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Abstract

Renewable energy sources (RES) play an increasing role in many electricity systems thanks to climate and support policies and subsequent cost reductions in recent years. Compared to conventional generation technologies, RES has two main important distinctive features: First, their cost pattern is characterized by high investment and negligible variable costs and second, their operational decision is governed by weather conditions limiting their availability. In this paper, we aim to analyze the role of RES in electricity markets focusing on the interplay of investment and dispatch decisions under different levels of market competitiveness and different support schemes; namely, feed-in tariff, feed-in premium, and investment subsidies. To this end, we develop a two-stage model of endogenous investment and operation with both intermittent and conventional technologies to obtain analytical solutions for investment and operation decisions. We show that there are feedback effects between the investments of different firms, and between the different technologies of the same firm. Exercise of market power results in underinvestment in the conventional technology; but the effect on renewables is ambiguous due to the interplay of opposing investment incentives. The results furthermore highlight that for the optimal design of a support policy the underlying competiveness of the market needs to be considered.

Keywords: renewable energy, electricity market, investment, renewable support, market power, two-stage game

JEL Classification: L94, C72, C73, L13, Q42

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1. Introduction

Electricity markets are in transition from predominantly fossil-based and centralized structures towards low-carbon and renewable generation. This transition will require significant investments in generation and transmission infrastructure in the coming decades (e.g. the 2017 World Energy Outlook assumes investment needs of ca. 19 trillion US$ until 2040, IEA. (2017)). Given the lumpiness, long construction times, and lifetimes of conventional power plants, uncertainty about future developments has always been a central part of electricity system assessments. In the regulated systems of the last century, this uncertainty could be buffered via adjustments of end-user tariffs. However, in a liberalized framework the investors have to bear a larger share of this risk and account for the uncertainty in its investment decision.

This development is further influenced by the increasing role of intermittent renewable energy sources in many electricity systems. When it comes to investment decision making, many renewables show distinct features compared to conventional power plants. They have a cost pattern characterized by high investment costs and very low marginal operation costs and their availability to operate in a given moment depends on the weather conditions. Furthermore, many electricity regulators support renewable deployment via various mechanisms. Given this setting, investors face a challenge to decide about which technology choices to make and account for the impact of uncertainty of renewables in production as well as the investment decision made by competitors.

In this paper, we take up this challenge and develop an equilibrium model of endogenous operation and investment decisions accounting for the intermittency of renewables, competition between firms and different renewable support schemes. The model is designed as a two-stage process with firms making investment decisions in the first stage and operational decisions in the second stage. We account for two types of firms, namely an exclusively renewable investor and a mixed renewable-conventional investor (called the generalist), and assess perfectly competitive markets as well as imperfectly competitive ones (in form of Cournot competition). Given the multitude of support schemes for renewables in many current electricity markets, we account for feed-in tariff, feed-in premium, and investment subsidies for renewables.

The model will be a first step in conceptualizing the incentive structures in electricity markets with high shares of renewable energies. We will apply the model to disentangle the impact of the different elements (intermittency, support schemes, and competitiveness) on the resulting investment and operation patterns and identify interactions that need to be accounted when designing renewable support.

The rest of the paper is organized as follows. Section 2 reviews the related literature. In section 3, the general model structure and assumptions are presented. In sections 4 and 5, we calculate equilibrium investments for the perfectly competitive and imperfectly competitive markets. Section 6 provides a comparison of the respective findings and a numerical representation. Section 7 briefly discusses limitations of the study. Finally, section 8 summarizes and concludes.

2. Literature Review

The analysis of investment and operational decisions is a cornerstone of economics with a subsequent extensive body of theoretic and applied literature. Our approach relates to four main fields within this literature. We first focus on the role of investments in reconstructed electricity markets and the role and difference of perfect and imperfect competition. Second, the developed model is formulated as a two-stage game with an investment and operational stage based on existing sequential investment modeling approaches. Third, as we extend this model by accounting for the intermittent nature of renewables, the paper is also linked to the literature on investment in renewable energy sources. Finally, as the model also addresses the impact of different support schemes on investment decision, we also relate to the literature on support policy evaluations. In the following, we will provide a short review of these four fields.

The electricity market has been traditionally regarded as a natural monopoly and hence highly regulated (Tamás et al. (2010)). Therefore, modeling the expansion of generating infrastructure has been traditionally approached by solving an operation and investment cost minimization problem carried out by a single monopolist, e.g. central planner or a regulator. However, the liberalization and reconstruction of the electricity sector into a competitive market framework caused changes in the structure of the power industry (e.g. new investors entering the market) and in the participants' investment and operation policies. Therefore, modeling approaches should be adjusted accordingly. Depending on the level of competition, either classical optimization approaches representing a perfectly competitive setting or game theoretic approaches representing imperfect competition can be used. The latter is especially relevant since, despite implementation of policies to promote competition, there is still evidence of market power in the electricity markets (Helgesen and Tomasgard (2018)). Moreover, even years after the first restructuring efforts, the majority of electricity markets are still highly or fairly concentrated due to technological and financial barriers to entry (Van Nuffel et al. (2016)). Crampes and Creti (2005) show that in oligopolistic electricity markets, firms may enforce market power by withdrawing generation in the short-term or restricting investment in capacity in the long-term. Several empirical studies also support this idea (e.g. Wolak and Patrick (2001)). Market power issues might also continue to exist in the future since the prospective forced capacity phase-outs (e.g. nuclear or coal) would reduce available capacity in the market which potentially decreases competition. However, recent discussions regarding the reform in European renewable support policies mostly fail to consider certain risks of market power in electricity markets (Dressler (2016)).

Since game theoretical approaches are able to model the strategic behavior of the involved parties, they are useful in modeling electricity markets. However, only a limited number of game theoretical models of imperfect competition have looked at the investment problem. The main reason is that equilibrium models lack robustness when applied to capacity expansion problems (F. Oliveira (2008)). The literature model the game using different approaches such as Stackelberg-based game (as in Ventosa et al. (2002)) and Cournot-based approach (as in Murphy and Smeers (2005)). Given the increased dynamics on liberalized electricity markets, the literature also explores multiple further topics related to investment/operation decisions and competitiveness. For instance, Garcia and Shen (2010) analyze the equilibrium level of investments when firms exercise market power in the short-run. Boom and Buehler (2007) discuss the impact of electricity market reconstruction on capacity investments under different market configurations. The literature also addresses the impact of price caps (Tishler et al. (2008)) and forward markets (Grimm and Zoettl (2006), and Murphy and Smeers (2010)) on firms' behavior in imperfectly competitive markets.

Given that electricity markets are characterized by irreversible capacity investment costs, several studies use a sequential structure to model investment and operation stages in electricity markets. In a two-stage approach, firms first commit to investing a certain capacity; then, in the next stage, they participate in a spot market, considering the installed capacity as the upper limit of their generation. Given that electricity markets are abundant with sources of uncertainty, a majority of the studies in this literature adopt a stochastic programming approach (e.g. Gabszewicz and Poddar (1997), Murphy and Smeers (2005), Liu et al. (2016), Pineda et al. (2018) and Weidmann et al. (2018)).

The emergence of renewable energy sources has influenced the dynamics of liberalized electricity markets and resulted in a large body of literature addressing the interplay of renewables and electricity markets. Many renewable energy sources (e.g., wind and photovoltaics) are of an intermittent nature, i.e. unlike conventional technologies, their production potential varies over time and thereby affects the outcome of the electricity markets, including capacity investment decisions (T. Oliveira (2015)). The consequences of intermittency will be accentuated as the share of renewables in the market increases. The literature on modeling effects of intermittency of renewables on investment decisions is expanding. However, most papers are either country-specific numerical simulations (e.g., Green and Vasilakos (2010), and Milstein and Tishler (2011)) and/or empirical studies (e.g., Liski and Vehviläinen (2016)). In contrast, there are few theoretical assessments. For instance, Ambec and Crampes (2012) analyze the optimal and market-based provision of electricity with intermittent sources of energy. Helm and Mier (2016) show that intermittency of renewables causes an S-shaped diffusion pattern. Chao (2011) develops efficient pricing and investment rules in a competitive market with intermittent resources. Other related theoretical contributions are Twomey and Neuhoff (2010) as well as Rouillon (2015). They consider the capacity of either the intermittent technology or the reliable technology as given.

In addition to their market feedback, renewable energy sources are usually supported by various schemes and thereby link the liberalization of electricity markets with the broader topic on energy and environmental policy. Consequently, there are many studies that analyze and/or compare effects of support schemes. The literature is dominated by qualitative and country-specific empirical studies (e.g. Mitchell et al. (2006), Haas et al. (2004), Butler and Neuhoff (2008), Lipp (2007) Klessmann et al. (2008) Haas et al. (2011)) and detailed numerical based approaches (e.g. Rubin and Babcock (2013) Boomsma et al. (2012) Winkler et al. (2016) Fagiani et al. (2013)). Analytical approaches are attracting more attention in recent years. Some of the studies also consider intermittency of renewable sources. Liu et al. (2016)) compare capacity choices of firms under different feed-in-tariff-based support schemes. To model intermittency of renewables, they consider an average model approach, i.e. instead of different states of availability, they use a single state in which only an average amount of the renewable capacity is available. Ambec and Crampes (2015) build on their earlier paper with an analytical assessment of carbon taxes, feed-in tariffs, and renewable portfolios. They consider a single stage framework. In addition, they model price-taking firms and enforce zero-profits conditions for the firms. Garcia et al. (2012) introduce feed-in tariffs and renewable portfolios in a stylized model of electricity production with an intermittent source of energy. They assume price-taking firms and force zero expected surpluses for the producers. In addition, they consider an inelastic demand and an exogenous price cap.

Our paper emerges from the interfaces of the aforementioned literature. One of our main contributions is to study investments and operation in markets with intermittent sources while allowing firms to act strategically under different support schemes. Our approach is based on the two-stage literature and includes the specific features of electricity markets and renewables based on the respective literature streams while the support policies directly relate to the renewable policy literature. Our paper, therefore, can be seen as a new combination of existing approaches. We combine those different dimensions in one analytical setting and analyze effects of market power on outcomes of renewable support schemes. Our approach is close to the model design of Weidmann et al. (2018). However, the focus of our analysis is on the impact of different renewable support schemes whereas Weidmann et al. (2018) focus on the interplay between consumer tariffs and wholesale competition.

3. Model Structure

In this section, we present the general structure of the underlying model including the two-stage setting, the renewable intermittency representation, players and their decision variables, as well as basic assumptions and simplifications.

3.1 General Model Design

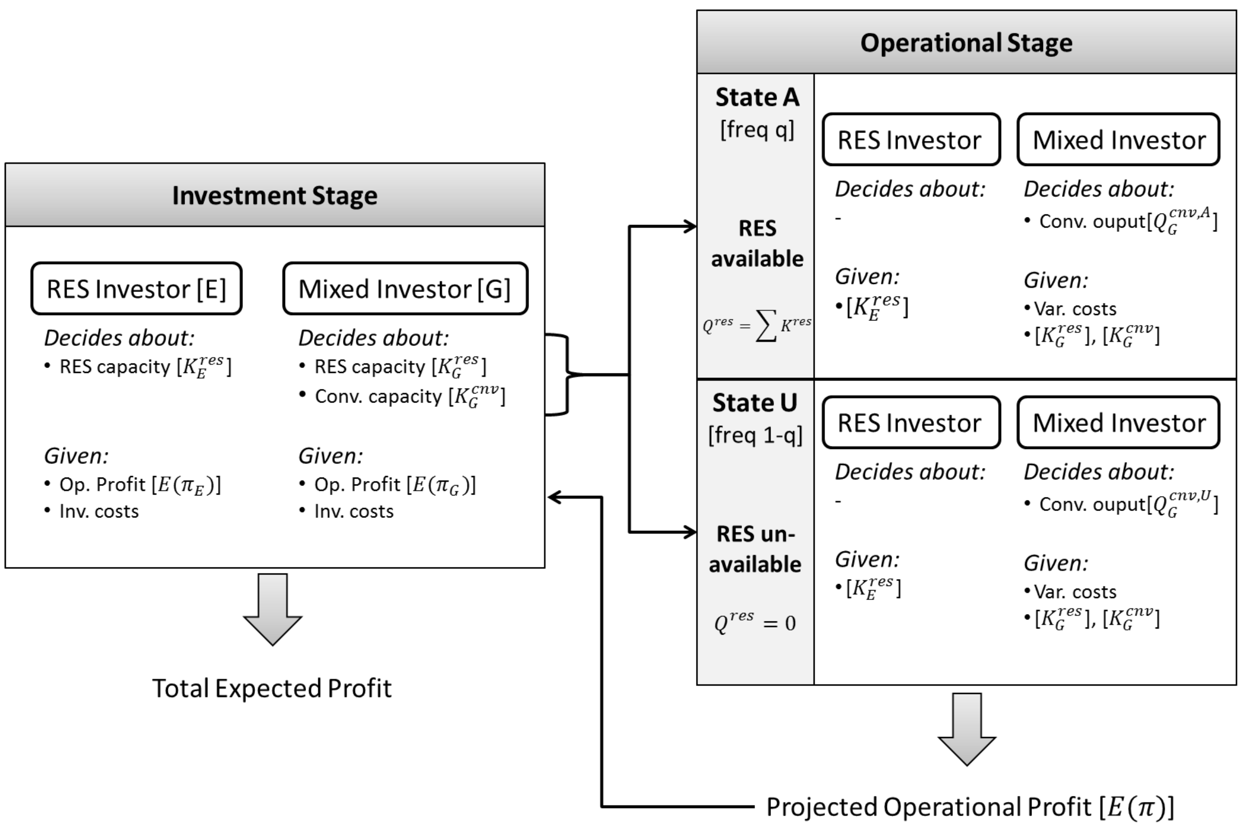

Figure 1: Schematic presentation of the two-stage model structure

We consider an electricity market with two types of technologies, i.e. conventional and renewable, and two types of firms, i.e. *generalist* and *exclusively renewable*, that make investment and operation decisions in two separate stages (Figure 1). While the conventional technology is dispatchable, the renewable source is non-dispatchable and intermittent. While the generalist firm, denoted by G, invests in both conventional and renewable plants, the exclusively renewable firm, denoted by E, invests in only renewable energy sources[1]. In the investment stage, the firms simultaneously decide on their capacity investments. Afterwards, in the operation stage, the firms participate in a uniform spot market for T periods. Since E owns only the non-dispatchable technology, it has no direct choices to make in the operational stage. On the other hand, G has dispatchable conventional technology; therefore, the conventional output Q_G^{cnv} is the only decision made in the operational stage. Firms' objective functions are to maximize their aggregate profits.

The investment cost and operation costs of the conventional technology are both linear, where c^{cnv} and c^{mrg} are per unit costs of investment and operation, respectively. On the other hand, the investment cost of the renewable technology is convex, which stems from the fact that potential sites for renewable investments vary in quality; therefore, later investments in renewables are costlier since more favorable sites are already occupied. For the sake of simplicity, we assume quadratic investment cost functions $\frac{1}{2}c^{res}K_G^{\mathrm{res}\ 2}$ and $\frac{1}{2}c^{res}K_E^{\mathrm{res}\ 2}$ for firm G and E, respectively. We assume the renewable investment cost coefficient c^{res} is identical for both firms so that the differences between renewable investments of the firms are due to their incentive structure rather than technological advantages of one firm over the other. The operation cost of the renewable technology is zero. For simplicity, we assume only one conventional and one renewable technology. It would be straightforward to extend the model to a setup with more players or more technologies.

We model intermittency of the renewable source in the operation stage by using a binary approach, similar to Ambec and Crampes (2012). We assume two states of availability for renewables: the *available* state, denoted by A, and the *unavailable* state, denoted by U. State A, is realized in q percent of the periods (qT periods). On the other hand, state U, occurs in $(1-q)T$ periods. The value of q is known to all firms in the investment stage. In the operation stage, firms know the state of nature of the period for which they are bidding. Consequently, the conventional output decision Q_G^{cnv} may differ for the two states.

The demand side is represented via a linear inverse demand function $P = a - bQ_{tot}$, where Q_{tot} is the aggregate generation and a and b are functional parameters. The inverse demand function is constant in all periods of the operation stage and independent of the renewable availability.

The two stages influence one another; installed capacity in the investment stage is the upper bound for the production in the operation stage. On the other hand, the expected profitability of the operation stage influences investments decisions of the firms in the investment stage.

[1] Assuming the existence of the exclusively renewable firm is in line with the fact that in many markets there are firms owning only renewables as investing in renewables faces fewer barriers to entry (T. Oliveira (2015)).

3.2 Mathematical Model Formulation

In this section, we formulate the general mathematical optimization problems of the firms in different stages and states for the benchmark case of no support scheme.

The exclusively renewable firm E faces the following profit maximization problem:

$$\max_{\mathrm{K_E^{res}}} \mathrm{qT\pi_E^A} - \frac{1}{2}\mathrm{c^{res}K_E^{res\ 2}} \tag{1}$$

where, π_E^A is the profit of firm E in state A of the operation stage. π_E^A depends on the firm's own capacity as well as G's behavior. By assumption, the profit in state U, π_E^U, is zero as the renewable source is unavailable. The profit is defined by the resulting equilibrium spot market price P^{A*} and the output in the state A which, due to non-dispatchability, is equal to the installed capacity:

$$\mathrm{\pi_E^A = P^{A*}K_E^{res}} \tag{2}$$

On the other hand, the generalist firm, G, faces the following optimization problem in the investment stage:

$$\max_{\mathrm{K_G^{cnv},K_G^{res}}} \mathrm{qT\pi_G^A} + (1-\mathrm{q})\mathrm{T\pi_G^U} - \mathrm{c^{cnv}K_G^{cnv}} - \frac{1}{2}\mathrm{c^{res}K_G^{res\ 2}} \tag{3}$$

where π_G^A and π_G^U are the spot market profits of G in state A and U, respectively. Due to non-dispatchability of the renewable technology, only the conventional production can be controlled in the operation stage, which may vary depending on the realized state. In state U, only the conventional capacity of G is present in the market:

$$\mathrm{\pi_G^U} = \max_{0\le \mathrm{Q_G^{cnv,U}} \le \mathrm{K_G^{cnv}}} \left[\mathrm{P^{U*}Q_G^{cnv,U}} - \mathrm{c^{mrg}Q_G^{cnv,U}}\right] \tag{4}$$

In state A, on the other hand, firm G's spot market problem is as follows:

$$\mathrm{\pi_G^A} = \max_{0\le \mathrm{Q_G^{cnv,A}} \le \mathrm{K_G^{cnv}}} \left[\mathrm{P^{A*}(Q_G^{cnv,A} + K_G^{res})} - \mathrm{c^{mrg}Q_G^{cnv,A}}\right] \tag{5}$$

Consequently, the choice variables of G are its renewable capacity, (K_G^{res}), its conventional capacity (K_G^{cnv}), and its conventional output in state A ($Q_G^{cnv,A}$) and state U ($Q_G^{cnv,U}$).

Equilibrium prices on the spot market are defined by the linear demand function and the type of competition. In general, the spot price in state A is defined by the output of conventional and renewable production:

$$\mathrm{P^A} = a - \mathrm{b}(\mathrm{Q_G^{cnv,A} + K_G^{res} + K_E^{res}}) \tag{6}$$

Whereas prices in state U are only defined by the conventional production:

$$\mathrm{P^U} = a - b(Q_G^{cnv,U}) \tag{7}$$

We solve the two-stage model using backward induction. First, we calculate the reaction functions of the firms in the operation stage for given installed capacities. Then, the reaction functions will be substituted in the first stage to obtain installed capacities.

To simplify the presentation, we limit the following analysis to the case where the equilibrium satisfies:

$$0 < \mathrm{Q_G^{cnv,A*}} \tag{8}$$

$$\mathrm{Q_G^{cnv,A*}} < \mathrm{Q_G^{cnv,U*}} \tag{9}$$

These assumptions collectively mean that, in equilibrium, the conventional technology is active in all states. Assumption (8) means that, in state A, the conventional technology is not fully crowded out by the renewable technology. On the other hand, assumption (9) suggests that renewable generations, at least marginally, reduce conventional generations in state A. Assumption (9) follows the logic that as the zero marginal cost renewables enter the market in state A, there is less room for the conventional technology generation compared to state U in which the conventional technology has the whole market to profit from[2]. Assumption (9) also implies that while the conventional technology will be bounded by the capacity limit in state U (Lemma 1), its optimal generation will be less than its capacity in state A (Lemma 2).

Lemma 1:
In state U, optimal conventional generation of firm G is equal to its capacity ($Q_G^{cnv,U*} = K_G^{cnv*}$).

Proof: Assume $Q_G^{cnv,U*} = K_G^{cnv*}$ does not hold true. Given the capacity constraint $Q_G^{cnv,U} \leq K_G^{cnv}$, the only possible case left is $Q_G^{cnv,U*} < K_G^{cnv*}$. Considering with assumption (9), we have $Q_G^{cnv,A\,*} < Q_G^{cnv,U\,*} < K_G^{cnv*}$. This means that the conventional production of firm G never hits its upper capacity limit. Given that capacity investment is costly, it is in contradiction to the profit maximization logic of the firm G to invest in a costly capacity that is never used. Therefore, this contradiction shows that $Q_G^{cnv,U*} = K_G^{cnv*}$. ■

Lemma 2:
In state A, optimal conventional generation of firm G is not limited by its capacity ($Q_G^{cnv,A*} < K_G^{cnv\,*}$).

Proof: $Q_G^{cnv,A*} < Q_G^{cnv,U*}$ and $Q_G^{cnv,U*} = K_G^{cnv*}$ gives $Q_G^{cnv,A*} < K_G^{cnv\,*}$. ■

We use these lemmas in all market designs to derive unique solutions for investment and operation stages[3].

4. Perfect Competitive Market Setting

In this section, we analyze the equilibrium market behavior in a perfectly competitive market. After describing the benchmark case of no support policy, we analyze effects of introducing investment subsidies, feed-in premium, and a feed-in tariff policy.

4.1 No Renewable Support

The basic model as described in Section 3.2 represents a pure spot market framework without any renewable support. Assuming that the two firms act as price takers on the spot markets, we can derive the following investment behavior.

[2] However, if investment cost of the conventional technology is relatively too high, it might be optimal for the generalist firm to invest so few in conventional technology that the conventional production hits its upper capacity limit in both states and consequently $Q_G^{cnv,A*} = Q_G^{cnv,U*} = K_G^{cnv*}$. We omit this case for the analysis at hand.

[3] Without these assumptions, we might either end up with markets with no capacity investment or face profit functions with multiple equilibria or multiple local optima.

Proposition 1:
In the case of no support scheme and perfect competition, equilibrium investment capacities are given by:

$$\mathrm{K_G^{cnv\,*}} = \frac{1}{\mathrm{b}}(a - \mathrm{c^{mrg}} - \frac{\mathrm{c^{cnv}}}{(1-\mathrm{q})\mathrm{T}})$$
$$\mathrm{K_G^{res\,*}} = \frac{\mathrm{c^{mrg}}}{\mathrm{c^{res}/qT}}$$
$$\mathrm{K_E^{res\,*}} = \frac{\mathrm{c^{mrg}}}{\mathrm{c^{res}/qT}}$$

Proof: Given that $Q_G^{cnv,U\,*} = K_G^{cnv\,*}$(Lemma 1), the optimization problem of firm G in state U can be rewritten as:

$$\mathrm{\pi_G^U = P^U K_G^{cnv} - c^{mrg} K_G^{cnv}} \tag{10}$$

In state A, firm G's profit is additionally influenced by its renewable output:

$$\mathrm{\pi_G^A} = \max_{\mathrm{Q_G^{cnv,A}}} \mathrm{P^A(Q_G^{cnv,A} + K_G^{res}) - c^{mrg} Q_G^{cnv,A}} \tag{11}$$

As K_G^{res} is given in the operational stage and by Lemma 2 the conventional output is not at its capacity limit, the resulting market price is $P^{A*} = c^{mrg}$ and the resulting profit function can be simplified to:

$$\mathrm{\pi_G^A = c^{mrg} K_G^{res}} \tag{12}$$

Similarly, the profit for firm E in state A is then given by:

$$\mathrm{\pi_E^A = c^{mrg} K_E^{res}} \tag{13}$$

Using equations (10), (12), and (13) in the investment stage yields the following optimization problems for the firms:

$$\max_{\mathrm{K_E^{res}}} \mathrm{qTc^{mrg} K_E^{res}} - \frac{1}{2}\mathrm{c^{res} K_E^{res\ 2}} \tag{14}$$

$$\max_{\mathrm{K_G^{cnv}, K_G^{res}}} \mathrm{qTc^{mrg} K_G^{res} + (1-q)T(P^U K_G^{cnv} - c^{mrg} K_G^{cnv}) - c^{cnv} K_G^{cnv}} - \frac{1}{2}\mathrm{c^{res} K_G^{res\ 2}} \tag{15}$$

The first order conditions with respect to K_E^{res} and K_G^{res} directly lead to the results stated in Proposition 1. The first order condition with respect to K_G^{cnv} is given by:

$$\mathrm{(1-q)T}\left(\frac{\partial P^U}{\partial \mathrm{K_G^{cnv}}}.\mathrm{K_G^{cnv} + P^U - c^{mrg}}\right) - \mathrm{c^{cnv}} = 0 \tag{16}$$

By assumption, the firms are treated as price takers and we have $\frac{\partial P^U}{\partial K_G^{cnv}} = 0$. Therefore, equation (16) can be written as:

$$\mathrm{(1-q)T}\,(a - \mathrm{bK_G^{cnv} - c^{mrg}}) - \mathrm{c^{cnv}} = 0 \tag{17}$$

leading to the respective equilibrium condition for $\mathrm{K_G^{cnv}}$ stated in Proposition 1. ■

The results of Proposition 1 are rather intuitive. Investments into renewable capacities are solely driven by the market price in state A, as this is the only state in which renewables can obtain a profit to cover their investment costs. As renewables are only available in q percent of the total periods, the respective investment costs need to be adjusted accordingly. Reformulating the equilibrium investment capacity results in a cost-price equality:

$$\mathrm{c^{res} K_G^{res\,*} = c^{res} K_E^{res\,*} = qTP^{A*}}$$

In other words, the marginal renewable investment costs ($c^{res} K_G^{res\,*}$ and $c^{res} K_E^{res\,*}$) are equal to the marginal market income. A feedback between conventional and renewable units occurs only via the resulting market price in state A. The price is defined by the marginal unit within the market; which is assumed to be conventional. Higher variable costs of conventional technologies would thereby lead to a higher renewable investment. The availability of renewables has a direct effect on equilibrium investments as renewables with a low availability required higher market prices to compensate the reduced income.

The availability also plays a role on the feedback effect of renewables on conventional investments. Adding one unit K_G^{cnv} gains marginal revenue only in state U since it is the only state in which conventional production is limited by K_G^{cnv}. In state A the conventional generator only recovers its marginal generation costs which does not provide investment incentives. As the price setting in state U is independent of renewable production, only the occurrence probability is important for the investment incentives. The market price in state U is given by $P^{U*} = c^{mrg} + \frac{c^{cnv}}{(1-q)T}$. Thus, an increase in the availability of renewables would lead to higher equilibrium market prices in the state in which they are unavailable so that conventional technology may refinance their investments. Note that average market price is simply equal to long-term marginal costs of the conventional technology: $\mathrm{P^{avg}} = \frac{(1-q)T\mathrm{P^U} + qTP^A}{T} = \frac{(1-q)T\left[c^{mrg} + \frac{c^{cnv}}{(1-q)T}\right] + qT[c^{mrg}]}{T} = c^{mrg} + \frac{c^{cnv}}{T}$.

The conventional investment logic also allows deriving the general impact of intermittent renewables on this market setting. Consider a framework with only conventional technologies, that is, q would become 0. This would result in the market price equalizing the long-term marginal costs of the conventional technology ($P^{NoRes} = c^{mrg} + \frac{c^{cnv}}{T}$). In other words, the market price would equal average production costs. Including renewables does not change this logic but affects the price structure. As conventional units still need to recover their average production costs, the market price in periods without renewable injection (state U) needs to jump high enough to compensate the price drop in periods with renewable injection (state A) ($P^U > P^{NoRes} = P^{avg} > P^A$). This essentially means that on the quantity side, introduction of renewables to the market decreases conventional production in periods without renewable injection and increases total production in periods with renewable injections ($Q^{U*} < Q^{NoRes} < Q^{A*}$).

4.2 Renewable Support Schemes

In the following, we extend the basic model to include different price-based renewables support schemes, namely investment subsidies, feed-in-premium (FIP), and feed-in-tariff schemes (FIT). In all cases, we assume the support scheme is financed from the general government budget (rather from the taxes levied on the consumer's electricity bill) and therefore ignore feedback effects stemming from changed end-consumer demand due to refinancing aspects.[4]

4.2.1 Investment Subsidies

First, we investigate investment-stage subsidies in which the regulator pays the investors a constant subsidy i per unit of renewable capacity investment in the investment stage. Therefore, the optimization problems of E and G in the investment stage are:

$$\max_{\mathrm{K_E^{res}}} \mathrm{qT\pi_E^A} - \frac{1}{2}\mathrm{c^{res}K_E^{res\ 2}} + \mathrm{iK_E^{res}} \tag{18}$$

$$\max_{\mathrm{K_G^{cnv},K_G^{res}}} \mathrm{qT\pi_G^A} + (1-\mathrm{q})\mathrm{T\pi_G^U} - \mathrm{c^{cnv}K_G^{cnv}} - \frac{1}{2}\mathrm{c^{res}K_G^{res\ 2}} + \mathrm{iK_G^{res}} \tag{19}$$

Compared to the no support case (equations (1) and (3)), terms iK_E^{res} and iK_G^{res} are added to the objective functions. The optimization problems of the operation are identical to the no support case.

Proposition 2:
In the case of an investment subsidy scheme and perfect competition, equilibrium investment capacities are given by:

$$\mathrm{K_G^{cnv\,*}} = \frac{1}{\mathrm{b}}\left(a - \mathrm{c^{mrg}} - \frac{\mathrm{c^{cnv}}}{(1-\mathrm{q})\mathrm{T}}\right)$$

$$\mathrm{K_G^{res\,*}} = \frac{\mathrm{c^{mrg}} + \mathrm{i/qT}}{\mathrm{c^{res}/qT}}$$

$$\mathrm{K_E^{res\,*}} = \frac{\mathrm{c^{mrg}} + \mathrm{i/qT}}{\mathrm{c^{res}/qT}}$$

Proof: Given that the operation stage of this investment subsidy scheme is the same as for the basic case, the resulting total investment objectives are as follows:

$$\max_{\mathrm{K_E^{res}}} \mathrm{qTc^{mrg}K_E^{res}} - \frac{1}{2}\mathrm{c^{res}K_E^{res\ 2}} + iK_E^{res} \tag{20}$$

$$\max_{\mathrm{K_G^{cnv},K_G^{res}}} \mathrm{qTc^{mrg}K_G^{res}} + (1-\mathrm{q})\mathrm{T}(\mathrm{P^U K_G^{cnv}} - \mathrm{c^{mrg}K_G^{cnv}}) - \mathrm{c^{cnv}K_G^{cnv}} - \frac{1}{2}\mathrm{c^{res}K_G^{res\ 2}} + iK_G^{res} \tag{21}$$

Consequently, the incentives for investment in conventional capacities are unaltered whereas the first order conditions with respect to K_E^{res} and K_G^{res} directly lead to the results stated in Proposition 2. ■

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[4] For the same reason we exclude quantity-based support mechanisms like a green quota with tradeable certificates, as this would introduce a second price element for consumers and thereby bias the envisioned comparison.

The resulting investment behavior is straightforward: the investment values for renewables are adjusted by the (normalized) subsidy rates (i/qT) as it provides additional marginal income for investments in renewable technology for both firms, which leads to a higher installed renewable capacity. The conventional investment is not influenced as, by assumption, their investment incentives stem from the periods without renewable production. As the increase in renewable capacities due to the investment subsidy has no impact on their availability, there is not feedback of the subsidy on the investment decisions of G regarding the conventional technology.

4.2.2 Feed-in Premium

A feed-in premium is a subsidy on the output instead of the capacity. The regulator pays the generator a constant additional payment p on top of the market price per unit of renewable energy generation. The operational profit optimizations of the two firms in state A are accordingly:

$$\pi_G^A = \max_{0 \le Q_G^{cnv,A} \le K_G^{cnv}} P^A(Q_G^{cnv,A} + K_G^{res}) - c^{mrg} Q_G^{cnv,A} + pK_G^{res} \tag{22}$$

$$\pi_E^A = (P^{A*} + p)K_E^{res} \tag{23}$$

As renewables are not available in state U, the corresponding profit optimization for firm G (giving π_G^U) is not altered.

Proposition 3:

In the case of a feed-in premium support scheme and perfect competition, equilibrium investment capacities are given by:

$$K_G^{cnv\,*} = \frac{1}{b}\left(a - c^{mrg} - \frac{c^{cnv}}{(1-q)T}\right)$$

$$K_G^{res\,*} = \frac{c^{mrg} + p}{c^{res}/qT}$$

$$K_E^{res\,*} = \frac{c^{mrg} + p}{c^{res}/qT}$$

Proof: Given assumption (8) the conventional technology is still active in state A and therefore is setting the price (i.e. $P^{A*} = c^{mrg}$). Therefore, the respective profit equations (22) and (23) can be simplified to:

$$\pi_G^A = (c^{mrg} + p)K_G^{res} \tag{24}$$

$$\pi_E^A = (c^{mrg} + p)K_E^{res} \tag{25}$$

which leads to the adjusted investment stage profits of:

$$\max_{K_E^{res}} qT(c^{mrg} + p)K_E^{res} - \frac{1}{2} c^{res} K_E^{res\;2} \tag{26}$$

$$\max_{K_G^{cnv}, K_G^{res}} qT(c^{mrg} + p)K_G^{res} + (1-q)T(P^U K_G^{cnv} - c^{mrg} K_G^{cnv}) - c^{cnv} K_G^{cnv} - \frac{1}{2} c^{res} K_G^{res\;2} \tag{27}$$

The first order conditions with respect to K_E^{res}, K_G^{res}, and K_G^{cnv} directly lead to the results stated in Proposition 3. ■

The resulting investment behavior shows many similarities to the investment subsidies. Feed-in premium increases the equilibrium renewable investments while it does not impact investments in conventional technology. Even though the feed-in premium and investment subsidies target different stages (operation and investment, respectively), their equilibrium investments are structurally similar to each other. This is mainly because the two schemes keep the remaining features of the systems identical to each other; in particular, both policies require renewables to participate in the market.

4.2.3 Feed-in Tariff

Contrary to the feed-in premium or investment subsidies, a feed-in tariff entitles renewable energies to receive a direct payment without participating in the market. The regulator pays the investors a constant payment f per unit of renewable production, regardless of the market price. However, the renewable production is still accounted for in the spot market as it reduces the residual demand conventional units face. For the renewable firm E, the profit optimization in the operational stages is:

$$\pi_E^A = fK_E^{res} \tag{28}$$

For the generalist, the profit in state U is again not impacted and the profit in state A is split into the market revenue for the conventional technology and the feed-in tariff for the renewable technology:

$$\pi_G^A = \max_{Q_G^{cnv,A}} P^A Q_G^{cnv,A} - c^{mrg} Q_G^{cnv,A} + fK_G^{res} \tag{29}$$

Proposition 4:
In the case of a feed-in tariff support scheme and perfect competition, equilibrium investment capacities are given by:

$$K_G^{cnv\,*} = \frac{1}{b}\left(a - c^{mrg} - \frac{c^{cnv}}{(1-q)T}\right)$$

$$K_G^{res\,*} = \frac{f}{c^{res}/qT}$$

$$K_E^{res\,*} = \frac{f}{c^{res}/qT}$$

Proof: Similar to the case of feed-in premium, the conventional technology is defining the price level in state A (i.e. $P^{A*} = c^{mrg}$) simplifying the spot market optimization for firm G to:

$$\pi_G^A = fK_G^{res} \tag{30}$$

which leads to the adjusted investment stage profits:

$$\max_{K_E^{res}} \; qTfK_E^{res} - \frac{1}{2} c^{res} K_E^{res\;2} \tag{31}$$

$$\max_{K_G^{cnv}, K_G^{res}} \; qTfK_G^{res} + (1-q)T(P^U K_G^{cnv} - c^{mrg} K_G^{cnv}) - c^{cnv} K_G^{cnv} - \frac{1}{2} c^{res} K_G^{res\;2} \tag{32}$$

The first order conditions with respect to K_E^{res}, K_G^{res} and K_G^{cnv} directly lead to the results stated in Proposition 4. ∎

The resulting investment is again straightforward: Conventional investments are not impacted by the feed-in tariff as their refinancing is based on the revenues in state U. Renewable investments are completely driven by the feed-in tariff and do not depend on market dynamics or other technologies.

4.3 Comparative Conclusion

Table 1 presents an overview of equilibrium capacity investments under different policies in perfectly competitive markets. In all settings, the equilibrium investment of the generalist firm in the conventional technology is the same. In other words, the renewable support schemes do not affect the equilibrium investment of conventional capacity. This result may seem as a contradiction to the ongoing debate on revenue impacts of renewable support on incumbents. One the one hand, this finding can be attributed to the chosen model structure and simplifying assumptions made. Given the setting with an externally defined binary renewable availability structure, only one conventional technology, and the assumption that its output is not at the capacity limit in the state with renewable injection, all investment incentives are limited to the period without renewable injection and thereby not impacted by renewable policies.

On the other hand, the driving economic concept behind this result is the equation between marginal costs of investments and market prices. This basic relation is indeed independent of the chosen model characteristic. Even with more technologies or a more complex renewable availability pattern, the finding would remain the same: investment incentives are only defined in those periods in which the technology is at its capacity limit. If a technology is not at its limit, it is, by definition, setting the market price (or completely out of the market) which is similar to our state A. If a unit is at its limit, the market price sets direct investment incentives as in our state U; even if another unit/technology sets the market price in this period. The relevant relation between renewable support and conventional investments is the frequency of those different states. As, by assumption, the frequency of those periods is not impacted by the amount of renewable capacity installed in our model formulation, we do not observe a direct feedback effect. However, in reality, with a multitude of different local renewable injection patterns, an increase in installed capacities is likely to also change the frequency of the two market states for a technology. Consequently, there will be a feedback effect as indicated by the $(1-q)T$ in the equilibrium capacity if q becomes a function of renewable capacity installed.

Table 1 Equilibrium investments under perfect competition

	No support	Investment subsidies	Feed-in premium	Feed-in tariff
K_G^{cnv*}	$\frac{1}{b}\left(a - c^{mrg} - \frac{c^{cnv}}{(1-q)T}\right)$			
K_G^{res*}	$\frac{c^{mrg}}{c^{res}/qT}$	$\frac{c^{mrg} + i/qT}{c^{res}/qT}$	$\frac{c^{mrg} + p}{c^{res}/qT}$	$\frac{f}{c^{res}/qT}$
K_E^{res*}	$\frac{c^{mrg}}{c^{res}/qT}$	$\frac{c^{mrg} + i/qT}{c^{res}/qT}$	$\frac{c^{mrg} + p}{c^{res}/qT}$	$\frac{f}{c^{res}/qT}$

Furthermore, we need to distinguish between conventional capacity and conventional generation. Most of the ongoing debate on incumbent revenues is focused on the pay-off streams for past investments whereas our model is focused on greenfield investments. Renewable generation pushes conventional generation out of the market (i.e. in state A the conventional output $Q_G^{cnv,A}$ is reduced by the output of renewable units $K_G^{res} + K_E^{res}$). In our model this has no impact on payoff streams as the conventional technology remains the price setter and exactly covers its generation costs regardless of the actual amount of energy produced in state A. In reality, this 'merit order effect' of renewables can lead to an alteration for the inframarginal units on their income stream as it reduces the price levels in those periods when they earn capacity rents (Cludius et al. (2014)). This reflects the challenge of uncertain market developments as most exiting power plants were committed with a different pay-off structure in mind (i.e. less renewables) and now cannot recover their full costs due to the alteration of price structures in the market. Without any further market interventions, those units receiving too little income would leave the market and the resulting market equilibrium would again be defined by the basic relation as presented in Table 1.

Turning to the renewable capacities, the results show that the investment incentives are independent of the firm's structure. Both firms, E and G, show the same equilibrium investments. Given the market structure, firm G has no advantage or disadvantage compared to firm E due to ownership of conventional units. Comparing the effect of the different support schemes on renewable incentives, the investment subsidies and feed-in premium show a nearly identical structure. The only difference is how to account for the frequency of the periods. If both subsidies are supposed to have the same effect, we need to set $i = qTp$. In other words, when comparing capacity and energy subsidies the capacity factor is crucial, otherwise their impact is identical. Feed-in tariffs, on the other hand, have the distinguishing feature that they are independent of the market price. Thus, if one aims to equalize their effect with a capacity or output subsidy, the market price needs to be accounted for; i.e. $f = P^{A*} + i/qT = P^{A*} + \mathrm{p}$ which can pose challenges if further market dynamics like variable fuel and emission prices need to be accounted.

5. Imperfect competitive market setting

In this section, we investigate the impact of renewable support schemes on investment incentives under imperfect competitive market conditions, i.e. when players exercise market power by withholding investment in the investment stage or generation in the operation stage. Similar to the previous section, we analyze a benchmark case of no support scheme in details and afterwards we extend the results to the markets with different support schemes.

The optimization problems of the players in imperfect markets are the same as those of the perfect markets. The main difference between imperfect and perfect markets is that players consider their influence on market price. As a result, throughout this section, we skip representing the optimization problems of the firms in the investment and operation stage, as they are identical to their counterparts in section 4.

5.1 No Renewable Support

First, we analyze a pure spot market framework without any renewable support. Assuming that the two firms can influence the spot prices by their output and capacity decisions, we can derive the following investment behavior.

Proposition 5:
In the case of no support scheme and imperfect competition, the equilibrium investment capacities are given by:

$$\mathrm{K}_{\mathrm{G}}^{\mathrm{cnv}\,*} = \frac{1}{2\mathrm{b}}(a - \mathrm{c}^{\mathrm{mrg}} - \frac{\mathrm{c}^{\mathrm{cnv}}}{(1-\mathrm{q})\mathrm{T}})$$

$$\mathrm{K}_{\mathrm{G}}^{\mathrm{res}\,*} = \frac{\mathrm{c}^{\mathrm{mrg}}}{\mathrm{c}^{\mathrm{res}}/\mathrm{qT}}$$

$$\mathrm{K}_{\mathrm{E}}^{\mathrm{res}\,*} = \frac{\frac{a + \mathrm{c}^{\mathrm{mrg}}}{2}}{\frac{\mathrm{c}^{\mathrm{res}}}{\mathrm{qT}} + \mathrm{b}}$$

Proof: Given that we know $Q_G^{cnv,U\,*} = K_G^{cnv\,*}$ (Lemma 1), the optimization problem of firm G in state U can be rewritten as:

$$\pi_{\mathrm{G}}^{\mathrm{U}} = \mathrm{P}^{\mathrm{U}}\mathrm{K}_{\mathrm{G}}^{\mathrm{cnv}} - \mathrm{c}^{\mathrm{mrg}}\mathrm{K}_{\mathrm{G}}^{\mathrm{cnv}} \tag{33}$$

Given that $P^U = a - bK_G^{cnv}$, we have:

$$\pi_{\mathrm{G}}^{\mathrm{U}} = (a - \mathrm{c}^{\mathrm{mrg}})\mathrm{K}_{\mathrm{G}}^{\mathrm{cnv}} - \mathrm{b}\mathrm{K}_{\mathrm{G}}^{\mathrm{cnv}\,2} \tag{34}$$

Assuming an interior solution (based on assumption (8) and Lemma 2), the optimization problem of G in state A is:

$$\pi_{\mathrm{G}}^{\mathrm{A}} = \max_{\mathrm{Q}_{\mathrm{G}}^{\mathrm{cnv,A}}} \mathrm{P}^{\mathrm{A}}(\mathrm{Q}_{\mathrm{G}}^{\mathrm{cnv,A}} + \mathrm{K}_{\mathrm{G}}^{\mathrm{res}}) - \mathrm{c}^{\mathrm{mrg}}\mathrm{Q}_{\mathrm{G}}^{\mathrm{cnv,A}} \tag{35}$$

Given that $P^A = a - b(Q_G^{cnv,A} + K_G^{res} + K_E^{res})$, the first order condition with respect to $Q_G^{cnv,A}$ yields:

$$\mathrm{Q}_{\mathrm{G}}^{\mathrm{cnv,A}\,*} = \frac{a - \mathrm{c}^{\mathrm{mrg}}}{2\mathrm{b}} - \frac{\mathrm{K}_{\mathrm{E}}^{\mathrm{res}}}{2} - \mathrm{K}_{\mathrm{G}}^{\mathrm{res}} \tag{36}$$

with the resulting price in state A given by:

$$\mathrm{P}^{\mathrm{A}\,*} = \frac{a + \mathrm{c}^{\mathrm{mrg}}}{2} - \frac{\mathrm{b}\mathrm{K}_{\mathrm{E}}^{\mathrm{res}}}{2} \tag{37}$$

Equation (36) and (37) allow us to state the optimization problem of G as:

$$\pi_{\mathrm{G}}^{\mathrm{A}} = \left(\frac{a + \mathrm{c}}{2} - \frac{\mathrm{b}\mathrm{K}_{\mathrm{E}}^{\mathrm{res}}}{2} - \mathrm{c}^{\mathrm{mrg}}\right)\left(\frac{a - \mathrm{c}^{\mathrm{mrg}}}{\mathrm{b}} - \frac{\mathrm{K}_{\mathrm{E}}^{\mathrm{res}}}{2}\right) + \mathrm{c}^{\mathrm{mrg}}\mathrm{K}_{\mathrm{G}}^{\mathrm{res}} \tag{38}$$

Similarly, the profit of firm E in state A is given by:

$$\pi_{\mathrm{E}}^{\mathrm{A}} = \frac{a + \mathrm{c}}{2}\mathrm{K}_{\mathrm{E}}^{\mathrm{res}} - \frac{\mathrm{b}}{2}\mathrm{K}_{\mathrm{E}}^{\mathrm{res}\,2} \tag{39}$$

Using (34), (38) and (39) in (1) and (3), we have the following terms for the optimization problems of the firms in the investment stage:

$$\max_{K_E^{res}} qT\left(\frac{a+c}{2}K_E^{res} - \frac{b}{2}K_E^{res\,2}\right) - \frac{1}{2}c^{res}K_E^{res\,2} \tag{40}$$

$$\max_{K_G^{cnv},K_G^{res}} qT\left(\left(\frac{a+c}{2} - \frac{bK_E^{res}}{2} - c^{mrg}\right)\left(\frac{a-c^{mrg}}{b} - \frac{K_E^{res}}{2}\right) + c^{mrg}K_G^{res}\right) + (1-q)T((a-c^{mrg})K_G^{cnv} - bK_G^{cnv\,2}) - c^{cnv}K_G^{cnv} - \frac{1}{2}c^{res}K_G^{res\,2} \tag{41}$$

First order conditions with respect to K_E^{res}, K_G^{res}, and K_G^{cnv} directly lead to the results stated in Proposition 5. ■

Renewable investments of the firms ($K_G^{res\,*}$ and $K_E^{res\,*}$) are different from each other. However, both $K_G^{res\,*}$ and $K_E^{res\,*}$ increase with lower normalized renewable investment costs, c^{res}/qT, and higher marginal generation cost of the substitute conventional technology, c^{mrg}.

For the generalist firm the optimal choice of K_G^{res}, $Q_G^{cnv,A}$ and K_G^{cnv} combines several interaction effects. Its investment in conventional capacity will only impact state U in which the firm acts as a monopoly. Consequently, the resulting choice of $K_G^{cnv\,*}$ follows the monopoly pricing rule while accounting for the frequency of state U in the investment cost share. If renewables are available for longer periods (having smaller $(1-q)T$), investments in conventional technology will be reduced since they make less total marginal profit to justify more investments.

Given $K_G^{cnv\,*}$, the choice for K_G^{res} and $Q_G^{cnv,A}$ depend only on state A and given that $Q_G^{cnv,A}$ is strictly smaller than $K_G^{cnv\,*}$ due to assumption (9), its choice does not influence marginal revenue of K_G^{cnv}. In state A conventional and renewable production have the same effects on G's income (since they both obtain the same spot price P^A). However, their cost effects differ. Whereas the conventional generation has variable costs and its capacity already refinanced via state U, the renewable generation has no variable costs, but its capacities need to be refinanced via the income in state A. As is evident from equation (35), $Q_G^{cnv,A}$ and K_G^{res} are in a direct relation, i.e. an additional unit of output from renewable capacities of G reduces the conventional output by the same amount. This in turn means that the income renewables generate in state A is the saved costs of generating via the conventional generation as the price itself is not impacted by this switch (equation (37)). Consequently, the equilibrium investment for K_G^{res} is defined by its internal substitution potential ($c^{res}K_G^{res} = qTc^{mrg}$) rather than the market price. This finding is in line with the analysis of von der Fehr and Ropenus (2017) for a feed-in premium market, which argues that a generalist firm should equate the marginal costs of conventional and renewable sources. On the other hand, the exclusively renewable firm E faces a different investment incentive structure compared to a generalist firm. Firm E considers market price (not the marginal cost of the conventional technology) and effects of its investments on the market price of state A given by $P^A = \frac{a+c^{mrg}}{2} - b\frac{K_E^{res}}{2}$ (equation (37)). A higher $\frac{a+c^{mrg}}{2}$ (higher base price) and lower b (less sensitive price) incentivize E to invest more in renewables.[5]

[5] The structure of $K_E^{res\,*}$is the consequence of having a linear as well as a quadratic cost function; equilibrium generation of a firm with quadratic cost function in a Cournot game against a firm with linear cost function generally follows the same basic structure as $K_E^{res\,*}$.

The availability of renewables impacts the prices in each state. A renewable source with higher availability increases market price in the periods without renewable injection[6] as it lowers investment in conventional technology as explained above. However, the decreased market price in periods with renewable injection (equation (37)) is great enough to compensate the market increase in periods without renewable injection to the extent that that the average market price[7] decreases with higher availability of renewables.

5.2 Renewable Support Schemes

In the following, we extend the model to analyze investment subsidies, feed-in-premium, and feed-in-tariff schemes. In all cases, we assume that the support scheme is financed from the general government budget.

5.2.1 Investment Subsidies

Proposition 6:
In the case of an investment subsidy scheme and imperfect competition, equilibrium investment capacities are given by:

$$\mathrm{K}_{\mathrm{G}}^{\mathrm{cnv}\,*}=\frac{1}{2\mathrm{b}}(a-\mathrm{c}^{\mathrm{mrg}}-\frac{\mathrm{c}^{\mathrm{cnv}}}{(1-\mathrm{q})\mathrm{T}})$$

$$\mathrm{K}_{\mathrm{G}}^{\mathrm{res}\,*}=\frac{\mathrm{c}^{\mathrm{mrg}}+\frac{\mathrm{i}}{\mathrm{qT}}}{\mathrm{c}^{\mathrm{res}}/\mathrm{qT}}$$

$$\mathrm{K}_{\mathrm{E}}^{\mathrm{res}\,*}=\frac{\frac{a+\mathrm{c}^{\mathrm{mrg}}}{2}+\frac{\mathrm{i}}{\mathrm{qT}}}{\frac{\mathrm{c}^{\mathrm{res}}}{\mathrm{qT}}+\mathrm{b}}$$

Proof: Given that the operation stage of this investment subsidy scheme is the same as for the no support case, the resulting total investment objectives are as follows:

$$\max_{\mathrm{K}_{\mathrm{E}}^{\mathrm{res}}}\mathrm{qT}\left(\frac{a+\mathrm{c}}{2}\mathrm{K}_{\mathrm{E}}^{\mathrm{res}}-\frac{\mathrm{b}}{2}\mathrm{K}_{\mathrm{E}}^{\mathrm{res}\,2}\right)-\frac{1}{2}\mathrm{c}^{\mathrm{res}}\mathrm{K}_{\mathrm{E}}^{\mathrm{res}\,2}+\mathrm{i}\mathrm{K}_{\mathrm{E}}^{\mathrm{res}} \tag{42}$$

$$\begin{aligned}\max_{\mathrm{K}_{\mathrm{G}}^{\mathrm{cnv}},\mathrm{K}_{\mathrm{G}}^{\mathrm{res}}}\mathrm{qT}&\left(\left(\frac{a+\mathrm{c}}{2}-\frac{\mathrm{b}\mathrm{K}_{\mathrm{E}}^{\mathrm{res}}}{2}-\mathrm{c}^{\mathrm{mrg}}\right)\left(\frac{a-\mathrm{c}^{\mathrm{mrg}}}{\mathrm{b}}-\frac{\mathrm{K}_{\mathrm{E}}^{\mathrm{res}}}{2}\right)+\mathrm{c}^{\mathrm{mrg}}\mathrm{K}_{\mathrm{G}}^{\mathrm{res}}\right)\\&+(1-\mathrm{q})\mathrm{T}((a-\mathrm{c}^{\mathrm{mrg}})\mathrm{K}_{\mathrm{G}}^{\mathrm{cnv}}-\mathrm{b}\mathrm{K}_{\mathrm{G}}^{\mathrm{cnv}\,2})-\mathrm{c}^{\mathrm{cnv}}\mathrm{K}_{\mathrm{G}}^{\mathrm{cnv}}-\frac{1}{2}\mathrm{c}^{\mathrm{res}}\mathrm{K}_{\mathrm{G}}^{\mathrm{res}\,2}+\mathrm{i}\mathrm{K}_{\mathrm{G}}^{\mathrm{res}}\end{aligned} \tag{43}$$

Consequently, the incentives for investment in conventional capacities are unaltered whereas the first order conditions with respect to K_E^{res} and K_G^{res} directly lead to the results stated in Proposition 6. ■

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[6] $\mathrm{P}^{\mathrm{U}*}=\frac{a+\mathrm{c}^{\mathrm{mrg}}}{2}+\frac{\mathrm{c}^{\mathrm{cnv}}}{2(1-\mathrm{q})\mathrm{T}}$

[7] $\mathrm{P}^{\mathrm{avg}}=\frac{a+\mathrm{c}^{\mathrm{mrg}}}{2}+\frac{\mathrm{c}^{\mathrm{cnv}}}{2\mathrm{T}}-\frac{\mathrm{bq}}{2}\frac{\frac{a+\mathrm{c}^{\mathrm{mrg}}}{2}}{\frac{\mathrm{c}^{\mathrm{res}}}{\mathrm{qT}}+\mathrm{b}}$

As with the perfectly competitive setting, the resulting equilibrium investment behavior is straightforward: the renewable investments are adjusted by the (normalized) subsidy rates (i/qT) as it provides additional marginal revenue for investments in renewable technology for both firms. This extra marginal revenue leads to a higher installed renewable capacity whereas the conventional investment is not impacted since their investment incentives stem from the periods without renewable production.

5.2.2 Feed-in Premium

Proposition 7:
In the case of a feed-in premium support scheme and imperfect competition, equilibrium investment capacities are given by:

$$K_G^{cnv*} = \frac{1}{2b}\left(a - c^{mrg} - \frac{c^{cnv}}{(1-q)T}\right)$$

$$K_G^{res*} = \frac{c^{mrg} + p}{c^{res}/qT}$$

$$K_E^{res*} = \frac{\frac{a + c^{mrg}}{2} + p}{\frac{c^{res}}{qT} + b}$$

Proof: π_G^U is not impacted by the premium while the optimization problem of G in state A is altered to:

$$\pi_G^A = \max_{Q_G^{cnv,A}} P^A(Q_G^{cnv,A} + K_G^{res}) - c^{mrg}Q_G^{cnv,A} + pK_G^{res} \tag{44}$$

leading to:

$$Q_G^{cnv,A*} = \frac{a - c^{mrg}}{2b} - K_G^{res} - \frac{K_E^{res}}{2} \tag{45}$$

$$P^{A*} = \frac{a+c}{2} - \frac{bK_E^{res}}{2} \tag{46}$$

And given $\pi_E^A = P^{A*}K_E^{res}$, we have:

$$\pi_E^A = \left(\frac{a+c}{2} - \frac{bK_E^{res}}{2} + p\right)K_E^{res} \tag{47}$$

As a result, the investment stage optimizations are:

$$\max_{K_E^{res}} qT\left(\left(\frac{a+c}{2} + p\right)K_E^{res} - \frac{b}{2}K_E^{res\,2}\right) - \frac{1}{2}c^{res}K_E^{res\ 2} \tag{48}$$

$$\begin{aligned}\max_{K_G^{cnv},K_G^{res}} qT&\left(\left(\frac{a+c}{2} - \frac{bK_E^{res}}{2} - c^{mrg}\right)\left(\frac{a - c^{mrg}}{b} - \frac{K_E^{res}}{2}\right) + c^{mrg}K_G^{res} + pK_G^{res}\right)\\ &+ (1-q)T((a - c^{mrg})K_G^{cnv} - bK_G^{cnv\,2}) - c^{cnv}K_G^{cnv} - \frac{1}{2}c^{res}K_G^{res\ 2}\end{aligned} \tag{49}$$

The first order conditions with respect to K_E^{res}, K_G^{res}, and K_G^{cnv} directly lead to the results stated in Proposition 7. ■

The results are similar to the investment subsidy. The premium provides additional revenue in the spot market stage, which is then considered in the investment stage.

5.2.3 Feed-in Tariff

Proposition 8:

In the case of a feed-in tariff support scheme and imperfect competition, equilibrium investment capacities are given by:

$$K_G^{cnv\,*} = \frac{1}{2b}\left(a - c^{mrg} - \frac{c^{cnv}}{(1-q)T}\right)$$

$$K_G^{res\,*} = \frac{\frac{f}{2b}\left(\frac{b}{C^{res}/q\,T} + 2\right) - \frac{1}{2b}\left(a - c^{mrg}\right)}{\frac{C^{res}/q\,T}{b} - \frac{1}{2}}$$

$$K_E^{res\,*} = \frac{f}{\frac{c^{res}}{qT}}$$

Proof: π_G^U is again not impacted by the renewable support scheme while the optimization problem of G in state A is altered to:

$$\pi_G^A = \max_{Q_G^{cnv,A}} P^A Q_G^{cnv,A} - c^{mrg} Q_G^{cnv,A} + fK_G^{res} \tag{50}$$

Solving the first order conditions yields:

$$Q_G^{cnv,A*} = \frac{a - c^{mrg}}{2b} - \frac{K_G^{res} + K_E^{res}}{2} \tag{51}$$

$$P^{A*} = \frac{a + c}{2} - \frac{b(K_E^{res} + K_G^{res})}{2} \tag{52}$$

Given that, $\pi_G^A = fK_G^{res}$, the adjusted investment stage optimizations are:

$$\max_{K_E^{res}} qT(fK_E^{res}) - \frac{1}{2}c^{res}K_E^{res\ 2} \tag{53}$$

$$\begin{aligned}\max_{K_G^{cnv},K_G^{res}} qT&\left(\left(\frac{a+c}{2} - \frac{b(K_E^{res}+K_G^{res})}{2} - c^{mrg}\right)\left(\frac{a-c^{mrg}}{2b} - \frac{K_G^{res}}{2} - \frac{K_E^{res}}{2}\right) + fK_G^{res}\right)\\ &+ (1-q)T((a-c^{mrg})K_G^{cnv} - bK_G^{cnv\ 2}) - c^{cnv}K_G^{cnv} - \frac{1}{2}c^{res}K_G^{res\ 2}\end{aligned} \tag{54}$$

The first order conditions with respect to K_E^{res}, K_G^{res}, and K_G^{cnv} directly lead to the results stated in Proposition 8. ■

The investment of the exclusively renewable firm is completely driven by the feed-in tariff and do not react to market dynamics. For the generalist firm the optimal choice of K_G^{cnv}, as in all previous cases, is not impacted by the feed-in tariff. However, its choice for K_G^{res} and $Q_G^{cnv,A}$ is more complicated: unlike the previous settings, the choice of K_G^{res} does affect market prices in state A and in turn the generalist has to account for the different interactions induced by the feed-in tariff.

As shown in equations (50), renewable and conventional generation are paid with different rates (f and P^A respectively). Consequently, they have different effects on G's marginal profit in the first place. P^A depends on the choice of K_G^{res} inducing a feedback effect on the choice of $Q_G^{cnv,A}$; i.e. firm G treats its own and opponent's renewable production identically when deciding on the optimal conventional output (equations (51)). Generalizing the formulation of the first part of equation (54) representing state A helps to visualize the different effects:

$$\mathrm{qT}\left(\mathrm{P}^{\mathrm{A}}(\mathrm{K}_{\mathrm{G}}^{\mathrm{res}})\mathrm{Q}_{\mathrm{G}}^{\mathrm{cnv,A}}(\mathrm{K}_{\mathrm{G}}^{\mathrm{res}}) - \mathrm{c}^{\mathrm{mrg}}\mathrm{Q}_{\mathrm{G}}^{\mathrm{cnv,A}}(\mathrm{K}_{\mathrm{G}}^{\mathrm{res}}) + \mathrm{f}\mathrm{K}_{\mathrm{G}}^{\mathrm{res}}\right) \tag{55}$$

The first part is the income from selling the conventional generation on the spot market, with both the market price and the generation quantity being dependent on the choice of renewable capacity (equations (51) and (52)). The second part is the variable cost block for conventional generation and the last part the income from the feed-in tariff. The first order condition of equation (55) with respect to K_G^{res}leads to:

$$\mathrm{qT}\left(\frac{\partial \mathrm{P}^{\mathrm{A}}}{\partial \mathrm{K}_{\mathrm{G}}^{\mathrm{res}}}\mathrm{Q}_{\mathrm{G}}^{\mathrm{cnv,A}} + \mathrm{P}^{\mathrm{A}}\frac{\partial \mathrm{Q}_{\mathrm{G}}^{\mathrm{cnv,A}}}{\partial \mathrm{K}_{\mathrm{G}}^{\mathrm{res}}} - \mathrm{c}^{\mathrm{mrg}}\frac{\partial \mathrm{Q}_{\mathrm{G}}^{\mathrm{cnv,A}}}{\partial \mathrm{K}_{\mathrm{G}}^{\mathrm{res}}} + \mathrm{f}\right) \tag{56}$$

Given that $\frac{\partial \mathrm{P}^{\mathrm{A}}}{\partial \mathrm{K}_{\mathrm{G}}^{\mathrm{res}}} = -\frac{\mathrm{b}}{2}$ and $\frac{\partial Q_G^{cnv,A}}{\partial K_G^{res}} = -\frac{1}{2}$, we can simplify this formulation to:

$$\mathrm{qT}\left(-\frac{\mathrm{b}}{2}\mathrm{Q}_{\mathrm{G}}^{\mathrm{cnv,A*}} - \frac{1}{2}\mathrm{P}^{\mathrm{A*}} + \frac{1}{2}\mathrm{c}^{\mathrm{mrg}} + \mathrm{f}\right) \tag{57}$$

Thus, an increase in renewable capacity will reduce the total income from conventional generation by a factor of $-\frac{b}{2}$. The replacement of conventional with renewable generation at a ratio of 1:2 will lead to a corresponding saving from reduced variable generation costs and income loss from the replaced conventional generation and an increased income due to the feed-in tariff. Combining this with the investment cost term leads to the optimal renewable capacity as stated in Proposition 8.

Furthermore, higher investment of the exclusively renewable firm causes the generalist firm to also invest more into renewables. This might seem counter intuitive at first glance since more invested capacity in the market should decrease the room for more investments. However, more renewable investment decreases the market price (equation (52)). Given that the marginal revenue of the renewable investment for the generalist is negatively related to the market price, a lower market price translates into higher renewable investments for the generalist since the substituted conventional production of the generalist faces less market losses. In other words, decreasing the market price for the conventional technology increases the relative favorability of the feed-in rate awarded to the renewable productions.

5.3 Comparative Conclusion

Table 2 presents an overview of the equilibrium capacity investments under different policies in imperfectly competitive markets. As with the perfectly competitive setting, support schemes do not change the equilibrium investments in conventional technologies as they do not impact marginal revenues gained in the state that renewables are unavailable, i.e. sate U.

With respect to renewable investments, the different cases show a divergence between the two players. The difference in renewable investments of the generalist and the exclusively renewable firm is mainly driven by the fact that firms have different investment motives. While the exclusively renewable firm maximizes the profit gained from only one source, the generalist aims to maximize its aggregate profit rather than the profit of each one of the technologies separately. In market-based approaches, the exclusively renewable firm exercises market power and withholds capacity investment to increase price in the operation stage while the generalist considers technology substitutions when allocating its aggregate production goal to its technologies. In other words, renewable investments of exclusively renewable firm are market driven while renewable investments of the generalist are mainly internal decision (plus possible support rates). On the other hand, under feed-in tariff policy, the exclusively renewable firm simply considers the feed-in rate and has no incentive to exercise market power while the generalist also has to consider the feedback loop between its renewable investment and the market price in state A. In other words, under feed-in tariff, the exclusively renewable firm is isolated from the market while that of the generalist is partially market driven.

In line with findings of T. Oliveira (2015), comparing (36) and (45) with (51) shows that conventional production of generalist firm in state A of the market-based schemes is more sensitive to its own renewable capacity additions (a ratio of 1:1 for market-based policies vs. a ratio of 2:1 for the feed-in rate policy). We may additionally show that if the regulator targets similar total aggregate renewable productions,[8] conventional generation in the market-based schemes is less than that of the feed-in tariff scheme.[9] In other words, market-based schemes are more successful in reducing CO2 emissions in imperfectly competitive markets.

Table 2 Equilibrium investments under imperfect competition

	No support	Investment subsidies	Feed-in premium	Feed-in tariff
$\mathrm{K_G^{cnv\,*}}$	$\frac{1}{2b}(a-\mathrm{c^{mrg}}-\frac{\mathrm{c^{cnv}}}{(1-\mathrm{q})\mathrm{T}})$			
$\mathrm{K_G^{res\,*}}$	$\frac{\mathrm{c^{mrg}}}{\mathrm{c^{res}/qT}}$	$\frac{\mathrm{c^{mrg}}+\frac{\mathrm{i}}{\mathrm{qT}}}{\mathrm{c^{res}/qT}}$	$\frac{\mathrm{c^{mrg}}+\mathrm{p}}{\mathrm{c^{res}/qT}}$	$\frac{\frac{\mathrm{f}}{2b}\left(\frac{\mathrm{b}}{\mathrm{C^{res}/q\,T}}+2\right)-\frac{1}{2b}(a-\mathrm{c^{mrg}})}{\frac{\mathrm{C^{res}/q\,T}}{\mathrm{b}}-\frac{1}{2}}$
$\mathrm{K_E^{res\,*}}$	$\frac{\frac{a+\mathrm{c^{mrg}}}{2}}{\mathrm{c^{res}/(qT)+b}}$	$\frac{\frac{a+\mathrm{c^{mrg}}}{2}+\frac{\mathrm{i}}{\mathrm{qT}}}{\mathrm{c^{res}/(qT)+b}}$	$\frac{\frac{a+\mathrm{c^{mrg}}}{2}+\mathrm{p}}{\mathrm{c^{res}/(qT)+b}}$	$\frac{\mathrm{f}}{\mathrm{C^{res}/qT}}$

[8] That is $\mathrm{K_E^{res,FIP}}+\mathrm{K_G^{res,FIP}}=\mathrm{K_G^{res,FIT}}+\mathrm{K_E^{res,FIT}}$ which is in contrast to the comparisons made in T. Oliveira (2015) that are carried out for assuming $\mathrm{K_E^{res,FIP}}=\mathrm{K_E^{res,FIT}}$ and $\mathrm{K_E^{res,FIP}}=\mathrm{K_E^{res,FIT}}$.

[9] Proof: We would like to show that $\mathrm{Q_G^{cnv,A\,*,FIP}}<\mathrm{Q_G^{cnv,A*,FIT}}$. Given that we know $\frac{\mathrm{K_G^{res,FIP}}}{2}>0$ and $\mathrm{K_E^{res,FIP}}+\mathrm{K_G^{res,FIP}}=\mathrm{K_G^{res,FIT}}+\mathrm{K_E^{res,FIT}}$, we have $\frac{a-\mathrm{c^{mrg}}}{2b}-\frac{1}{2}(\mathrm{K_E^{res,FIP}}+\mathrm{K_G^{res,FIP}})-\frac{\mathrm{K_G^{res,FIP}}}{2}<\frac{a-\mathrm{c^{mrg}}}{2b}-\frac{1}{2}(\mathrm{K_G^{res,FIT}}+\mathrm{K_E^{res,FIT}})$ which according to (36) and (51) means: $\mathrm{Q_G^{cnv,A\,*,FIP}}<\mathrm{Q_G^{cnv,A*,FIT}}$.

Comparing (37) and (46) with (52) shows that investment behavior of the exclusively renewable firm has a crucial effect on market prices in all settings whereas the generalist's renewable investments only impact prices in a feed-in tariff setting. This finding is in line with Acemoglu et al. (2017) which shows, that in a market-based approach, if all firms own both conventional and renewable capacity, market price becomes independent of total renewable investments. In contrast, Dressler (2016) predicts that, under FIP, for sufficiently high available renewable capacity and a sufficiently low feed-in rate, market price could become independent of renewable capacity. This independence is mainly driven by the assumption that renewable capacity is exogenously set. On the other hand, under feed-in tariffs, increasing renewable production of any one of the firms reduces the obtained market price equally as a feed-in tariff provides less room for technology coordination of the generalist firm. This echoes the finding in T. Oliveira (2015) that states "under FIT, the addition of renewable capacity by any type of firm reduces the markup on thermal energy".

Comparing market prices of different support policies for similar total aggregate renewable productions shows that market-based schemes (e.g. FIP) lead to a higher market price compared to a feed-in tariff approach.[10] This follows directly from the fact that under market-based policies, the generalist has more incentives to withhold conventional production. Our result is in contrast to the findings in Dressler (2016) stating that for relatively low renewable targets, market price under FIP and FIT are identical. This is mainly driven by the author's assumption that only an exclusively renewable firm can invest in renewables, which will result in a lower estimation of market price under FIP than in our setting. Comparison of quantities and prices for different support policies shows that even though market-based policies result in a desirable lower CO2 emission, it comes at a cost for the consumer that is higher market price.

6. Comparison of perfect and imperfect competition

In this section, we analyze and compare the insights from the two pervious sections to identify the impact of strategic behavior on renewable support and market performance. We first focus on analytical aspects and then turn to a numerical illustration to highlight the relevance of the derived insights.

6.1 Analytical comparison

Exercise of market power raises the issue of underinvestment in the conventional technology. $K_G^{cnv\,*}$ in Section 5 is only half the size of the investments in the competitive setting in Section 4. This is the normal quantity effect when comparing output of a monopoly and competitive setting with constant cost and linear demand structures. Given that the refinancing of conventional investments only occurs via state U this is a direct effect of the chosen model structure.

[10] Acemoglu et al. (2017) and T. Oliveira (2015) do not intend to compare market and non-market based support policies at similar total renewable productions. Being focused on a market-based approach, Acemoglu et al. (2017) does not analyze a feed-in tariff policy. On the other hand, under FIT, T. Oliveira (2015) ends up with only corner solutions for renewable investments, which makes comparison with FIP difficult.

With respect to renewable investments, firms invest identically in the perfect competitive case, but support schemes have different effects on the investors if they exercise market power. As a result, if markets are imperfectly competitive, heterogeneity of investors should be considered while estimating the effects of support schemes or the budget required.

The exercise of market power by the generalist firm, G, incentivizes the exclusively renewable firm, E, to invest more while E's exercise of market power decreases its own renewable investments. In state A of market-based schemes, the prices of imperfectly competitive cases are going to be higher than that of the perfectly competitive markets (c^{mrg}). This higher market price incentivizes firm E to invest more in renewables compared to perfectly competitive markets. In fact, if E does not exercise market power while G continues to exercise market power, renewable investments of E in a market without support equals to: [11]

$$\mathrm{K}_{\mathrm{E}}^{\mathrm{res}\,*} = \frac{\frac{a + \mathrm{c}^{\mathrm{mrg}}}{2}}{\mathrm{c}^{\mathrm{res}}/(\mathrm{qT}) + \mathrm{b}/2} \tag{58}$$

However, if also firm E exercises market power, it withholds capacity investments to increase the market price even further ($K_E^{res\,*}$ in (58) > $K_E^{res\,*}$in Proposition 5). As a result, if firms exercise market power, the effect on total renewable generation is theoretically ambiguous. If market price mark-up effect outweighs the capacity withholding incentives of E, E invests more in renewables in an imperfectly competitive market compared to a perfectly competitive market.[12]

A higher demand (in form of higher a) has different effects across the cases. In perfectly competitive markets, higher demand results in more investments only in conventional technologies. Renewables are not affected since the market price of state A is only set by the marginal cost of the conventional producer. On the other hand, in imperfectly competitive markets with market-based schemes, higher a motivates not only more investments in conventional technology, but also more investments in renewable technologies from the exclusively renewable firm since the market price in state A is increased by the higher demand. On the other hand, in a feed-in tariff scheme, higher demand has just the opposite effect: higher a leads to less renewable investments because higher demand translates to higher market price, which makes conventional production relatively more interesting to firm G.

Naturally, strategic behavior influences also the average market price. In a perfectly competitive market, under different market designs, average market price is fixed to $P^{avg} = c^{mrg} + \frac{c^{cnv}}{T}$ which is sufficient for the conventional technology to refinance investment and operation costs. In an imperfectly competitive market, the average market price under market-based support schemes is $P^{avg} = \frac{a+c^{mrg}}{2} + \frac{c^{cnv}}{2T} - \frac{bq}{2} K_E^{res\,*}$. As a result, more investment in renewables by the exclusively renewable firm decreases the market price while investments of the conventional technology do not alter the average market price.

[11] This is given by solving $\pi_E^A = P^A K_E^{res}$ in theorem 5 considering $\frac{dP^A}{dK_E^{res}} = 0$.

[12] Which will be the case if $b < \frac{c^{res}}{2qT}\left(\frac{a}{c^{mrg}} - 1\right)$.

6.2 Numerical comparison

To showcase the impact of the different market and support settings, we now turn to a simple numerical illustration based on a general set of parameters: $a = 100$, $b = 1$, $c^{mrg} = 30$, $q = 0.2$, $T = 30$, $c^{res} = 20$, and $C^{cnv} = 100$. We consider the case that the regulator targets a total renewable capacity and sets the premium and feed-in tariff accordingly. [13]

Figure 2 highlights the resulting conventional and renewable quantities at various regulatory renewable targets in perfectly and imperfectly competitive markets. As discussed in the conceptual comparison above, the generalist withholds production in either states of imperfectly competitive markets. Moreover, renewable support do not impact conventional generations in state U (and thereby the total installed conventional capacity). However, with an increase in renewable capacities in the system, the output of conventional power plants in state A is steadily decreasing (Figure 2, left panel). Unlike perfectly competitive markets, in imperfectly competitive markets the type of support policy affects the conventional production of the firm in state A: Under a FIT, generalist's conventional output is higher than under a FIP regime, as the renewable output is also benefiting from higher market prices in a FIP regime increasing incentives to withhold output. With respect to renewable investments (Figure 2, right panel) firm G is always investing less than firm E in the imperfect market setting whereas both firms invest equally under perfect competitive conditions. The support schemes have divergent effects on the incentives for G and E; however, the scale is rather minor in the example.

Combining conventional and renewable quantities for firm G under imperfect competition shows that under a FIT regime the overall output in state A remains rather constant (firm G has a slight increase from 31.6 to 33.3 units in the considered range). However, under a FIP regime the combined output of firm G is reducing (from 27.5 to 22.4 units). As the overall market quantity is increasing, this translates into a reduction of market share for firm G under a FIP regime for higher renewable targets.

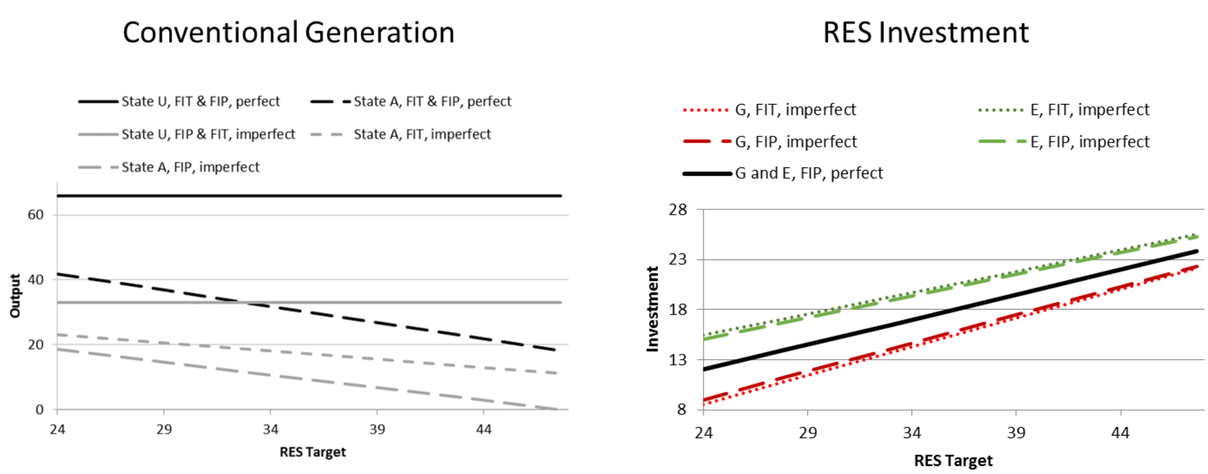

Figure 2: Quantity results of numerical example

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[13] We skip presenting the investment subsidy scheme since it is equivalent to a feed-in premium case if tailored properly.

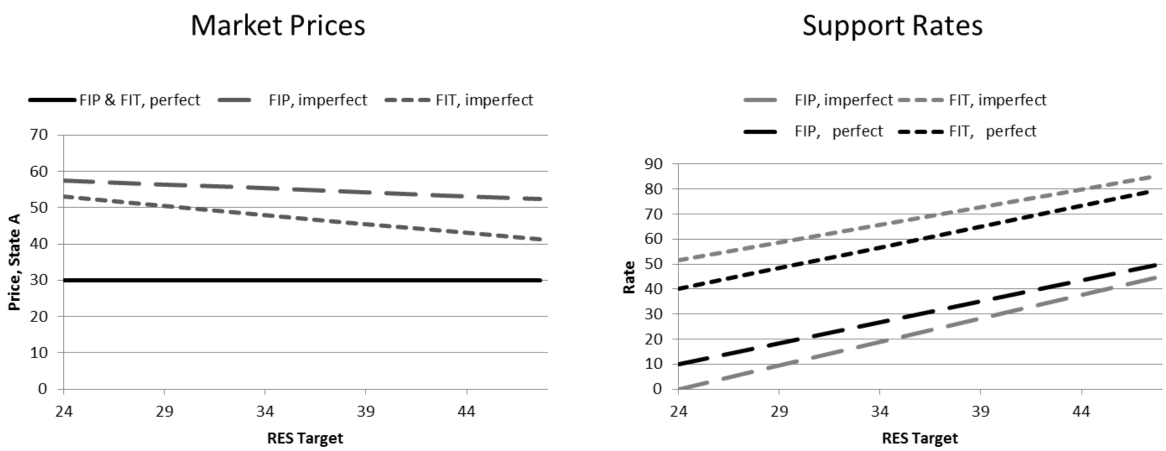

Figure 3: Price results of numerical example

The quantity results translate also into respective market price effects (Figure 3, left panel). Whereas under perfect competition the market price in state A is fixed and defined by the conventional generation costs, under imperfect competition we observe a price mark-up that is generally decreasing with higher renewable targets. This decrease is more pronounced under a FIT regime than under a FIP reflecting the overall faster quantity increase under a FIT regime.

With respect to the needed support rates to obtain the desired renewable target (Figure 3, right panel), the perfect competition results highlight the general difference between a FIT and a FIP: the market prices. The spread between both rates is always equal to the market price reflecting the fact that under a FIT renewable generation does not obtain income on the wholesale market. The support rates are generally increasing with the renewable target as renewable investments have an increasing cost function. Under imperfect competition the needed support rate in a FIP regime is slightly less than under perfect competition reflecting the fact that market prices (and thereby income for renewable generation) is higher due to the price mark-up. However, the difference is less than the mark-up and gradually decreasing with the increasing renewable target. For the FIT regime the reverse effect is observable. The support rate needs to be higher under imperfect competition to at least partially compensate for the foregone higher market prices for renewable output.

The right panel of Figure 3 highlights the importance for the regulator to know the competitiveness level of the market. The same support rates will lead to different renewable investments depending on the company behavior and subsequent the desired renewable target may not be reached. Figure 4 highlights this effect for a setting in which the regulator assumes perfect competition whereas the market outcome is defined by strategic company behavior. In case of a FIP regime the resulting renewable investment is larger than anticipated as the perfectly competitive rate assumes a lower market price than what actually will emerge. The reverse is true for the FIT regime. The relative difference is higher for smaller renewable targets as for higher targets both the imperfect FIP and FIT support rate levels converge to the perfect competitive ones (see Figure 3, right panel).

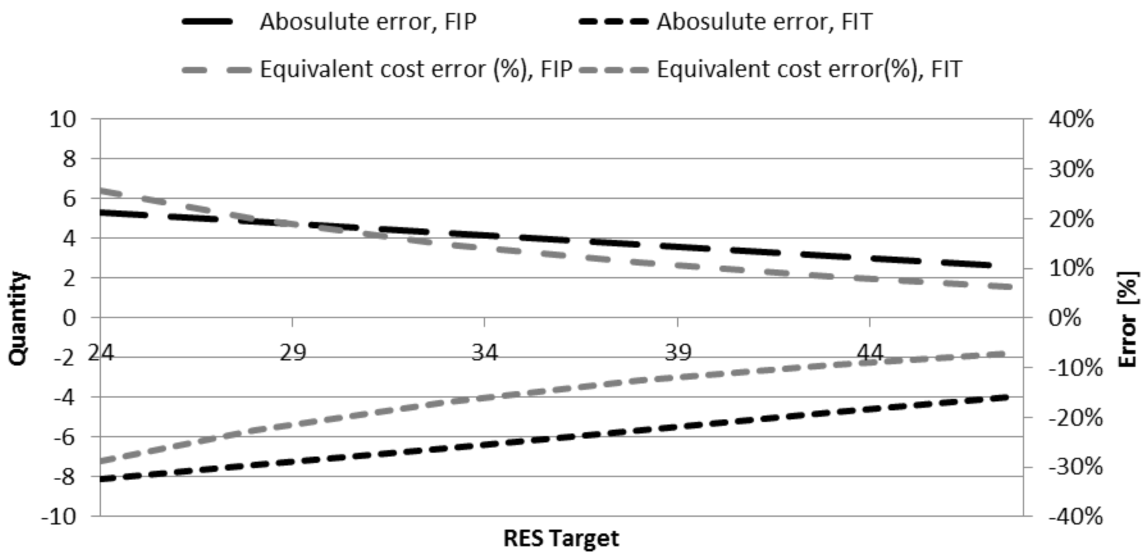

Figure 4: Deviation of RES investment from target level due to misidentification of competitiveness

The scale of this error can be compared to another potential forecast error with high relevance for renewable support schemes: renewable cost estimates.[14] Especially for the lower renewable targets, the resulting error stemming from a wrong perception of market competitiveness is equivalent to a cost estimation error of 20 to 30%. Albeit a stylized example, this highlights the importance to not only account for technical aspects when designing renewable support schemes but also investigate the market dynamics and structures to derive a robust support regime.

7. Limitations

Given the highly stylized structure of our model the results and insights are naturally subject to limitations. Following we will shortly highlight the main structural aspects neglected by the model and their impact on our findings.

One central aspect of our analysis is the differentiation between only two states and two technologies. In reality, a set of different conventional and renewable technologies is available for investment purposes and market conditions are shaped by more than just an on/off availability of renewables. However, breaking the findings down into their main conclusions many of those additional dynamics do not necessarily alter the conclusions.

Renewable investments in market-based systems are defined by the income they can generate during periods they are available. Under perfectly competitive conditions those periods will have price levels equal to the fuel costs of the marginal conventional power plant. Whereas in our model this was predefined by the restriction to only one conventional technology, in reality this will likely be a set of different plants at different periods. But renewable investments will still be shaped by the average

[14] For example, most feed-in tariff regimes assume a gradual decreasing tariff rate due to assumed cost improvements for renewable technologies.

market price they can obtain during their operation periods. In a strategic setting this price is further influenced by the market power mark-ups. Thus, investment incentives for firm E remain largely similar to the structures defined by our model.

For the generalist firm G, the interactions between conventional and renewable investments become important. The finding that the conventional investment is not impacted by renewable support is given by the fact that, by definition, their capacity limit is only binding in state U. In reality the interplay of demand dynamics, renewable injection and different plant technologies will lead to situations where plants are at their capacity limit but not the price setting unit; i.e. they are inframarginal in some of the periods. Introducing support policy for renewables will likely impact market prices in those periods and in turn impact investment decisions of those units that are inframarginal. This is represented by the availability element in the conventional capacity results (i.e. $(1-q)T$). However, the basic investment logic still follows the structure presented by the model: conventional generators only earn profit in those periods their capacity limit is binding. If the duration and/or price level in those periods is impacted by renewables, there will be a feedback effect (i.e. investments in conventional technologies will scale back as renewable investments scale up). How exactly this feedback effect plays out is subject for further research as this also depends on the representation of renewable technologies.

In practice, multiple renewable technologies coexist with potentially different availability patterns, which might affect decisions in imperfectly competitive markets. Marginal decision-making concept suggests that if availability pattern of two technologies have no overlap, their investment decisions will be made independently from each other since they have no effects on each other's marginal profit. Also, in the case of overlapping availabilities under FIT, renewable investments of the exclusively renewable firm are independently decided since their marginal profit depends only on their corresponding feed-in rates. Therefore, their renewable investments will be structurally similar to our results. The generalist firm, on the other hand, would invest more in renewables if overlap of availability results in lower market price and consequently mark-ups on conventional technology. On the other hand, under other policies (namely FIP, investment subsidies and no subsidies), marginal profit of each technology would depend on other technologies (via effects on market price). Therefore, the renewable investment of overlapping technologies would impact each other.

The same arguments on inframarginal suppliers and impact of availabilities also applies to demand related aspects. A more detailed representation of the demand dynamics over periods (i.e. peak and off-peak demand) as well as demand elasticities will interact with the availability pattern of renewable technologies and thereby impact the potential for marginal profits for conventional technologies. The same basic incentive structures as in our model will prevail but depending on the correlation between availability and demand level (e.g. solar generation and demand are at least partially correlated) there can be structures that favor or disfavor specific technology combinations.

Another important restriction of our model is its deterministic nature. As long-term renewable production involves some degrees of uncertainty and investors can have different levels of risk-aversion, including both aspects could alter incentive structures. This is also important in regard to the risk hedging provided by the support mechanism; e.g. a FIT regime will shield investors from market related uncertainties and could have positive feedback effects on investment costs due to lower capital expenses.

Our model is designed as a greenfield setting whereas real world electricity markets represent a brownfield setting with existing technologies in place. In the long run the investment incentives should follow the structure presented by our model as exiting plants will eventually by phased out and their sunk cost nature should not impact new investment decisions. However, given their potential impact on price structures across periods they may alter the transition pathway until a stable investment equilibrium is reached.

One final important simplification of our model is the assumption that the support schemes are financed by the state budget and there is no feedback effect from refinancing. However, in many real-world electricity markets, support schemes are at least partially self-financed by a levy on electricity bills of end-consumers or a lump-sum tax. As a result, more support for renewables increases the total costs of the consumers and consequently influence market demand and market prices. This feedback effect is also highly relevant for support systems based on green quotas and tradeable permits.

8. Conclusion

In this paper we investigate investment and dispatch decisions of conventional and renewable technologies in electricity markets. Accounting for two types of firms – an exclusively renewable investor and a mixed renewable-conventional investor – we derive their equilibrium behavior under perfect and Cournot competition for different renewable support schemes; namely feed-in tariff, feed-in premium, and investment subsidies for renewables.

Using a two-stage model setting we can show that heterogeneous firms behave similarly in perfectly competitive markets but differently in the presence of market power. The feedback effect from their own investment decisions and the consideration of their competitor's behavior leads to divergent incentive structures. While an exclusively renewable firm focuses on market price, a generalist firm considers also the substitution possibility between its technologies. As a result, heterogeneity of investors as well as the competitive level of the market should be considered while estimating the effects of support schemes or the budget required. These interactions may increase in importance if beside environmental objectives, renewable support is also expected to enhance competition levels.

Albeit highly stylized in its structure, the model highlights the basic incentive structures for investments into conventional and renewable technologies. The former being completely dependent on those states of the world in which they reach their own capacity limits. Only in those periods they will be able to obtain revenue streams to cover their investment costs. Renewables on the other hand are heavily impacted by the price levels defined by marginal cost structures from conventional units and/or additional income provided by support schemes. Coupled those two effects reflect the current challenge many electricity markets face: increased renewable generation is pushing conventional units to the fringe and reducing their own market income due to the merit-order effect. This in turn requires higher cross-financing via support schemes to maintain sufficient income streams. In the long run, such a market setting would lead to a price divergence between periods with high renewable injection with low prices (being capped at marginal generation costs of the remaining conventional generators) and periods when conventional plants reach their capacity limits and prices spike to refinance their investments. This price spread between available and unavailable states (replacing the former peak and off-peak spread) will furthermore set potential incentives for storage technologies.

Consequently, the model presented here can be seen as a first step to conceptualize the dynamics in today's electricity markets. Naturally, there is the need for further adjustments to identify challenges and opportunities for the different technologies and derive robust policy and market design concepts.

References

Acemoglu, D., Kakhbod, A., & Ozdaglar, A. (2017). Competition in Electricity Markets with Renewable Energy, *38*, 137–156.

Ambec, S., & Crampes, C. (2012). Electricity provision with intermittent sources of energy. *Resource and Energy Economics*, *34*(3), 319–336.

Ambec, S., & Crampes, C. (2015). Decarbonizing electricity generation with intermittent sources of energy. *Toulouse School of Economics Working Paper TSE -603*.

Boom, A., & Buehler, S. (2007). *Restructuring electricity markets when demand is uncertain: Effects on capacity investments, prices and welfare*. Centre for Industrial Economics, Institute of Economics, University of Copenhagen.

Boomsma, T. K., Meade, N., & Fleten, S. E. (2012). Renewable energy investments under different support schemes: A real options approach. *European Journal of Operational Research*, *220*(1), 225–237.

Butler, L., & Neuhoff, K. (2008). Comparison of feed-in tariff, quota and auction mechanisms to support wind power development. *Renewable Energy*, *33*(8), 1854–1867.

Chao, H. po. (2011). Efficient pricing and investment in electricity markets with intermittent resources. *Energy Policy*, *39*(7), 3945–3953.

Cludius, J., Hermann, H., Matthes, F. C., & Graichen, V. (2014). The merit order effect of wind and photovoltaic electricity generation in Germany 2008-2016 estimation and distributional implications. *Energy Economics*, *44*(2014), 302–313.

Crampes, C., & Creti, A. (2005). Capacity competition in electricity markets. *Economia Delle Fonti Di Energia e Dell'ambiente*, *2*, 59–83.

Dressler, L. (2016). Support schemes for renewable electricity in the European Union: Producer strategies and competition. *Energy Economics*, *60*, 186–196.

Fagiani, R., Barquín, J., & Hakvoort, R. (2013). Risk-based assessment of the cost-efficiency and the effectivity of renewable energy support schemes: Certificate markets versus feed-in tariffs. *Energy Policy*, *55*, 648–661.

Gabszewicz, J. J., & Poddar, S. (1997). Demand Fluctuations and Capacity Utilization Under Duopoly. *Economic Theory*, *10*(1), 131-146.

Garcia, A., Alzate, J. M., & Barrera, J. (2012). Regulatory design and incentives for renewable energy. *Jounral of Regulatory Economics*, *41*, 315–336.

Garcia, A., & Shen, Z. (2010). Equilibrium capacity expansion under stochastic demand growth. *Operations Research*, *58*(1), 30–42.

Green, R., & Vasilakos, N. (2010). Market behaviour with large amounts of intermittent generation. *Energy Policy*, *38*(7), 3211–3220.

Grimm, V., & Zoettl, G. (2006). Access to commitment devices reduces investment incentives in oligopoly. *Working Paper Series in Economics 25, University of Cologne, Department of Economics*.

Haas, R., Eichhammer, W., Huber, C., Langniss, O., Lorenzoni, A., Madlener, R., … Verbruggen, A. (2004). How to promote renewable energy systems successfully and effectively. *Energy Policy*, *32*(6), 833–

839.
Haas, R., Resch, G., Panzer, C., Busch, S., Ragwitz, M., & Held, A. (2011). Efficiency and effectiveness of promotion systems for electricity generation from renewable energy sources - Lessons from EU countries. *Energy*, *36*(4), 2186–2193.
Helgesen, P. I., & Tomasgard, A. (2018). An equilibrium market power model for power markets and tradable green certificates, including Kirchhoff's Laws and Nash-Cournot competition. *Energy Economics*, *70*, 270–288.
Helm, C., & Mier, M. (2016). Efficient diffusion of renewable energies : A roller-coaster ride. *Oldenburg Discussion Papers in Economics*, *389*(16), 1–30.
IEA. (2017). *World Energy Outlook 2017*. Organisation for Economic Co-operation and Development, OECD.
Klessmann, C., Nabe, C., & Burges, K. (2008). Pros and cons of exposing renewables to electricity market risks - A comparison of the market integration approaches in Germany, Spain, and the UK. *Energy Policy*, *36*(10), 3646–3661.
Lipp, J. (2007). Lessons for effective renewable electricity policy from Denmark, Germany and the United Kingdom. *Energy Policy*, *35*(11), 5481–5495.
Liski, M., & Vehviläinen, I. (2016). Gone with the Wind? An Empirical Analysis of the Renewable Energy Rent Transfer. *CESifo Working Paper Series No. 6250*.
Liu, C., Li, N., & Zha, D. (2016). On the impact of FIT policies on renewable energy investment: Based on the solar power support policies in China's power market. *Renewable Energy*, *94*, 251–267.
Milstein, I., & Tishler, A. (2011). Intermittently renewable energy, optimal capacity mix and prices in a deregulated electricity market. *Energy Policy*, *39*(7), 3922–3927.
Mitchell, C., Bauknecht, D., & Connor, P. M. (2006). Effectiveness through risk reduction: A comparison of the renewable obligation in England and Wales and the feed-in system in Germany. *Energy Policy*, *34*(3), 297–305.
Murphy, F. H., & Smeers, Y. (2005). Generation Capacity Expansion in Imperfectly Competitive Restructured Electricity Markets. *Operations Research*, *53*(4), 646–661.
Murphy, F. H., & Smeers, Y. (2010). On the impact of forward markets on investments in oligopolistic markets with reference to electricity. *Operations Research*, *58*(3), 515–528.
Oliveira, F. (2008). The value of information in electricity investment games. *Energy Policy*, *36*(7), 2364–2375.
Oliveira, T. (2015). Market signals and investment in intermittent renewables. In *International Conference on the European Energy Market, EEM* (Vol. 2015–Augus, pp. 1–39).
Pineda, S., Boomsma, T. K., & Wogrin, S. (2018). Renewable generation expansion under different support schemes: A stochastic equilibrium approach. *European Journal of Operational Research*, *266*(3), 1086–1099.
Rouillon, S. (2015). Optimal and Equilibrium Investment in the Intermittent Generation Technologies. *Revue d'economie Politique*, *125*(3), 415–452.
Rubin, O. D., & Babcock, B. A. (2013). The impact of expansion of wind power capacity and pricing methods on the efficiency of deregulated electricity markets. *Energy*, *59*, 676–688.
Tamás, M. M., Bade Shrestha, S. O., & Zhou, H. (2010). Feed-in tariff and tradable green certificate in oligopoly. *Energy Policy*, *38*(8), 4040–4047.
Tishler, A., Milstein, I., & Woo, C. K. (2008). Capacity commitment and price volatility in a competitive electricity market. *Energy Economics*, *30*(4), 1625–1647.
Twomey, P., & Neuhoff, K. (2010). Wind power and market power in competitive markets. *Energy Policy*, *38*(7), 3198–3210.
Van Nuffel, L., Rademaekers, K., Yearwood Travezan, J., Post, M., Hoogland, O., & Lopez, P. (2016). Energy Union: Key Decisions for the Realisation of a Fully Integrated Energy Market. *European*

Parliment.
Ventosa, M., Denis, R., & Redondo, C. (2002). Expansion planning in electricity markets. Two different approaches. *Proceedings of the 14th PSCC Conference*, (June), 24–28.
von der Fehr, N.-H. M., & Ropenus, S. (2017). Renewable Energy Policy Instruments and Market Power. *The Scandinavian Journal of Economics*, *119*(2), 312–345.
Weidmann, N., Krysiak, F. C., & Weigt, H. (2018). *Electricity market design: Policy coordination and zonal configurations*. *Project report for the Swiss Federal Office of Energy SFOE*.
Winkler, J., Gaio, A., Pfluger, B., & Ragwitz, M. (2016). Impact of renewables on electricity markets - Do support schemes matter? *Energy Policy*, *93*, 157–167.
Wolak, F. A., & Patrick, R. H. (2001). The impact of market rules and market structure on the price determination process in the England and Wales electricity market. *No. W8248. National Bureau of Economic Research*.