Regulation and Grid Expansion Investment with Increased Penetration of Renewable Generation

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Abstract

The recent trend toward decarbonization led to crucial challenges for network operators and regulators in terms of network reliability and optimal grid expansion. In order to analyze the effects of rising production uncertainty caused by renewable energy sources on further investment timing decisions in both generation and transmission sector, the following article brings the two sectors in a single real options framework together. This allows us to derive the optimal timing of the production capacity expansion and the optimal transmission price. We find that increasing penetration through renewables leads to investment postponement in both sectors, which goes along with increased systematic risk. However, we show that the negative effects on the transmission firm can be overcome by choosing an appropriate incentive system.

Keywords: Regulation, Renewables, Price Cap, Real Option
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1 Introduction

Renewable energy generation is one of the most discussed topics in the recent European energy policy debate. Unbundling the electricity production from transmission and distribution allowed smaller companies to enter the market and helped boost renewable electricity investments. Based on the Kyoto Protocol and the EU's climate change package, the European leaders set a renewables target by 2020 (20% cut in emissions and 20% increase in clean energy sources). One major characteristic of renewable energy sources is that its output is hardly predictable and highly volatile. Hence, it challenges both the owners of production facilities and the downstream firms within the energy cycle who have to handle the varying production output when transmitting and distributing the energy from the producers to the final consumers. The current debate on investment needs into the transmission sector rises for many reasons. First, the existing assets that are at the end of their lives need to be replaced and second, the system needs to accommodate the growing amount of renewables that are often situated far away from the existing grid (Pollitt (2008)). However, the financial crisis has raised some concerns about the ability of the electricity markets to deliver efficient and timely investment in capacity. In Northern Europe, the supply volatility from wind generation already causes significant grid management challenges that could be solved by further EU market integration and interconnector capacity investments (Pollitt (2009)).

From the perspective of regulatory economics, the interdependency between the producing sector and the regulated transmission and distribution market as well as the impact of renewable energy sources (further denoted as RES) and the changing production mix on the efficiency and effectiveness of regulation are the most important questions that have to be addressed in the near future. Therefore, the interactions between producers and transmission or system operators as well as regulators lie the center of the following article. In particular, we focus on the interdependencies between investment decisions of producers and transmission or distribution operators when they are confronted with increasing shares of production stemming from RES. For this, we derive a dynamic real options model in which both investment decisions can be analyzed simultaneously.

In this context, the real options related literature can be divided into two different strands, studies dealing with energy production facilities and studies related to transmission. Investments into energy producing facilities in general are studied for example by Frayer and Uludere (2001), who analyze two generation assets in a regional market in order to demonstrate how a real options-based valuation framework uncovers and quantifies the value of efficient plant operation when facing volatile electricity market prices. They show that a peaking gas-fired facility may be more valuable than a mid-merit coal-fired plant, even though traditional methodologies would favor the coal-fired asset given its lower marginal cost. Also Hlouskova, Kossmeier, Obersteiner, and Schnabl (2005) analyze the value of generation capacity via real options modeling in the German market. The paper by Martinez-Cesena and Mutale (2011) proposes an advanced real options methodology for renewable energy planning. Based on this hydropower case study, they conclude, that the real options theory requires further development to significantly enhance renewable projects. Kumbaroglu, Madlener, and Demirel (2008) develop an investment planning model that integrates learning curve information on renewable power generation technologies into a real options model. They show that renewable energy investments occur in large measures only if targeted polices exist. However, because of the learning by doing effect, the renewable investment cost converges to the investment cost of non-renewable alternatives in the long run and can successfully compete with them. For the second strand of research on grid investments, Ramanathan and Varadan (2006) have to be mentioned, who develop a real options model that is solved by using binomial tree valuation. Also, Boyle, Guthrie, and Meade (2006) use a real options framework to evaluate the investment proposed by the regulator in New Zealand. An earlier study is given by Saphores, Gravel, and Bernard (2004) who analyze investment decisions into grid facilities with a dynamic real option model.

While many of these papers use the real options approach to derive optimal investment decisions in both production and transmission facilities, none looks at the interdependencies of investments within the different sectors. In the following article the producing firm is confronted with different development stages, which are distinguished by the share of energy produced by renewable sources. With an increasing renewables penetration, the production volatility increases, and thus influences further investments into generation facilities indirectly. However, this affects also the investment decision at the transmission grid level (i.e. into grid expansion and replacement investments). As the energy grid is a natural monopoly, we refer to a system operator confronted with a constant transmission price cap. Hence the benevolent regulator plays an important role in incentivizing the system operator to adapt the grid to the new requirements in order to assure the system's reliability.

The article is organized as follows. Section 2 describes the model and derives the optimal timing of the production and transmission investments. This section furthermore computes the optimal transmission price and also sheds light on the value and risk implications of these investments. Section 3 analyzes the case of discrete production capacity expansion by offshore wind power and is based on European data. Finally, section 4 summarizes the findings and concludes.

2 Model Description

In this section, we develop the model that allows us to study investment decisions into RES production simultaneously with investments into transmission facilities.

Hence, we introduce an increasing level of RES penetration that takes place in discrete steps. This makes the final electricity production more volatile, which also affects the prospective grid expansion. Therefore, we start with the investigation of the investment decisions into clean energy production facilities and derive the optimal timing of the future production expansions that are highly influenced by the increasing generation volatility. This analysis is followed by the examination of the transmission side. We develop an optimal incentive regulation, in which the uncertainty that comes from the production side is considered. Finally, we give insights into the risk implications for both firms dealing in the unbundled production and transmission sector.

Let the total electricity production at time t be given by the following function:

$$Q_t = Q_0 + X_t(Q_i - Q_0), \tag{1}$$

where i denotes the level of RES penetration that is increasing in i. For simplicity, the initial production capacity level (Q_0) is assumed to have no renewable generation source that yields a constant production. Further we assume that the firm can only invest into clean energy sources, hence Q_i denotes the increased production capacity level at the i^{th} level of RES penetration. As indicated in (1), only the electricity produced by RES ($Q_i - Q_0$) is subject to a production uncertainty variable X_t that follows a geometric Brownian motion process specified as[1]

$$dX_t = gX_t dt + \sigma X_t dW_t,$$

where W_t is a standard Wiener process and g and σ stand for the growth rate and volatility of X_t, respectively. Following Carlson, Fisher, and Giammarino (2004), we refer to a risk neutral formulation, such that the construction of a hedging portfolio is possible[2] with

$$dX_t = (r - \delta)X_t dt + \sigma X_t dW_t,$$

where r denotes risk free rate and δ stands for the convenience yield. The overall production function is visualized by Figure 1. The figure shows that the electricity production is constant until the first capacity expansion (Q_1). Due to the production uncertainty parameter, higher renewable penetration leads to higher volatility in the overall electricity generation.

For market clearing, we assume further that the linear industry demand function for electricity is given by

$$P_t = D - \phi Q_t = D - \phi(Q_0 + X_t(Q_i - Q_0)),$$

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[1] In reality, this production uncertainty refers to the uncertainty in the load factor.

[2] This weighted portfolio consists of a riskless bond B_t with the dynamics $dB_t = rB_t dt$ and a risky asset S_t, with dynamics $dS_t = \mu S_t dt + \sigma S_t dW_t$, where $\delta = \mu - g > 0$.

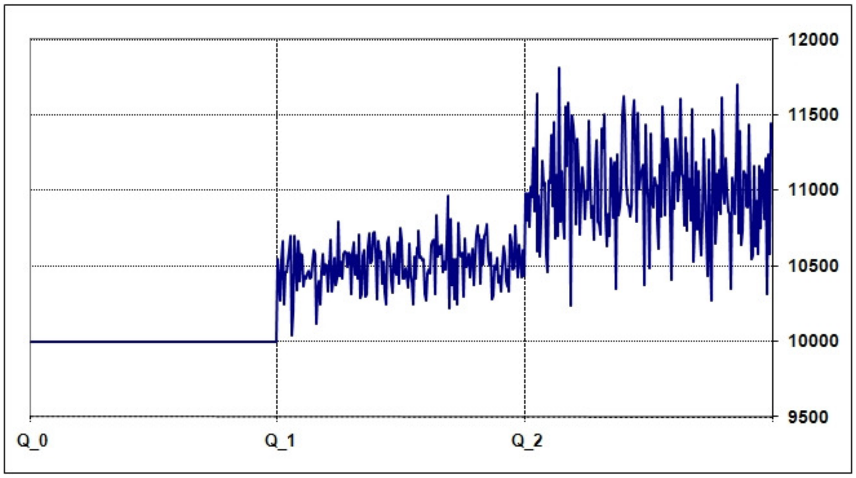

Figure 1: Simulated final electricity production with increasing share of renewables

where P_t and Q_t denote the price and the demand for electricity[3].

2.1 Investment into Renewable Energy Sources

Feed-in tariffs (FIT) are payments for renewably-generated electricity that were designed to promote renewable energy generation. Under FIT the grid utility has an obligation to be able to transmit and distribute all electricity produced by RES. Consequently, when a RES generation unit is built, it can be assumed that it always produces at full capacity. Otherwise, it would leave money on the table. Based on EWEA (2005), the share of renewable electricity generation in total electricity generation is technically bounded and cannot exceed an upper limit around 25%. Therefore, it is assumed that the electricity production can be expanded only for finitely many times (n) at investment cost I, i.e. it can be expanded in discrete and finite steps. With a fixed feed-in tariff, the profit flow for the generator at the i^{th} level of RES penetration can be written as

$$\begin{aligned} f_i &= P_t(Q_t)Q_0 + \bar{P}X_t(Q_i - Q_0) - F_i \\ &= DQ_0 - \phi Q_0^2 - X_t\phi Q_0(Q_i - Q_0) + \bar{P}X_t(Q_i - Q_0) - F_i, \end{aligned} \tag{2}$$

where F_i denotes the fixed cost of production. The firm is selling electricity from non-RES at the market price (P_t), while for all the electricity produced by RES it obtains a fixed price $\bar{P}$.

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[3] In this article demand uncertainty is neglected. The nonstorability of electricity implies that demand meets supply of electricity at every period (t). Consequently, the uncertainty coming from the production side also affects the market price of electricity.

Following **?**, for a given production level Q_i, the overall value of assets in place V_i^A is given by[4]

$$V_i^A(X) = \frac{X(Q_i - Q_0)(\bar{P} - \phi Q_0)}{\delta} - \frac{F_i + \phi Q_0^2 - DQ_0}{r}.$$

However, the market value (V_i) of the firm consists of the sum of the value of assets in place and the corresponding value of the growth options denoted by V_j^G that includes the possibility for a production capacity expansion by RES. Hence, it must hold that

$$V_i(X) = V_i^A(X) + \sum_{j=i+1}^{\infty} V_j^G(X).$$

Given the firm's profit flow and applying standard techniques based on Dixit and Pindyck (1994), the optimal investment timing can be derived by backward solution.

Proposition 1. *If the profit flow of the firm is given as* (2)*, the optimal timing of the investment is*

$$X_i^* = \frac{\delta \lambda_2}{(\lambda_2 - 1)} \frac{(rI_i + F_i - F_{i-1})}{r(Q_i - Q_{i-1})(\bar{P} - \delta Q_0)}; \qquad \forall \;\; i = 1, ..., n, \tag{3}$$

where λ_2 *corresponds to the positive root of the Bellman equation given by*

$$\lambda_2 = \frac{1}{2} - \frac{\mu}{\sigma^2} + \sqrt{\left(\frac{\mu}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma^2}} > 1.$$

Proof: See the Appendix.

Proposition 1 relates the optimal investment timing to the production uncertainty parameter X. When this parameter reaches a certain value, the investment into production capacity is triggered[5]. The obtained optimal investment timing is in line with the standard results in the real options literature (Dixit and Pindyck (1994)), however it is adjusted by a delay caused by the increasing level of RES. Thus, the

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[4] Without an investment option, the value of assets in place is equal to the expected discounted present value of future payoffs. For the detailed derivation see the Appendix.

[5] Since the production volatility in the model is constant, an implicit assumption is a single production technology. However, the model can be easily adapted to a diversified renewable production portfolio. In this context, the changing production volatility (σ_i) has to be considered at every stage of RES penetration. The optimal investment timing can be derived analogously and it has the same formulation as given in Proposition 1. The only difference appears in the positive root of the Bellman equation that will depend on the actual level of production volatility. With a diversified portfolio, the positive root of the Bellman equation is given as

$$\lambda_{2,i} = \frac{1}{2} - \frac{\mu}{\sigma_i^2} + \sqrt{\left(\frac{\mu}{\sigma_i^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma_i^2}}.$$

higher the share of renewable generation, the later will be the decision in favor of a new investment.

2.2 Grid Investment

In order to feed in all additional electricity from the RES into the transmission grid, an adaptation of the existing system is necessary (at least in the long run, but also as soon as the existing grid operates at its limits). This goes along with investments into existing or additional transmission lines. In order to incorporate this in our model, the previous part is enhanced by an additional investment possibility into grid facilities, which allows connecting the new production units and the transmission system. As the transmission market is subject to regulation in most countries, the following section will also consider the possibility of the regulator to shape the market. Therefore, let I^T denote the amount of investment necessary to connect the new RES production facility with the grid. The regulator's objective is now to assure that this amount will be invested at the previously derived threshold X_i^* at the latest such that no gap between the two investment timings occurs, which may endanger the systems' security of supply. This can be assured by optimally chosen incentive price caps, P_i.

The profit flow for the transmission firm that faces the price cap P_i is given by

$$f_i^T = (P_i - M)(Q_0 + X_t(Q_i - Q_0)), \tag{4}$$

where M denotes the marginal cost of transmission. Similar to the generation side, the transmission company's value of assets in place is defined as

$$V_i^A(X) = \frac{X(Q_i - Q_0)(P_i - M)}{\delta} + \frac{Q_0(P_i - M)}{r} - I_i^T.$$

Using this result, we are able to derive the transmission company's optimal timing of the grid investment for given transmission prices $\vec{P} = (P_0, P_1, ..., P_n)$.

Proposition 2. *Given the transmission company's profit flow as defined in* (4) *and fixed price cap levels* $\vec{P}$, *the value function and the optimal timing of the grid investment are given by*

$$V_i(X) = B_i^T X^{\lambda_2} + \frac{X(Q_i - Q_0)(P_i - M)}{\delta} + \frac{Q_0(P_i - M)}{r}; \qquad \forall \ i = 0, 1, ..., n \tag{5}$$

and

$$X_i^{T*} = \frac{\lambda_2 \delta}{r(\lambda_2 - 1)} \frac{(rI_i^T - Q_0(P_i - P_{i-1})}{(P_i(Q_i - Q_0) - P_{i-1}(Q_{i-1} - Q_0) - M(Q_i - Q_{i-1}))}, \forall \ i = 1, ..., n, \tag{6}$$

respectively, where the growth option parameter is defined as

$$B_i^T = \frac{[(Q_i - Q_0)(P_i - M) - (Q_{i-1} - Q_0)(P_{i-1} - M)]}{\delta \lambda_2 X^{\lambda_2 - 1}}. \qquad \forall \ i = 1, ..., n-1. \quad (7)$$

Proof: The proof results by following the same steps as introduced in the proof of Proposition 1. □

The optimal investment timing for the transmission operator is determined by (6). Similar to (3), the well known standard result in real options forms the basis that is adjusted by the markup on downstream market. As mentioned above, the regulator's objective is to assure the optimal grid expansion timing at the lowest possible transmission price. Assuming zero building time for the transmission investments, the optimal price cap has to be chosen to assure that the timing of the grid investment anticipates the timing of the generation expansion, i.e. $X_i^{T*} \leq X_i^*$. Since the higher the chosen price cap, the earlier the grid investment and vice versa (a direct implication of (6)), the optimal price cap must satisfy

$$X_i^{T*} = X_i^*, \qquad \forall \ i = 1, ..., n. \quad (8)$$

Using (8) we are able to derive an explicit formula for the optimal price cap denoted by P_i^*.

Proposition 3. *Under the assumption that the transmission company introduces the desired amount of investment (IC_i^T) before the i^{th} RES expansion is performed, the optimal price cap is given by*

$$P_i^* = \frac{arI_i + MX_i^*(Q_i - Q_{i-1}) - P_{i-1}^*(aQ_0 + X_i^*(Q_{i-1} - Q_0))}{aQ_0 + X_i^*(Q_i - Q_0)}; \ \forall \ i = 1, ..., n, \quad (9)$$

where

$$a = \frac{\lambda_2 \delta}{r(\lambda_2 - 1)}.$$

Proof: The proof follows immediately by substituting equation (3) and equation (6) into (8), and solving the resulting equation system for P_i^*. □

When the maximum renewable generation capacity is reached, there is no need for further investment incentives to stimulate grid expansions. Therefore, P_n^* becomes the last regulated price level, while the initial transmission price level P_0^* has no restrictions, i.e. it is a free variable.

2.3 Risk Implications

In the following section we give insights into the risk implications of the increasing volatility in the generation market that is caused by the increasing share of energy coming from renewable energy sources. Intuitively, one would expect a strong dependence of the generator's firm value and risk on the production uncertainty, whereas for the downstream firm, a more indirect effect can be expected. Production uncertainty increases the risk on both generation and transmission side, which is however dampened by increased production (at fixed FIT) and by appropriate regulation, respectively. While many papers study investment decisions into production and grid capacity, only few of them examine the risk implications of these investments, as for example Dockner, Kucsera, and Rammerstorfer (2011). To characterize firm risk, a risk measure is required that can be eventually quantified. Following Berk, Green, and Naik (2004), the firm's beta is given by

$$\beta_i(X) = \frac{\frac{\partial V_i(X)}{\partial X} X}{V_i(X)}; \qquad \forall \;\; i = 1, ..., n.$$

Based on this risk concept, the derivation of systematic risk for the production and the transmission side is straightforward.

Proposition 4. *The production utility's dynamic beta at the i^{th} level of RES penetration is given by*

$$\beta_i(X) = 1 + \frac{(\lambda_2 - 1)B_i X^{\lambda_2} + \frac{F_i + \phi Q_0^2 - DQ_0}{r}}{V_i(X)}; \qquad i = 1, ..., n,$$

where the value function, $V_i(X)$ and the growth option parameters are defined in equation (12) *and equation* (16), *respectively*[6].

Proof: The proof follows immediately by differentiating the value function defined by equation (12) with respect to X and applying the above mentioned definition of beta. □

Analogously, we are able to derive the systematic risk for the transmission operator.

Proposition 5. *The transmission operator's dynamic beta at the i^{th} level of RES penetration is given by*

$$\beta_i(X) = 1 + \frac{(\lambda_2 - 1)B_i^T X^{\lambda_2} - \frac{Q_0(P_i - M)}{r}}{V_i(X)}; \qquad i = 1, ..., n,$$

where the value function, $V_i(X)$ and the growth option parameters are defined in equations (5) *and* (7), *respectively.*

Proof: The proof follows immediately by differentiating the value function defined by equation (5) with respect to X and applying the definition of beta. □

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[6] Equation (16) shows the growth option parameter only for the case after $(n-1)$ capacity increases. However, this formulation can be easily generalized for the previous growth option parameters by replacing the $n-1$ index with i. As stated above, with maximum RES penetration the firm has no longer a growth option, which yields $B_n = 0$.

3 Numerical Simulations

The real options model derived above allows for a complete analytical solution. Our numerical procedure is divided into three parts. In the first part, the optimal timing of the RES investments and the optimal transmission price cap are analyzed. Moreover, we explore as an aside the effect of electricity storage on the optimal investment decisions. In the second part, we determine the dynamic risk values measured by the beta factor for both generation and grid expansion investments. In the last part we finish our analysis with exploring the role of the chosen parameter values on the optimal investment timing.

3.1 Data

For the numerical simulations, we refer to benchmark values of the included parameters as presented in Table 1. The value of the risk-free rate is chosen at 5%[7], while the convenience yield, based on Kjærland (2007), is given by 2.5%. The choice of the initial production capacity level has no influence on the investment timing, hence a value of 50 TWh per year is set. The reference market price for electricity is given by 40 EUR/MWh. There is a large amount of literature studying the elasticity of demand for electricity, see e.g. Dahl (1993) and Espey and Espey (2004). Based on these articles we set price elasticity of demand at -0.9 and using the reference market price for electricity, we derive the parameters for the inverse industry demand function. For environmentally friendly technology we have chosen offshore wind and for the approximation of its production cost, we refer to IEA/OECD (2005). Following Brakelmann (2004) and DENA (2005), we approximate the transmission investment cost with 100 € per km per MW.

Given these parameter values, we assume five possible production capacity increases (i.e. $i = 0, 1, ..., 5$). Recall, each i stands for a different share of RES within the market, which is assumed to be increasing in i. Therefore, we assume that after an investment takes place, the total production capacity increases by 10% in every stage. Hence, the total fixed costs also follow the same path and increase by 10% with every stage. For simplicity, the unit investment costs for both production and transmission are constant in each period.

3.2 Optimal investment timing and regulation

The goal of the EU electricity policy is to promote renewable generation and consequently, to reduce CO2 emissions. To support environmentally friendly electricity generation, feed-in tariffs have been introduced, under which grid access for renewable power plants is guaranteed. The transmission grid utilities are obliged to

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[7] The current risk free rate (2009/2010) determined in international capital markets lies between 1 and 3 percent. Thus, the chosen value of 5 % can be seen as rather conservative.

Parameters	**Unit**	**Value**
Risk-free rate	[%]	5
Convenience yield	[%]	2.5
Initial production level	[TWh/yr]	50
Volatility of the capacity factor	[%]	10
Electricity output	[TWh/yr]	3,285
Capacity factor	[%]	45
Investment costs of production	[1000 €]	1,049,358
O&M production costs	[1000 €/yr]	49,392
Marginal costs of transmission	[€/ MWh]	4
Unit investment costs of transmission	[€/MWkm]	100
Reference market price	[€/MWh]	40
Price elasticity of demand		-0.9

Table 1: Benchmark parameter values

For the clean energy technology offshore wind power is chosen. Based on the data provided by IEA/OECD (2005), we can derive the unit investment cost for production (IC) and the fixed costs (F_i) the utility faces.

transmit all the electricity produced by RES. This FIT 'premium' is in general designed as a declining tariff rate (degression rate) which is mainly due to technical improvements. Therefore, in order to implement this degression rate in our model, we assume that the price of the electricity coming from RES ($\bar{P}$) is set initially at 110 EUR/MWh. This price is kept constant until the new production facility is introduced. Subsequently, when the new investment is triggered, the tariff rate is decreased by 3 EUR/MWh.

Based on the above described parameter values we can obtain the optimal timing of the RES investments ($X^\star$) from which the optimal market price level for electricity can be derived. Based on these values we determine the optimal transmission price cap level that is necessary to incentivize grid expansion investments. Table 2 lists the results for this case. As expected, the increasing production uncertainty resulting from higher RES penetration makes it profitable to postpone the production expansion investment.

RES stage, i	**0**	**1**	**2**	**3**	**4**	**5**	**5***
Prod. shock volatility	0.1	0.1	0.1	0.1	0.1	0.1	0.07
Production capacity level	50000	55000	60500	66550	73205	80525,5	80525,5
Optimal investment timing	0.45	0.49	0.54	0.59	0.66	0.74	0.69
Optimal price cap	N.A.**	12.69	13.17	13.64	13.78	13.81	13.25

Table 2: Results for the decreasing feed in tariff

*The column refers to the case with electricity storage, namely when the volatility of the production shock decreases from 10% to 7%.

**Free variable defined above

More interesting results emerge from the transmission side visualized in Figure 2. We can see that the optimal investment incentives are increasing with increasing RES penetration. This also proves the negative effect of increasing production uncertainty on the transmission side and on the necessary investment incentives. At high levels for the load factor (X), which is essential for new RES investment, the probability of small values for this parameter becomes lower. Although this results in a positive effect on the investment decision, the negative effect of the increased production volatility dominates it. This means that the risk the transmission utility faces becomes larger, which require higher necessary transmission prices.

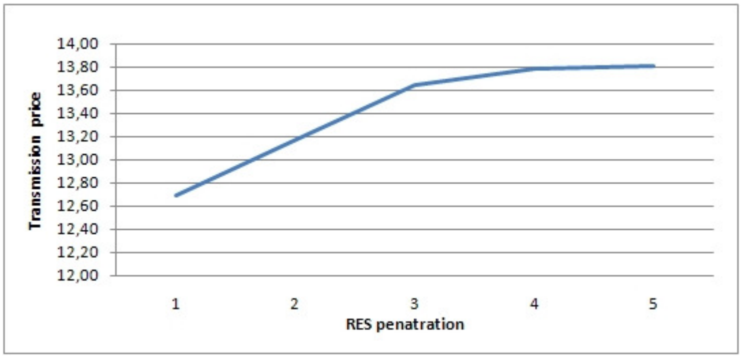

Figure 2: Optimal transmission price cap with decreasing FIT

Electricity Storage The recent discussion also includes electricity storage and its effect on optimal investment timing and transmission planning, which is assumed to become vital with increasing renewable electricity production. In our model, the availability of electricity storage decreases the volatility of electricity generation[8]. Therefore, we modify the decreasing feed-in tariff example, such that the production volatility with renewables becomes smaller in the last capacity expansion, i.e. the benchmark value for production volatility decreases from 0.1 to 0.07. The last column of Table 2 lists the corresponding results. Obviously, a decrease in production volatility positively affects the timing of further production expansions. Consequently, the new capacity increase is triggered earlier, because lower production uncertainty decreases the risk of the capacity expansion. Moreover, a positive effect can also be seen for the optimal transmission prices. In this case, stable production implies lower risk for the transmission company, leading to optimal transmission prices.

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[8] The variation of the production volatility allows us to relax the implicit assumption that the producer relies only on one specific clean energy production technology. However, diversified RES portfolios, i.e. producers with different energy mixes are neglected in this analysis.

3.3 Value and Risk Implications

In this subsection we examine the value and risk implications for the production capacity expansion and the transmission grid investments, visualized in Figures 3 and 4, respectively. We find that the value and the risk implications in both sectors follow similar paths. The figure on the left side visualizes the evolution of firm value depending on the production uncertainty variable (X). The curves stand for the different level of RES penetration and show a positive upward slope. The higher the load factor, the higher will be the share of electricity produced by RES in total electricity production, which leads to higher firm values. Instead, when the load factor level is low, the different RES penetration curves coexist, since the higher RES penetration yields only a minor change in total electricity production, and hence in the value function. The horizontal lines reflect the investment trigger levels computed in the previous subsection. At the investment trigger level, the production capacity jumps up leading to a discrete jump in the firm's value function by the investment amount and valuation changes.

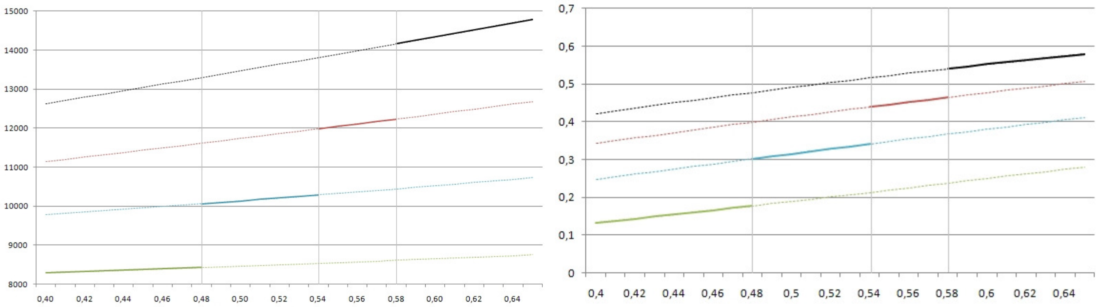

Figure 3: Value and risk implication for the production side

The left and the right figures visualize the value function (in thousands) and the firm beta respectively as a function of the production uncertainty variable (X). The vertical lines denote the trigger levels for RES penetration.

Similarly to this, the right figure shows the firm's beta as a function of the production uncertainty. Overall, we see a positive relationship between the increasing RES production and systematic risk. Similar to the results for the value function, a capacity expansion leads to a discrete jump in the firm's beta value.

3.4 Comparative Statics

The presented model shows that the real option value for the RES investment and the respective optimal grid investment strongly depend on the estimates of the key parameters included. Since in the previous subsection we have already studied the effect of production uncertainty, our focus lies now on the remaining parameters, namely investment cost, risk free rate and convenience yield. For this, we proceed to analyze how a change of +/- 10 % of the benchmark values affect the investment timing in the unregulated upstream market of electricity production and the optimal

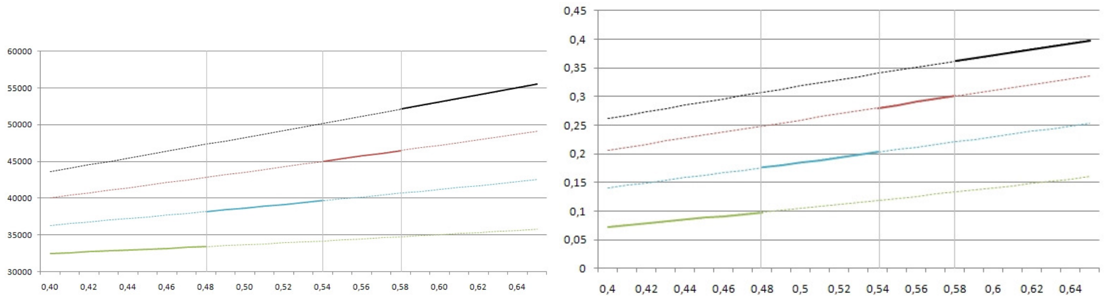

Figure 4: Value and risk implication for the transmission side

The left and the right figures visualize the value function (in thousands) and the firm beta respectively as a function of the production uncertainty variable (X). The vertical lines denote the trigger levels for RES penetration.

price cap in the regulated transmission and distribution market. The results are computed for the last capacity expansion and highlighted in Table 3.

Parameters	**Bench. value**	**Adj. value**	**Opt. timing**	**Price cap**
Benchmark parametrization	-	-	*0.74*	*13.81*
Inv. cost of prod., [1000 €]	1,049,358	944,422	0.70	14.04
Inv. cost of prod., [1000 €]	1,049,358	1,154,293	0.78	13.58
Inv. cost of trans., [€/MWkm]	100	90	0.74	11.54
Inv. cost of trans., [€/MWkm]	100	110	0.74	16.08
Risk-free rate, [%]	5	4.5	0.72	11.74
Risk-free rate, [%]	5	5.5	0.77	15.81
Convenience yield, [%]	2.5	2.25	0.73	13.82
Convenience yield, [%]	2.5	2.75	0.75	13.80

Table 3: Comparative statics

This Table summarizes the impact of a 10 % change in the variables investment cost, risk free rate and convenience yield on the investment timing of production expansion and on the optimal price cap.

Unit investment cost, IC and IC^T: Similarly to the case of production uncertainty, an increase in production cost yields to a postponed investment as it becomes more costly. However, its impact on the transmission side is positive, leading to lower optimal transmission prices. The reason for lower investment incentives is the later RES penetration. The transmission investment cost has no direct influence on the timing of production investment. However, lower profit flows for the grid owners caused by increased unit investment costs have to be compensated with higher optimal transmission price caps.

Risk free rate, r: An increasing risk free rate causes investment to be postponed on the generation side and indirectly leads to higher transmission prices. Hence, the results go in line with standard discounted cash flow models, in which increased discount rates reduce the net present value of the project.

Convenience yield, δ: As outlined in section 2, δ stands for the opportunity costs of delaying investments. If opportunity costs are high, investments into grid capacity occur earlier. Hence, similar to the case for production investment cost, later investments lead to a decrease in transmission prices.

4 Concluding Remarks

Worldwide and especially in Europe there is a continual debate about the effects of renewable energy production and the related rising uncertainty in electricity supply on investment incentives in the generation as well as in the transmission market. This article aims to contribute to this ongoing discussion as it is the first one that analyzes the investment decision into generation- and grid facilities within one model (and simultaneously). The model is based on real options modeling, allowing us to focus on the impact of uncertainty (inherent in renewable electricity generation) on the value and the timing of investments into generation facilities. Prices and costs for the generators are not restricted or subject to any kind of regulation. Based on these investments, the downstream supplier, i.e. the transmission and distribution operator, is confronted with the necessity to connect the new generators to the existing grid and/or to adapt the grid if the overall electricity supply fluctuations require additional expansions to maintain system security. We find that the increasing share of renewables in energy production goes along with investment delay in the production sector. In other words, the higher the volatility in the generation market, the lower generators' willingness to invest in the environmentally friendly sources with highly volatile outputs. For the downstream market we find that the higher supply uncertainty in the generation market also leads to an investment postponement although the negative effects might be compensated via an appropriate incentive system. These findings are also confirmed by the value and risk implications. The systematic risk for all firms in both markets increases (although they are affected to different extent). Therefore, we suggest regulators set higher investment incentives as delaying investments may reduce the overall system's reliability in a crucial manner. The presented model cannot be applied to a certain country directly, hence an introduction of a more country-specific incentive system in the model framework is left for further research.

5 Appendix

Proof of Proposition 1. Without investment options, the firm value[9] equals the expected discounted present value of the future payoffs. From equation (2), the value of the firm $V_i(X)$, with a starting position of the process $X = X_0$ and a discount rate r, can be written as

$$\begin{aligned} V_i(X) &= \mathbb{E}\left[\int_0^\infty f_i(X_t)e^{-rt}dt|X = X_0\right] \\ &= \frac{X(Q_i - Q_0)(\bar{P} - \phi Q_0)}{\delta} - \frac{F_i + \phi Q_0^2 - DQ_0}{r}. \end{aligned} \tag{10}$$

Therefore, assuming a finite expected present value, the denominator of the first term has to be positive, yielding the condition $\delta > 0$. With investment options available, splitting the expected value in equation (10) into two time-separated parts yields

$$\begin{aligned} V_i(X) &= \mathbb{E}\left[\int_0^{dt} f_i(X_t)e^{-\rho t}dt|X = X_0\right] + \mathbb{E}\left[\int_{dt}^\infty f_i(X_t)e^{-\rho t}dt|X = X_0 + dX\right] \\ &= f_i(X)dt + e^{-\rho dt}\mathbb{E}[V_i(X + dX)]. \end{aligned}$$

Using $e^{-\rho dt} = 1 - \rho dt$ and ignoring all terms smaller than dt results in

$$\begin{aligned} V_i(X) &= f_i(X)dt + (1 - \rho dt)(V_i(X) + \mathbb{E}[V_i(X + dX)] - V_i(X)) \\ &= f_i(X)dt + V_i(X) - \rho V_i(X)dt + \mathbb{E}[dV_i]. \end{aligned}$$

Rearranging the terms yields the following arbitrage equation:

$$\rho V_i(X)dt = f_i(X)dt + \mathbb{E}[dV_i].$$

Using Itô's lemma, $\mathbb{E}[dV_i] = (r - \delta)XV_i'(X)dt + \frac{1}{2}(\sigma_i X)^2 V_i''(X)dt$, this can be rewritten as the following Bellman equation:

$$\frac{1}{2}\sigma_i^2 X^2 V_i^{''}(X) + (r - \delta)XV_i^{'}(X) - rV_i(X) + f_i(X) = 0. \tag{11}$$

The solution to this second-order differential equation is the sum of the solutions to the homogenous part and a particular solution. The homogenous part is linear with respect to the expected present value term, V_i. Therefore, the solution to this part can be represented as a linear combination of two independent solutions. To find these solutions we substitute AX^λ into equation (11), which leads to the following fundamental quadratic equation

$$\frac{1}{2}\sigma^2\lambda(\lambda - 1) + (r - \delta)\lambda - r = 0$$

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[9] That is equal to the value of the assets in place.

The two roots of this equation are given by

$$\lambda_1 = \frac{1}{2} - \frac{r-\delta}{\sigma^2} + \sqrt{\left(\frac{r-\delta}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma^2}} > 1$$

$$\lambda_2 = \frac{1}{2} - \frac{r-\delta}{\sigma^2} - \sqrt{\left(\frac{r-\delta}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma^2}} < 0.$$

Therefore, the solution of the homogenous part becomes

$$V_i^h(X) = A_i X^{\lambda_1} + B_i X^{\lambda_2},$$

where A_i and B_i are constants that remain to be determined. A particular solution can be written as

$$V_i^p(X) = \frac{X(Q_i - Q_0)(\bar{P} - \phi Q_0)}{\delta} - \frac{F_i + \phi Q_0^2 - DQ_0}{r}.$$

Having determined the homogenous and the particular solution, we can combine them to reach the general solution

$$V_i(X) = V_i^h(X) + V_i^p(X) = A_i X^{\lambda_1} + B_i X^{\lambda_2} + \frac{X(Q_i - Q_0)(\bar{P} - \phi Q_0)}{\delta} - \frac{F_i + \phi Q_0^2 - DQ_0}{r}. \tag{12}$$

Because of a finite number of possible capacity increases, the firm does no longer hold a growth option when the maximum capacity level (Q_n) is reached, yielding $V_n(X) = V_n^A(X)$. Solving backwards, the firm value at capacity level Q_{n-1} has to satisfy equation (12)

$$V_{n-1}(X) = A_{n-1} X^{\lambda_1} + B_{n-1} X^{\lambda_2} + \frac{X(Q_{n-1} - Q_0)(\bar{P} - \phi Q_0)}{\delta} - \frac{F_{n-1} + \phi Q_0^2 - DQ_0}{r}, \tag{13}$$

where A_{n-1} and B_{n-1} are still undetermined constants. Without investment options both constants are equal to zero, since the value of the firm is equal to the expected value of the discounted future profit flows. However, with investment options the process X has no restriction on the lower side, but has an upper barrier X_n^* that triggers the investment. Due to the no bubble condition, A_{n-1} has to be set equal to zero in order to ensure a finite expected value as X approaches zero. In order to determine the remaining constant B_{n-1} and to solve for the optimal investment threshold X_i^*, we impose the value matching and smooth pasting conditions (see e.g. Dixit (1993)). The value matching condition says that the value of the firm at the original production level equals the firm value at the expanded production level, net of the irreversible investment costs[10]. Therefore, it follows

$$B_{n-1}(X_n^*)^{\lambda_2} + \frac{X^*(Q_{n-1} - Q_0)(\bar{P} - \phi Q_0)}{\delta} - \frac{F_{n-1} + \phi Q_0^2 - DQ_0}{r} = \frac{X^*(Q_n - Q_0)(\bar{P} - \phi Q_0)}{\delta} - \frac{F_n + \phi Q_0^2 - DQ_0}{r} - I_n, \tag{14}$$

where I_n is the necessary investment level for the capacity increase from Q_{n-1} to Q_n. The smooth pasting condition[11] yields

$$B_{n-1}\lambda_2(X_n^*)^{\lambda_2-1} + \frac{(Q_{n-1} - Q_0)(\bar{P} - \phi Q_0)}{\delta} = \frac{(Q_n - Q_0)(\bar{P} - \phi Q_0)}{\delta}. \tag{15}$$

Hence, the growth option parameter is given by

$$B_{n-1} = \frac{(Q_n - Q_{n-1})(\bar{P} - \phi Q_0)}{\delta\lambda_2(X_n^*)^{\lambda_2-1}}. \tag{16}$$

Combining (14) and (15), we can obtain the optimal investment timing

$$X_n^* = \frac{\delta\lambda_2}{(\lambda_2 - 1)}\left(\frac{(rI_n + F_n - F_{n-1})}{r(Q_n - Q_{n-1})(\bar{P} - \delta Q_0)}\right). \tag{17}$$

For all the previous RES production expansion cases ($i \in \{1, ..., n-1\}$) the investment threshold levels can be determined using similar arguments.

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[10] $V_{n-1}(X_n^*) = V_n^A(X_n^*) - IC_n$.

[11] $(V_{n-1}(X_n^*))^{'} = (V_n^A(X_n^*))^{'}$.

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