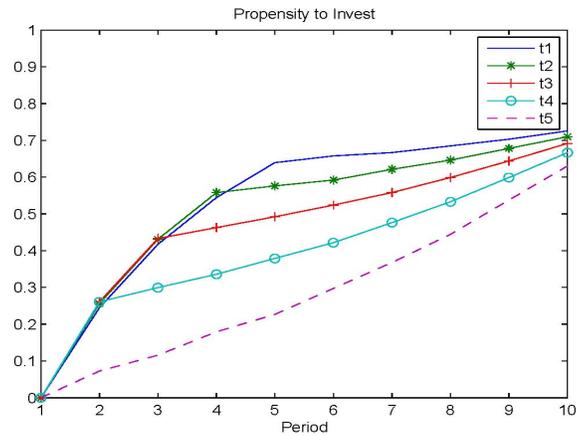
under the QS price process (detrended)

Figure 6: Propensity to Invest



under the FiT price process (with trend)

Figure 7: Propensity to Invest



under the QS price process (with trend)