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Renewable Energy Sources and Investment in European Power Transmission Networks

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Abstract

During the past decade, renewable energy sources have become an indispensable pillar in European electricity generation. This paper aims at examining if the increasing importance of renewables stimulates investment in European power transmission networks. The question of interest is addressed by an error correction investment model that builds on Neoclassical theory and is further augmented by recent literary findings. Under the proposed threefold estimation strategy, the share of renewables is not found to significantly influence investment spending when the full set of transmission system operators are considered. However, a slight and justified sample restriction leads to the conclusion that a rising share of renewable energy sources substantially increases investment in power transmission networks.

JEL classification: C33, L50, L94, Q42, Q48.

Keywords: Renewables, Investment, Transmission Network, Electricity.

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Contents

1 Introduction

During the past decade, renewable energy sources have become an indispensable pillar in European electricity generation. Today, the market share of renewables amounts to 66% in Sweden, 75% in Austria and even 100% in Norway. If power from hydroelectric sources is excluded, renewables still account for more than 25% of electricity generation in Germany, Denmark, Estonia and Portugal (Eurostat, 2017a).

The present paper joins a rapidly growing body of literature which analyses the consequences of this relatively novel energy source. More specifically, the paper aims at examining if the increasing importance of renewables stimulates investment in European power transmission networks.

This empirical question is addressed by an error correction model that builds on Neoclassical investment theory and is further augmented by capital constraints, future expectations, output prices, capacity considerations, interest rates and the regulatory environment. Within this framework, the proportion of renewable generation in total electricity output constitutes the variable of main interest.

The proposed models are estimated with a threefold strategy that consists of Granger (1969) causalities, ordinary least squares techniques and general methods of moments procedures. While the variable of main interest is not found to significantly influence investment spending when the full set of transmission system operators is considered, a slight and justified sample restriction leads to the conclusion that a rising share of renewable energy sources substantially increases investment in power transmission networks. What is more, evidence indicates that power transmission investment is characterised by path dependencies and determined by an operator's cash flow.

To summarise, the present paper is organised as follows. Section 2 begins with an introduction to the topic of renewable energy sources by summarising the relevant literature, before Section 3 presents the available dataset. Subsequently, Section 4 establishes the econometric modelling approach, while regression results are provided in Section 5. Finally, Section 6 states policy implications and concludes this paper.

2 Literature Review

The theoretical framework of this paper is based on the contributions of Jorgenson (1966), Jorgenson and Siebert (1968), Jorgenson (1971), Jorgenson (1972), Lucas (1976), Bean (1981), Banerjee, Dolando, Galbraith, and Hendry (1993), Chirinko (1993), Hubbard (1998), Bond, Harhoff, and Van Reenen (2005), Hassler and Wolters (2006), Bond and Van Reenen (2007), Pindyck and Rubinfeld (2009) and Hindriks and Myles (2013) as summarised in Section 4 below. In addition, the econometric approach pursued in this paper builds on Granger (1969), White (1980), Nickell (1981), Holtz-Eakin, Newey, and Rosen (1988), Arellano and Bond (1991), He and Maekawa (2001), Nair-Reichert and Weinhold (2001), Bowsher (2002), Stock and Watson (2008), Petersen (2009), Roodman (2009), Greene (2012) as well as Wooldridge (2013).

So far, most studies which focus on the increasing importance of renewable energy sources have analysed the issues of market prices and integration. To begin with, a downward pressure on prices induced by renewables can be addressed theoretically with the so-called *merit order effect* which is outlined in a publication of The European Wind Energy Association (2010) and summarised in Figure 1. On the one hand, this figure depicts a steep demand curve which reflects the relatively inelastic demand for electricity: Should the price alter, the quantity of power demanded remains almost unchanged. On the other hand, the dashed line represents a typical electricity supply curve. This graph is labelled *merit order curve*, because it considers all generation capacities available and orders them from the cheapest (renewables) to the most expensive (oil) power source. The cost differences are represented by steps and primarily depend on technological reasons and fuel prices. A stable market equilibrium can be found in the intersection of the supply and demand curves. If the condition of perfect competition is satisfied, the market price equals marginal cost and takes the value p_A. As can be seen in Figure 1, an expansion of renewable energy supply shifts the merit order curve to the right as represented by the solid line. Due to the inelastic nature of demand, price decreases are very likely. In the figure below, the price drops to the level of p_B. Empirically, this merit order effect has been confirmed[1] by Munksgaard and Morthorst (2008), Jacobsen and Zvingilaite (2010) as well as Jónsson, Pinson, and Madsen (2010) for Denmark, Sensfuß, Ragwitz, and Genoese (2008), Weigt (2009) as well as Ketterer (2014) for Germany and Gelabert, Labandeira, and Linares (2011) for Spain. What is more, Gianfreda, Parisio, and Pelagatti (2016) find that increasing shares of renewable energy sources reduce the impact of prices for hydrocarbon sources on the electricity price. Still, Ketterer (2014) argues that the discussed decrease in average prices comes with a growing price volatility.

Turning to the integration of power markets, Woo, Zarnikau, Moore, and Horowitz (2011) analyse the effect of wind generation on price discrepancies between intercon-

[1] See The European Wind Energy Association (2010) for a literature review.

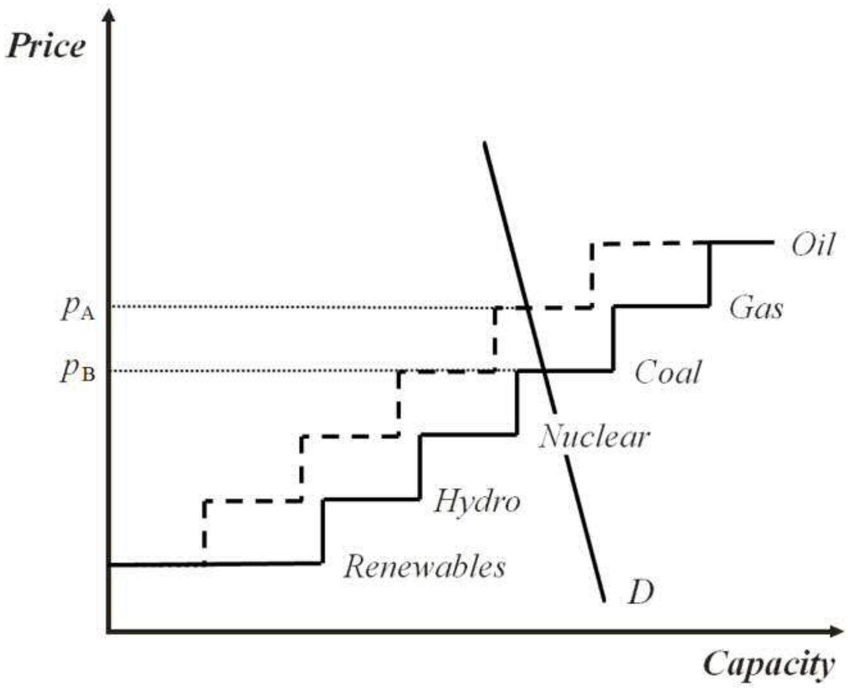

Figure 1: Merit order effect. Figure adapted from The European Wind Energy Association (2010) and Gugler et al. (2016).

nected sub-markets which lie within the Texan electricity market. Overall, the authors find that this renewable energy source causes zonal electricity prices to diverge considerably due to network congestion (Woo et al., 2011). Similarly, Grossi, Heim, Hüschelrath, and Waterson (2015) focus on the interconnected European electricity market and analyse how unilateral policies of the individual member states can harm this harmonised power system. Specifically, the German support schemes for renewables are found to have significantly reduced electricity prices not only in the fully integrated German-Austrian, but also in adjacent electricity markets. Among these, the largest price decreases have been identified in the Czech Republic and Denmark. What is more, the introduction of a control for network congestion lowers the domestic, but even increases the effect on neighbouring markets (Grossi et al., 2015). A resembling contribution is provided by Keppler, Phan, and Le Pen (2016) who explore spreads in electricity prices between France and Germany and associate solar as well as wind production with rising differences. Eventually, Gianfreda et al. (2016) examine the relationship between the growth of renewable energy sources and European power market integration. They conclude that during peak hours, the electricity market is now less integrated, while no change is found for off-peak times (Gianfreda et al., 2016).

In contrast, the consequences of renewables for the power transmission network and grid investment have thus far mainly been explored theoretically. For example, Groschke, Eßler, Möst, and Fichtner (2009) discuss the structural and locational changes of German power plants which result, among other factors, from the expansion of wind turbines. Consequently, the transmission distance for electrical energy rises, which faces existing power networks with increasing challenges. Therefore, the authors present novel energy system models which take network constraints explicitly into account and aim at enhancing efficiency with regard to power plant construction, network utilisation and grid investment (Groschke et al., 2009). In addition, Schaber, Steinke, and Hamacher (2012) also begin with the observation that variable renewable energy sources like solar and wind become increasingly important. Based on a regional model of the European electricity grid, the authors argue that power network expansions are required in order to distribute the merit order effect resulting from renewables equally in time and space, to guarantee price stability and to protect conventional plants in regions with high capacities of renewables from becoming unprofitable (Schaber et al., 2012). A further contribution that centres on the stochastic nature of renewables originates from Spiecker, Vogel, and Weber (2013) who argue that this volatility should be accounted for during the planning process of transmission systems and introduce a suitable model which is applied to assess the benefits of additional grid capacities between continental and northern Europe. Fürsch et al. (2013) also state that transmission grid extensions are essential in order to cost-efficiently achieve the European targets of 80% share of renewables and 80% reduction of CO_2 emissions in the electricity sector by 2050. Quantitatively, the authors perceive a transmission network expansion of 228,000 kilometres between the years 2010 and 2050 as being necessary. Another study which outlines the importance of grid investment is provided by the International Renewable Energy Agency (2015). In this paper, the concept of *base load* is addressed by stating that this minimum load is a demand side characteristic which must not be mixed up with the concept of power supply. Therefore, it is not necessary that base demand is met by specific nuclear or coal power plants. Rather, these plants operate continuously nowadays due to their high capital and relatively low variable costs. As a possible alternative, this study proposes an interconnected system of flexible (e.g. gas), dispatchable (e.g. hydro, biomass and geothermal) and variable (e.g. wind and solar photovoltaic) power plants in order to fully cover the electricity demand. This can, however, only be achieved by carefully planning and continuously strengthening the power transmission grid (International Renewable Energy Agency, 2015).

Another strand of literature identifies a coordination problem between investment in generation capacities and power networks in a liberalised market environment. Höffler and Wambach (2013) show that inefficient investments are likely to arise if private individuals own generation facilities and the regulator is responsible for the grid. Building on this, Wagner (2016) formulates a theoretical model which reveals that under conventional support schemes, wind power plants are not optimally distributed. Provided that transmission grid investment follows the locations of wind turbines, inefficient power networks are constructed (Wagner, 2016).

Building on all these contributions, the novel approach pursued in this paper aims at identifying the link between the share of renewable energy sources and investment in power transmission networks by using a dataset of 34 European transmission system operators ranging from 1999 to 2015. The proposed models account for several other covariates which are found to significantly impact grid investment in comparable studies published by Alesina, Ardagana, Nicoletti, and Schiantarelli (2005), Bond et al. (2005), Lyon and Mayo (2005), Cambini and Rondi (2010), Grajek and Röller (2012), Nardi (2012), Gugler, Rammerstorfer, and Schmitt (2013), Cullmann and Nieswand (2016), Poudineh and Jamasb (2016) and Cambini and Rondi (2017).

3 Data and Descriptive Statistics

The succeeding regression analysis of Section 5 relies on a number of variables and data sources which will subsequently be introduced. Furthermore, descriptive statistics are presented in order to provide an impression of the database's main characteristics.

First of all, the dataset comprises an unbalanced panel of 34 European transmission system operators ranging from 1999 to 2015. Table 1 lists these operators at the national level, while a graphical representation can be found in Figure 2.

Table 1: Transmission system operators at the national level.

AT	**Austria**	Austrian Power Grid AG
BE	**Belgium**	Elia System Operator SA
BG	**Bulgaria**	Electricity System Operator EAD
CH	**Switzerland**	Swissgrid AG
CY	**Cyprus**	Transmission System Operator Cyprus
CZ	**Czech Republic**	Ceská Energetická Prenosová Soustava AS
DE	**Germany**	50Hertz Transmission GmbH
		Amprion GmbH
		TenneT TSO GmbH
		TransnetBW GmbH
DK	**Denmark**	Energinet.DK
EE	**Estonia**	Elering AS
ES	**Spain**	Red Eléctrica de España SA
FI	**Finland**	Fingrid OYJ
FR	**France**	Réseau de Transport d'Electricité, SA
GR	**Greece**	Independent Power Transmission Operator SA
HR	**Croatia**	Croatian Transmission System Operator Ltd
HU	**Hungary**	Magyarország Átviteli Hálózata
IE	**Ireland**	Eirgrid Plc
IT	**Italy**	Terna - Rete Elettrica Nazionale
LT	**Lithuania**	Litgrid AB
LU	**Luxembourg**	Creos Luxembourg SA
LV	**Latvia**	Augstsprieguma Tīkls AS
NL	**Netherlands**	Tennet TSO BV
NO	**Norway**	Statnett SF
PL	**Poland**	Polskie Sieci Elektroenergetyczne
PT	**Portugal**	Redes Energéticas Nacionais, SGPS, SA
RO	**Romania**	Compania Nationala de Transport al Energiei Electrice Transelectrica SA
SE	**Sweden**	Svenska Kraftnät
SI	**Slovenia**	Elektro-Slovenija, doo
SK	**Slovak Republic**	Slovenská Elektrizacná Prenosová Sústava, AS
UK	**United Kingdom**	National Grid Electricity Transmission Plc
		Scottish Hydro Electric Transmission Plc
		System Operator of Northern Ireland Ltd

In respect of the underlying research question, the *proportion of renewable generation in total electricity output*, which is categorised into two different types, constitutes the variable of main interest in this paper. Specifically, the numerator of the first proposed parameter captures the renewable sources of wind, solar, different forms of bio fuels, municipal waste, geothermics, tide, wave as well as ocean, but excludes hydroelectric power

Figure 2: Sample at the national level. Illustrated in Mathematica.

and is therefore labelled *share of renewables (without hydro)*. This exclusion is undertaken because unlike the remaining renewable electricity sources, water power constitutes a base load component[2] (Gugler et al., 2016). The second proposed measure is referred to as *share of renewables (total)* as its numerator also contains electricity generated from hydroelectric sources. This variable is employed in Section 5.4 for robustness checks of the main regression results. Turning to the denominator, both measures incorporate the total annual electricity generated from all sources. Finally, both parameters rely on Eurostat (2017a) and are available for the period from 2004 to 2015 at the national level. It is therefore assumed that all transmission system operators within a country offer the same energy mix[3].

The two types of this paper's main variable of interest are illustrated in Figure 3 and Figure 4 for a set of eight selected countries (Austria, Germany, Spain, France, Italy, Poland, Sweden and the United Kingdom). As depicted by Figure 3, the market share of renewables excluding hydroelectric power amounted to less than 10% in all considered countries at the beginning of the observation period, but exhibited a rising trend in the subsequent years. Until 2015, Germany, Spain, Italy and the United Kingdom experienced the largest growth, while the rate of increase was smaller in Austria, Poland and France.

[2]It can also be argued that geothermics and - to a certain extent - some sorts of bio fuels also supply the base load. Therefore, the issue of (solid) bio fuels will be readdressed in Section 5.3 below. As statistics are, however, not separately available for the remaining types of suspected base load components, it is not possible to preclude them. This minor inaccuracy is not expected to bias the results, because the relative importance of these miscellaneous sources is negligible.

[3]This assumption is of particular relevance for Germany and the United Kingdom, where more than one transmission system operator exists.

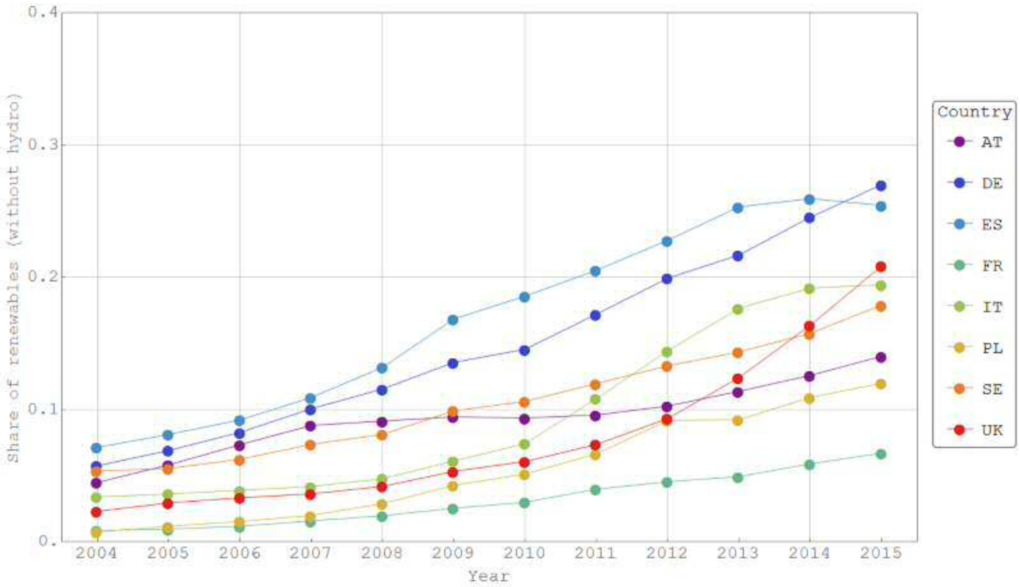

Figure 3: Proportion of renewable generation without hydroelectric power in total electricity output. Data from Eurostat (2017a). Illustrated in Mathematica.

Turning to the total share of renewables summarised in Figure 4 evidences that hydroelectric sources play a significant role in Austria and Sweden. Again, the proportion of renewable energy sources increases in the entire sample with the most substantial growth in Germany, Spain, Italy and the United Kingdom.

Furthermore, two variables are crucial in order to analyse the transmission operators' investment behaviour, namely the *capital expenditure on tangible fixed assets* and the *stock of tangible fixed assets*. As discussed in Section 4.1, these indicators constitute the *investment rate* which serves as the dependent variable in all regression models. Data for these variables was provided by the operators either directly upon request or indirectly through their annual reports.

In addition, transmission system operators' data concerning *cash flow* and *revenues* originates from the Orbis Database of Bureau Van Dijk (2017). In Section 4.1, the former variable will be divided by the *tangible fixed assets* in order to establish the *cash flow rate*.

Moreover, the variable capturing the *harmonised index of consumer prices for electricity* is published by Eurostat (2017b) and normalised to 100 as of 2015 for all countries. Again, electricity prices are assumed as homogeneous for all operators within a certain country.

Further, *load* data emphasises the demand side and constitutes itself from figures of the monthly electricity consumption in gigawatt hours provided by the European Network of Transmission System Operators for Electricity (2015). As figures are only available at the national level, they are allocated to the various operators in Germany and the United Kingdom with respect to their relative tangible fixed assets.

What is more, the *long term interest rate* is based on the EMU convergence criterion bond yields made available by Eurostat (2016) for all countries and therefore transmission system operators except for Estonia, where this indicator is not applicable. In order not

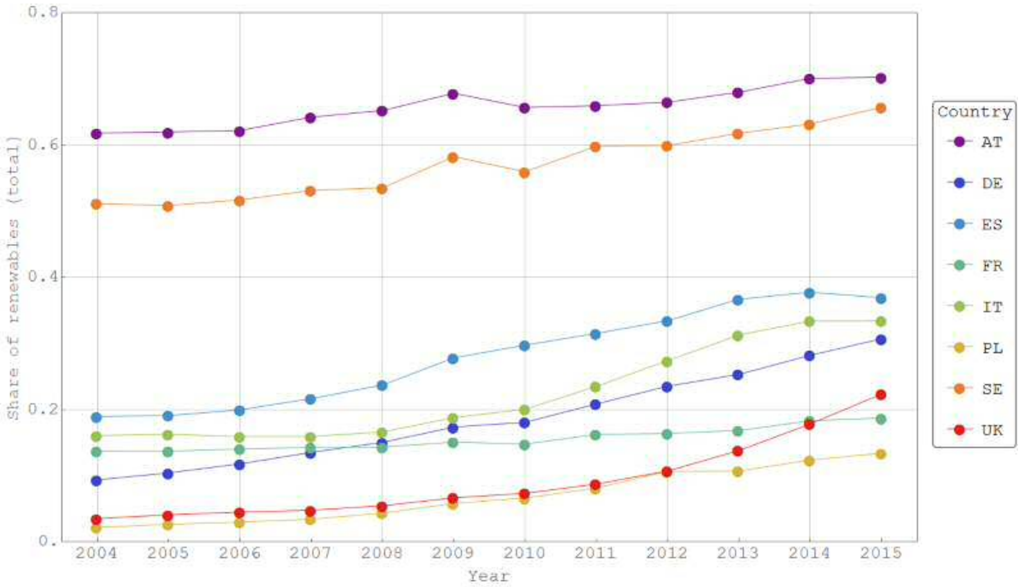

Figure 4: Proportion of renewable generation in total electricity output. Data from Eurostat (2017a). Illustrated in Mathematica.

to entirely exclude this country, its real lending interest rate provided by the World Bank (2017) is utilised as a substitute.

Finally, the *regulatory indicators* are published by the Organisation of Economic Co-operation and Development (2017) and cover the dimensions of *entry*, *public ownership*, *vertical integration* as well as *market structure* in the electricity sector. Quantitatively, these measures range between zero and six, where lower values imply a more liberalised business environment (Organisation of Economic Co-operation and Development, 2017).

The following Table 2 presents descriptive statistics for all variables under consideration.

Table 2: Descriptive statistics for the variables under consideration. Implemented in R. Table adapted from *stargazer* (Hlavac, 2015).

Statistic		N	Mean	St. Dev.	Min	Max
Share of Renewables without Hydro (Ratio)	(1)	396	0.086	0.082	0.000	0.513
Share of Renewables Total (Ratio)	(2)	396	0.228	0.210	0.000	1.000
Capital Expenditure on Tangible Fixed Assets (Million euro)	(3)	281	289.500	352.800	2.792	1,764.000
Tangible Fixed Assets (Million euro)	(4)	310	2,582.000	3,280.000	14.010	16,170.000
Investment Rate (Ratio)	(5)	258	0.141	0.103	0.011	0.932
Cash Flow (Million euro)	(6)	234	231.600	330.700	−72.790	1,640.000
Cash Flow Rate (Ratio)	(7)	177	0.115	0.142	−0.638	1.309
Revenues (Million euro)	(8)	247	1,615.000	2,699.000	1.990	15,618.000
Consumer Prices for Electricity (Index)	(9)	560	0.776	0.210	0.285	1.544
Load (Gigawatt Hours per Year)	(10)	396	97,620.000	113,690.000	283.200	513,292.000
Long Term Interest Rate (Percentage Points)	(11)	508	4.328	2.087	0.370	22.500
Regulation Entry (Index)	(12)	426	1.008	1.662	0.000	6.000
Regulation Public Ownership (Index)	(13)	426	3.038	2.243	0.000	6.000
Regulation Vertical Integration (Index)	(14)	426	4.541	0.763	2.438	6.000
Regulation Market Structure (Index)	(15)	389	1.382	2.010	0.000	6.000

Lastly, Table 3 shows correlations among all indicators, whose respective numbers are quoted in Table 2.

Table 3: Correlations among the variables under consideration. Implemented in R using the packages *xtable* (Dahl, 2016) and *Hmisc* (Harrell & Dupont, 2016). Table adapted from *stargazer* (Hlavac, 2015).

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
(2)	0.19***													
(3)	0.05	−0.09												
(4)	0.05	−0.06	0.90***											
(5)	0.10	−0.09	0.03	−0.19***										
(6)	0.11*	−0.02	0.88***	0.94***	−0.23***									
(7)	0.07	−0.06	−0.10	−0.10	0.20**	0.02								
(8)	0.40***	−0.04	0.22***	0.19***	0.17**	0.19***	−0.03							
(9)	0.30***	0.23***	0.02	−0.01	0.16***	−0.04	−0.06	−0.02						
(10)	0.03	−0.02	0.74***	0.86***	−0.25***	0.86***	−0.05	0.43***	−0.10**					
(11)	−0.34***	−0.11**	−0.16***	−0.13**	−0.09	−0.09	−0.11	−0.30***	−0.25***	−0.13**				
(12)	−0.37***	−0.24***	−0.22***	−0.16**	−0.08	−0.19**	−0.05	−0.17**	−0.34***	−0.20***	0.14***			
(13)	−0.17***	0.23***	−0.28***	−0.07	−0.12	−0.15*	−0.10	−0.44***	0.14***	−0.04	0.11**	0.34***		
(14)	−0.30***	−0.19***	0.08	0.07	−0.14*	−0.05	0.00	0.28***	−0.35***	−0.02	0.07	0.50***	−0.03	
(15)	−0.27***	−0.20***	−0.01	0.19***	−0.17**	0.07	−0.06	−0.19**	−0.23***	0.03	0.09*	0.41***	0.39***	−0.03

Note: *p<0.1; **p<0.05; ***p<0.01

4 Econometric Modelling Approach

The aim of this section is to develop an investment model and afterwards to define how to estimate it empirically. Therefore, Section 4.1 starts with a Neoclassical model of investment behaviour, before augmenting it with recent findings in the literature. Finally, Section 4.2 summarises the threefold estimation strategy.

4.1 Error Correction Investment Model

The roots of the model presented here lie in the Neoclassical theory of investment behaviour pioneered by Jorgenson and Siebert (1968) and Jorgenson (1971). These studies start with a *flexible accelerator model* that focuses on a profit maximising firm's investment strategy. Defined more closely, a firm is assumed to have a desired level of capital stock K_t^* that depends on its long-run expectations. Furthermore, as the actual capital stock is denoted by K_t, the following Equation 1 illustrates that at each period t, the focal firm adjusts its capital stock to the target level by a constant rate $(1-\kappa)$ of the difference between desired and current capital (Jorgenson & Siebert, 1968) (Jorgenson, 1971).

$$K_t - K_{t-1} = (1-\kappa) * (K_t^* - K_{t-1}) \tag{1}$$

Equation 2 provides an alternative measure of the actual capital stock by representing current capital K_t as the weighted average of all preceding levels of targeted capital, K_{t-s}^*. It should further be noted that the weights μ_s only take positive values and that their sum equals unity (Jorgenson & Siebert, 1968).

$$K_t = \sum_{s=0}^{\infty} \mu_s * K_{t-s}^* \tag{2}$$

This distributed lag function is called *flexible accelerator model* and can be further developed to a comprehensive investment theory by making use of the definition from accounting that actual changes in the capital stock correspond to gross investment I_t, less replacement expenditure. In general, it is assumed that these expenses for restoration are proportional to the capital stock of the preceding period. Equation 3 summarises this relation and regards the rate of depreciation δ as a fixed constant (Jorgenson & Siebert, 1968).

$$K_t - K_{t-1} \equiv I_t - \delta K_{t-1} \tag{3}$$

Differencing Equation 2 and combining it with Equation 3 yields the following generalised accelerator mechanism (Jorgenson & Siebert, 1968).

$$I_t = \sum_{s=0}^{\infty} \mu_s * (K_{t-s}^* - K_{t-s-1}^*) + \delta K_{t-1} \tag{4}$$

In Equation 4, the sequence of weights goes to infinity, which means that the actual investments are determined by *all* preceding desired levels of capital stock. Obviously, this generous inclusion of the past makes parameter estimations impossible. It is therefore of crucial importance to find an appropriate lag distribution that realistically corresponds to investment patterns. Jorgenson and Siebert (1968) rely on a Pascal distributed lag function[4] and explain current gross investment by actual as well as previous changes in the desired level of capital stock, lagged *net* investment and present replacement expenditure, as shown in Equation 5.

$$I_t = \zeta_1(K_t^* - K_{t-1}^*) + \zeta_2(K_{t-1}^* - K_{t-2}^*) - \zeta_3(I_{t-1} - \delta K_{t-2}) + \delta K_{t-1} \tag{5}$$

A subsequent important step is to find an expression for K_t^*. This requested stock of capital is assumed to be proportional (expressed by γ) to the ratio between a firm's revenues Y_t and the rental price of capital C_t. Furthermore, the model presented in Equation 6 supposes that the focal firm is faced with a production function characterised by a constant elasticity of substitution σ between capital and variable inputs (Jorgenson, 1971) (Chirinko, 1993).

$$K_t^* = \gamma Y_t C_t^{-\sigma} \tag{6}$$

The equations derived so far lead to the formulation of the Neoclassical model of investment. Specifically, combining Equation 4 with Equation 6 yields the following specification

$$I_t = \sum_{s=0}^{S} \iota * \mu_s * \Delta(Y_{t-s} C_{t-s}^{-\sigma}) + \delta K_{t-1} + \epsilon_t, \tag{7}$$

where S has already been chosen (e.g. accordingly with Equation 5), ι is a parameter, Δ denotes the delta operator and ϵ_t is a zero mean as well as constant variance error term (Chirinko, 1993).

With respect to the real world, it is advantageous to extend the Neoclassical investment model by taking explicitly into account that the firm's investment behaviour may be affected by financing constraints. More specifically, an organisation could be faced with different costs for internal and external financing, should a setting of imperfect information in capital markets be considered. Then, if a firm's investments rely on external funds, the lenders are not able to accurately assess the quality and risk of a certain undertaking.

[4]This type of lag function relies on the Pascal probability distribution and takes the form

$$a_t = \frac{(1-\xi)^d}{(1-\xi L)^d} * b_t,$$

where $0 < \xi < 1$, $d > 0$ and L is the lag operator (Jorgenson, 1966).

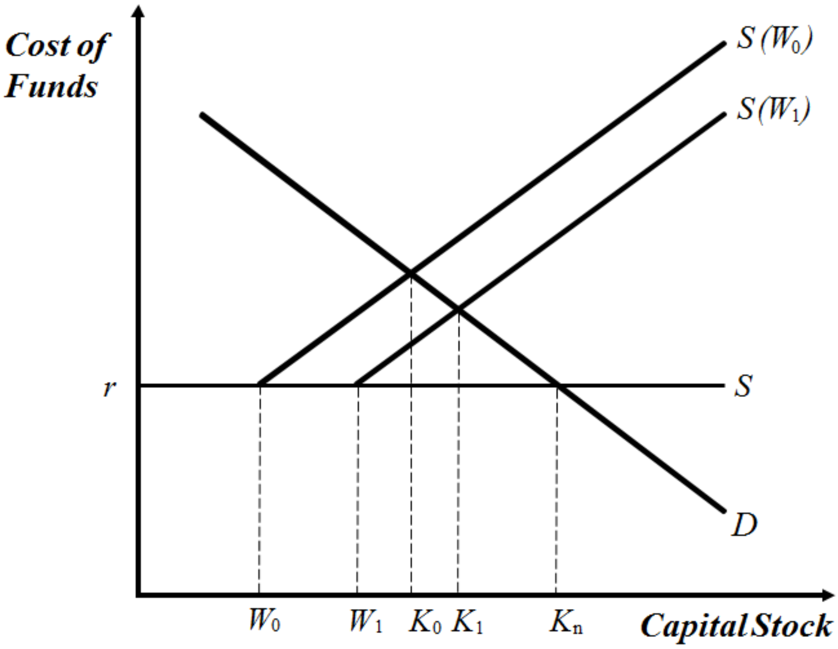

Figure 5: Capital market imperfections and the cost of funds. Figure adapted from Hubbard (1998).

Therefore, they require a premium for the compensation of potential adverse selection[5], moral hazard[6] and monitoring costs (Hubbard, 1998).

This relationship is illustrated graphically in Figure 5, where the organisation's capital can be found on the horizontal and the cost of funds on the vertical axis. Graph D illustrates that the firm's demand for capital decreases as a result of higher prices for (external) means, while *D's* location depends on the investment opportunities of the focal organisation. In a strictly Neoclassical setting, the presumed perfect information regarding profitability, risk and production technologies justifies constant costs of funds S that amount to the (risk-adjusted) real rate of interest r. This means that the organisation is able to borrow any desired amount at r and that its opportunity cost of internal liquid assets equals this market interest rate. As can be seen in Figure 5, K_n denotes the first-best capital stock which lies in the intersection of S and D. Therefore, the firm's internal pecuniary resources per se do not affect its decision whether to invest or not (Hubbard, 1998).

A more realistic framework is based on the assumption that an entrepreneur enjoys a net worth of W_0 and can undertake a certain project that requires capital and other factors of production. These other inputs comprise organisational or maintenance expenditure, enhance the productivity of existing capital and are subsumed under the term *soft capital*. As the opportunity cost of the firm's net worth equals $r * W_0$, the risk-neutral entrepreneur would invest in the project if, and only if, its yield is larger than $(1 + r) * W_0$. How does

[5]To provide an example, if suppliers and demanders of loans have different levels of information regarding the associated risks available, credible borrowers are expected to be driven out of the market by defaulters. Therefore, those individuals of unfavourable character remain (Hindriks & Myles, 2013).

[6]It is likely that the creditor cannot observe the actions of the debtor, who controls the usage of the funds (Hubbard, 1998) (Hindriks & Myles, 2013).

the situation, however, look if the entrepreneur requires more capital than W_0 and has to acquire external funds? At this point, an agency problem can be introduced by assuming that the organisation's creditors are able to observe expenditure on the capital stock, but not those on the soft capital. This might induce the entrepreneur to redirect the funds for the latter type of capital to his personal benefit and hold bad luck liable for any default. As a consequence, for uncollateralised financing exceeding the level of W_0, a forward-looking creditor requires a premium to be compensated for the existing risk of opportunistic behaviour. This is depicted by the upward-sloping part of $S(W_0)$ and implies that the entrepreneur is faced with different shadow costs for internal and external financing. It should further be noted that D and $S(W_0)$ intersect at the capital stock K_0, which lies below the strict Neoclassical solution and signifies considerable underinvestment (Hubbard, 1998).

Ceteris paribus, a rise in the organisation's net worth from W_0 to W_1 shifts the supply-of-funds curve rightwards to $S(W_1)$ and the entrepreneur's possibilities to divert funds decrease. As a result, the equilibrium capital stock rises to K_1 (Hubbard, 1998).

To summarise, as long as the firm's net worth is below K_n, the external lenders demand a compensation for the information asymmetries and the origin of funds might influence investment behaviour. Therefore, an investment model like Equation 7 should also control for the firm's net value that can be approximated by cash flow (Hubbard, 1998).

It should have become apparent that the investment model presented so far further relies on a number of simplifying assumptions as capital adjustment costs and, to a certain extent, lags between investment orders and delivery are not considered (Chirinko, 1993).

In addition, the theoretical model outlined in Equation 7 can be criticised with regard to consistency issues. First of all, simultaneous interactions between the explanatory variables (e.g. the relationship between the firm's user cost of capital and its optimal level of output) are not taken into account. Furthermore, if the production technology of the considered firm exhibits constant returns to scale, K_t^* can only be regarded as a "moving target rather than the long-run equilibrium of capital" (Jorgenson, 1972, p. 246) (Chirinko, 1993).

Another question concerns the way in which technological aspects are captured by the model. To begin with, vintage effects are implicitly assumed away although it seems conceivable that after the installation of a capital good, the combination possibilities with other inputs cannot be chosen arbitrarily any more. In addition, treating the depreciation rate δ as exogenous and given raises doubts, because empirical investigations do not unambiguously justify this assumption (Chirinko, 1993).

Furthermore, Lucas (1976) states in his well-known critique that even if an econometric model contains optimal heuristics of economic individuals, alterations of the policy framework should change the model's structure, because agents' optimal decisions depend on the policy foundations. With regard to investment models, expectation parameters ought to be identified separately from the policy invariant technology parameters. The coefficients in the Neoclassical model presented in Equation 7 are, however, a mixture of expectation as well as technology parameters and therefore exposed to the Lucas (1976) critique (Chirinko, 1993). Similarly, if a firm's net worth is approximated by its cash flow, a positive and significant relationship between this variable and investment expenditure does not necessarily mean that raising external funds is indeed more costly than internal financing. Specifically, if current cash flow positively affects expected future profitability, investments could rise due to enhanced expectations (shifting curve D in Figure 5 to the right) rather than the rise in internal funds available. Separating out investment opportunities adequately is, however, extremely challenging (Hubbard, 1998) and therefore beyond the scope of this paper.

The final set of controversies concerning the Neoclassical model emerges from the relative importance of the investment determinants summarised in Equation 7, particularly ΔY_t and ΔC_t. Although empirical studies do not provide consistent results, it seems that output is the dominant determinant (Chirinko, 1993).

Keeping the discussed caveats of the Neoclassical model in mind and realising that structural models of investment dynamics which permit the assumption of capital adjustment costs (e.g. *Q model*, *Euler equation model*) do not portray the complex adaptation fairly successfully, makes intermediate modelling approaches seem attractive. In general, such *reduced form models* empirically approximate the complex adjustment process which has generated the observed data. It should be noted, however, that these models are still affected by the Lucas (1976) critique as their parameters are an amalgam of structural adjustment and expectations-formation variables (Bond & Van Reenen, 2007). Since this paper seeks to identify fundamental determinants of investment rather than defining an underlying structural adjustment process, a reduced form model is nevertheless suitable for answering the underlying research question.

Therefore, the development of an investment model continues by taking the logarithm of Equation 6, leading to the following specification

$$k_t^* = \gamma + y_t - \sigma c_t, \tag{8}$$

where a lower-case character denotes a variable in logarithmic form. For simplicity, it is assumed that σ takes a value of one, corresponding to a Cobb-Douglas production function[7] (Bond et al., 2005).

In order to allow for dynamic interactions, Equation 8 is addressed by an *autoregressive distributed lag* (ADL) model, which is defined as follows (Hassler & Wolters, 2006).

[7]A Cobb-Douglas production function takes the form $Y = F(K, N) = \Gamma * K^{\phi_1} * N^{\phi_2}$, where Y denotes output, determined by the inputs capital K as well as labour N and ϕ_1 as well as ϕ_2 lie between zero and one. If $\phi_1 + \phi_2 = 1$, a firm produces with *constant returns to scale*, meaning that a doubling of both factors of production doubles the output (Pindyck & Rubinfeld, 2009)

$$a_t = \sum_{u=1}^{U} \psi_u * a_{t-u} + \sum_{v=0}^{V} \boldsymbol{\omega}_v' * \boldsymbol{b}_{t-v} + \epsilon_t \tag{9}$$

While a_t designates a scalar variable, $\boldsymbol{b}_t$ summarises a column vector of dimension M. Accordingly, the coefficients ψ_u denote scalars and $\boldsymbol{\omega}_v'$ row vectors. Furthermore, the scalar ϵ_t is an error term with a mean of zero and a constant variance. In addition, the commonly included constant is neglected here to keep the model as simple as possible. Finally, in order to fulfil the condition of dynamic stability, $|\sum_{u=1}^{U} \psi_u|$ must be less than 1 (Hassler & Wolters, 2006).

Transforming Equation 8 into an ADL-model and considering the unbalanced structure of the panel dataset as outlined in Section 3 by setting $U = V = 1$ yields the subsequent dynamic regression model, where α_i, β_i and θ_i are parameters.

$$k_t^* = \gamma + \alpha_1 k_{t-1}^* + \beta_0 y_t + \beta_1 y_{t-1} - \theta_0 c_t - \theta_1 c_{t-1} + \epsilon_t \tag{10}$$

In a static equilibrium, k_t^*, y_t and c_t are treated as jointly stationary[8] and therefore, taking the expected value from both sides of Equation 10 yields the following specification (Banerjee et al., 1993).

$$E(k_t^*) = \frac{\gamma + (\beta_0 + \beta_1) * E(y_t) - (\theta_0 + \theta_1) * E(c_t)}{1 - \alpha_1} \tag{11}$$

Equation 11 illustrates that the long-run elasticity of capital with respect to output is given by

$$\frac{\beta_0 + \beta_1}{1 - \alpha_1}$$

and with respect to the rental price of capital by

$$-\frac{\theta_0 + \theta_1}{1 - \alpha_1}.$$

To go one step further, Bean (1981) suggests to transform the model presented by Equation 10 into an error-correction form. This can be done by subtracting k_{t-1}^* from both sides and further adding to, as well as deducting from, the specification's right-hand side the term $\beta_0 y_{t-1} + (\alpha_1 - 1) * y_{t-1}$ (Banerjee et al., 1993). The result is summarised in Equation 12.

[8]Under the assumption of *strict stationarity*, a stochastic process (i.e. an ordered series of random variables) has to fulfil the subsequent condition.

$$F(x(p_1), x(p_2), ..., x(p_n)) = F(x(p_1 + q), x(p_2 + q), ..., x(p_n + q))$$

Here, x is the stochastic process, while $p_1, p_2, ..., p_n$ denotes a subset of the index set $\mathbb{P} = \{1, 2, ..., T\}$ and q can be any real number, provided that $p_i + q \in \mathbb{P}$ if $i = 1, 2, ..., n$. Finally, $F(\cdot)$ designates the joint distribution function of the n entries (Banerjee et al., 1993).

$$\Delta k_t^* = \gamma + (\alpha_1 - 1) * (k_{t-1}^* - y_{t-1}) + \beta_0 * \Delta y_t + (\beta_0 + \beta_1 + \alpha_1 - 1) * y_{t-1} \\ -\theta_0 * c_t - \theta_1 * c_{t-1} + \epsilon_t \tag{12}$$

It is of particular importance that Equation 10 and Equation 12 represent the same relationship between the exogenous and endogenous variables of interest as the equality has not been violated and the error process has been conserved. The advantage of such an error correction model lies in the feature that the speed of the short-run adjustment to a disequilibrium is explicitly captured by the term $(\alpha_1 - 1)$ (Banerjee et al., 1993).

In order to complete the evolution of this paper's base model, the subsequent five further widely adopted principles are applied on Equation 12.

- First of all,

$$\Delta k_t^* = \Delta k_t \approx \frac{I_t}{K_{t-1}} - \delta, \tag{13}$$

  where, as before, I_t denotes a company's investment, K_{t-1} its capital stock one period earlier and δ the depreciation rate (Bond & Van Reenen, 2007). As in Alesina et al. (2005), Cambini and Rondi (2010), Gugler et al. (2013), Cullmann and Nieswand (2016), Poudineh and Jamasb (2016) and Cambini and Rondi (2017), the rate of depreciation is, however, incorporated in the individual firm fixed effects (see below). Therefore, the fraction

$$\frac{I_t}{K_{t-1}}$$

  is labelled $investment\ rate_t$.

- Secondly, the *investment rate* of the previous period enters the specification's right-hand side (Alesina et al., 2005) (Bond et al., 2005) (Cambini & Rondi, 2010) (Gugler et al., 2013) (Cullmann & Nieswand, 2016) (Poudineh & Jamasb, 2016) (Cambini & Rondi, 2017).

- As discussed previously, an investment model should control for the firm's net worth which can be approximated by current cash flow. Following the methodology of Bond et al. (2005), Cambini and Rondi (2010) as well as Cambini and Rondi (2017), the variable

$$\frac{Cash\ Flow_t}{K_{t-1}}$$

  is added to Equation 12 and will be called $cash\ flow\ rate_t$ from now on.

- Analogous to Gugler et al. (2013), the rental price of capital c is assumed to be inversely captured by the *harmonised consumer price index of electricity*. This prerequisite is justified by the fact that c depends on the ratio between the purchase price of additional capital and the output price (Gugler et al., 2013). It should however be noted that consumer prices are not related to the transmission system operators' *cash flow* and *revenues*, as summarised in Table 3. Still, the *electricity price index* is highly correlated with the *investment rate* and several other covariates which qualifies this variable as indispensable for the analysis conducted in this paper.

- In order to account for those unobserved factors affecting the *investment rate* which are constant over time and to allow for differences across years firm, as well as year, fixed effects are included in Equation 12. Alesina et al. (2005), Lyon and Mayo (2005), Cambini and Rondi (2010), Grajek and Röller (2012), Gugler et al. (2013), Cullmann and Nieswand (2016) and Cambini and Rondi (2017) pursue comparable strategies. The respective dummies are labelled with η_i and ν_t.

To summarise, the following Equation 14 shows the error correction investment model proposed in this paper. In order to curtail concerns with regard to endogeneity problems, all explanatory variables are lagged by one period (see for example Gugler et al. (2013)). Furthermore, λ_j denotes a specific coefficient, i the firm and t the time index. Finally, η_i, ν_t as well as $\epsilon_{i,t}$ take values as defined above.

$$
\begin{aligned}
&Investment\ Rate_{i,t} \\
&= \lambda_1 * Investment\ Rate_{i,t-1} + \lambda_2 * log(Tangible\ Fixed\ Assets)_{i,t-1} \\
&+ \lambda_3 * log(Revenues)_{i,t-1} + \lambda_4 * log(Consumer\ Price)_{i,t-1} \\
&+ \lambda_5 * \Delta\ log(Revenues)_{i,t} + \lambda_6 * Cash\ Flow\ Rate_{i,t-1} \\
&+ \eta_i + \nu_t + \epsilon_{i,t}
\end{aligned}
\tag{14}
$$

In this model, a positive and significant coefficient λ_1 would suggest a path dependency and therefore highlight that adjustment costs are prevailing in the electricity sector. What is more, λ_2 and λ_3 assess the error correction of the model. Particularly, an error correction mechanism is verified provided that λ_2 takes a significantly negative and λ_3 a significantly positive value, respectively. It should further be noted that $\lambda_2 - \lambda_3 < 0$ in order to produce a stable equilibrium. In addition, λ_4 captures the relationship between electricity consumer prices and grid investment. Moreover, accelerator effects are captured by λ_5, where a significantly positive coefficient would be in line with the Neoclassical theories discussed above. Finally, λ_6 does not only control for financial constraints, but also for an organisation's expectations. Therefore, this coefficient is expected to take a positive value (Bond et al., 2005) (Gugler et al., 2013).

In order to further simplify the relationship of interest, a number of models presented in Section 5 below do not control for the error correction processes and therefore take the form of Equation 15, whose interpretation is analogous to Equation 14.

$$\begin{aligned}
&Investment\ Rate_{i,t} \\
&= \rho_1 * Investment\ Rate_{i,t-1} + \rho_4 * log(Consumer\ Price)_{i,t-1} \\
&+ \rho_5 * \Delta\ log(Revenues)_{i,t} + \rho_6 * Cash\ Flow\ Rate_{i,t-1} \\
&+ \eta_i + \nu_t + \epsilon_{i,t}
\end{aligned} \tag{15}$$

Having described the base models of this paper, it is worth noting that specifications similar to Equation 14 and Equation 15 have been estimated by various studies. Explicit examples comprise the contributions of Alesina et al. (2005), Bond et al. (2005), Lyon and Mayo (2005), Cambini and Rondi (2010), Grajek and Röller (2012), Nardi (2012), Gugler et al. (2013), Cullmann and Nieswand (2016), Poudineh and Jamasb (2016) as well as Cambini and Rondi (2017).

The novel contribution of this paper lies in linking the current *share of renewable energy resources* with the investment models outlined in Equation 14 and Equation 15. It has to be determined empirically if a larger dominance of renewable energy sources is connected with enhanced investment in power transmission networks. Therefore, Equation 14 is extended by the two measures of renewable generation as a share of total electricity output which were defined in Section 3 as *share of renewables (without hydro)* and *share of renewables (total)*. While the former parameter enters into the full set of models, the latter is utilised for robustness checks.

Referring to the underlying research question, the main interest of this paper lies in identifying the coefficients associated with these two measures. It should be recalled that significantly positive coefficients lead to the conclusion that a rising *share of renewables* indeed stimulates the power transmission investments necessary for a stable grid. On the contrary, insignificant (or even significantly negative) coefficients would find no evidence that transmission networks are adapted to the challenges associated with the increasing importance of renewable energy resources and could therefore be seen as a threat potentially causing congestion and network instability.

In order to thoroughly examine the coefficients of interest, the model is further expanded consecutively by the subsequent covariates.

- The logarithm of electrical *load* as yearly average in order to control for capacity constraints. This strategy resembles the contributions of Lyon and Mayo (2005) and Poudineh and Jamasb (2016).

- The logarithm of the *long term interest rate*, similar to Alesina et al. (2005), Lyon and Mayo (2005), Cambini and Rondi (2010), Gugler et al. (2013) and Cullmann and Nieswand (2016) in order to approximate the operators' *weighted average cost of capital*.

- The *regulatory indicators for entry, public ownership, vertical integration and market structure*, respectively, comparable with Alesina et al. (2005), Grajek and Röller (2012), Nardi (2012), Gugler et al. (2013), Cullmann and Nieswand (2016), Poudineh and Jamasb (2016) as well as Esposito, Kaloud, Doleschel, and Urban-Kozlowska (in press).

Detailed definitions of these variables have been summarised in Section 3 above. Before the models' results are presented in Section 5, the applied estimation strategies are outlined in the following subsection.

4.2 Estimation Strategy

In order to properly address the relationship of interest, this paper proposes a threefold strategy. More specifically, the analysis starts with testing for causality among all variables and thereby relies on the techniques published by Granger (1969). Subsequently, in order to provide benchmark results, *fixed effects estimates* are presented. Finally, endogeneity concerns are diminished by applying the *one step first-differenced GMM estimator* proposed by Arellano and Bond (1991).

Granger (1969) causalities To begin with, Granger (1969) argues that difficulties exist with regard to causality issues among two linked variables. The author therefore provides the following definition of causality for a stationary stochastic process[9]. Provided that A_t and B_t are indeed stationary time series with a mean of 0, if

$$\sigma^2(A|\overline{A},\overline{B}) < \sigma^2(A|\overline{A}), \tag{16}$$

$B_t \Rightarrow A_t$. In Equation 16, a bar over a variable represents its past values and σ designates the error variance.

Similarly, if

$$\begin{aligned} \sigma^2(A|\overline{A},\overline{B}) &< \sigma^2(A|\overline{A}), \\ \sigma^2(B|\overline{A},\overline{B}) &< \sigma^2(B|\overline{B}), \end{aligned} \tag{17}$$

feedback between the two variables (indicated by $A_t \Leftrightarrow B_t$) can be identified (Granger, 1969).

Referring back to the condition established in Equation 16, Granger (1969) proposes the subsequent linear model to empirically test for causality.

$$A_t = \sum_{j=1}^{J} \alpha_j A_{t-j} + \sum_{j=1}^{J} \beta_j B_{t-j} + \epsilon_t \tag{18}$$

[9] A *stochastic process* is a series of random variables (Wooldridge, 2013).

While J could theoretically tend towards infinity, a practical approach is to associate it with a finite integer. Presuming that ϵ_t is again an independent and identically distributed error term, B_t causes A_t if at least one β_j is significantly different from zero (Granger, 1969).

It should have become apparent that the concept of causality outlined here relies on the criterion of minimising the error variance. Granger (1969) recognises that other criteria might exist, but also states that the advantage of this variance approach lies in its unproblematic way of implementation and its straightforward interpretation. However, the author suggests to refer to his approach by using the term *causality in mean* (Granger, 1969).

Even more importantly, Granger (1969) causalities could suffer from considerable biases. The first source of bias becomes evident from Equation 18 directly and refers to only considering two variables in the regression. If, however, a third series H_t caused both A_t and B_t, spurious causality between the two latter variables would likely be found (Granger, 1969). Secondly, He and Maekawa (2001) show that the conventional F test statistics[10] identify spurious Granger (1969) causality for non-stationary series relatively often. These considerations indicate that Granger (1969) causality tests might determine causality all too frequently.

Similar to comparable studies (see for example Edwards and Waverman (2006), Gasmi and Recuero Virto (2010), Resende (2009), Bortolotti, Cambini, Rondi, and Spiegel (2011), Cambini and Rondi (2012) and Gugler et al. (2013)), strict Granger (1969) causalities are calculated in this paper in order to detect possible reverse causal relationships among the variables of interest. Therefore, it seems reasonable to employ this oversensitive test.

Fixed Effects Estimation Having identified possible causality flows, the analysis digs deeper by estimating the relationship derived above with ordinary least squares. Section 3 pointed out that the available data comprises an (unbalanced) panel. In order to allow for fundamental differences in the dependent variable which arise out of unobservable fixed factors among the considered firms and years, it proves beneficial to deduct the firm as well as temporal average of each observation[11]. As long as these unobserved factors are constant for firms over time and for time periods over firms, this procedure is conductive in diminishing concerns with regard to omitted variable bias (Wooldridge, 2013). As pointed out by Nickell (1981), specifications similar to Equation 14 can, however, not be estimated consistently with the fixed effects estimator due to their autoregressive structure. More specifically, a simple time-demeaned model takes the form

[10] Testing in Equation 18 for the restriction that $\sum_{j=1}^{J} \beta_j = 0$ (Wooldridge, 2013).

[11] An equivalent strategy would be to include a dummy for each firm and time period in the estimation equation (Wooldridge, 2013).

$$a_t - \frac{1}{T} * \sum_{t=1}^{T} a_t = \alpha \left(a_{t-1} - \frac{1}{T} * \sum_{t=0}^{T-1} a_t \right) + \left(\epsilon_t - \frac{1}{T} * \sum_{t=1}^{T} \epsilon_t \right). \tag{19}$$

Obviously, $\frac{1}{T} * \sum_{t=1}^{T} \epsilon_t$ is not only correlated with a_{t-1}, but also with a_t. This produces a bias in α even if the number of firms in the sample tends towards infinity as long as the amount of time periods (T) available remains small (Nickell, 1981) (Bond & Van Reenen, 2007).

On the other hand, Lyon and Mayo (2005), Alesina et al. (2005), Cambini and Rondi (2010), Gugler et al. (2013), Cullmann and Nieswand (2016) as well as Poudineh and Jamasb (2016) show that path dependencies play a crucial role with regard to investments in the electricity sector. Excluding the lagged investment rate is therefore likely to create a considerable omitted variable bias, resulting from dependencies between this factor and the remaining regressors (Wooldridge, 2013).

These considerations in mind, the empirical strategy proposed in this paper opts for including the lagged dependent variable when performing fixed effects estimations. Therefore, prudence should be exerted when interpreting these benchmark results. Moreover, the error correction mechanism which focuses on specific interaction between past and current observations is exclusively modelled with general methods of moments techniques that are discussed below.

General Method of Moments Estimation Specifications like Equation 14 are adequately addressed by using the *general methods of moments* (GMM) estimation technique proposed by Arellano and Bond (1991). This *difference* estimator performs the subsequent two steps. First, an estimation equation's variables are replaced by their respective changes over time in order to remove all unobservable fixed effects. Secondly, the variables in the equation are instrumented with their past values[12].

In doing so, it is of crucial importance that the error term is not serially correlated. Obviously, if serial correlation among the errors is an issue, preceding terms correlate with the current one and the requirement for exogeneity of instruments is not fulfilled. Should,

[12] The idea of instrumental variables estimation in its simplest way can be illustrated with a cross-sectional model. Provided that a is explained by the exogenous variable b and by another variable $\tilde{b}$ that correlates with elements of the error term ϵ, simply estimating the following equation with ordinary least squares would produce biased and inconsistent coefficients (Wooldridge, 2013).

$$a = \beta_0 + \beta_1 b + \beta_2 \tilde{b} + \epsilon$$

A way to address this problem of omitted variables lies in finding an instrument for $\tilde{b}$. Such an instrumental variable e must fulfil the conditions of exogeneity (i.e. $Cov(e, \epsilon) = 0$) as well as relevance (i.e. $Cov(\tilde{b}, e) \neq 0$) even after partialling out b. Then, $\tilde{b}$ is computed as shown in the subsequent regression, where the symbol $\widehat{}$ denotes an estimated variable or coefficient (Wooldridge, 2013).

$$\widehat{\tilde{b}} = \widehat{\pi_0} + \widehat{\pi_1} b + \widehat{\pi_2} e$$

Finally, $\tilde{b}$ is replaced by $\widehat{\tilde{b}}$ and consistent estimators for the coefficients are identified. Analogously, even reverse causality issues can properly be addressed by instrumental variable techniques (Wooldridge, 2013).

on the contrary, the application of GMM be justified, issues regarding reverse causality are properly addressed and autoregressive processes can be estimated consistently even for finite sample sizes. Based on the specific estimation procedure, Arellano and Bond (1991) propose two different GMM techniques which they label *one step* and *two step* estimators. In an application, the authors suspect a finite sample bias in the standard errors estimated with the latter (Arellano & Bond, 1991). Therefore, this paper prefers and applies the former one step estimator.

Estimation of Standard Errors Particularly in the context of panel data, it is worth putting special attention on the techniques associated with the calculation of standard errors which depend on the assumptions made with regard to the variance of the error term. In the most simplified setting, the vector of disturbances has a constant variance that is independent from the explanatory variables, including individual and temporal fixed effects (Wooldridge, 2013). As this restrictive assumption does not seem convincing in empirical applications, White (1980) presents an estimator for the parameter covariance matrix to achieve heteroskedasticity robust standard errors in an OLS framework[13]. Moreover, Petersen (2009) argues that standard errors in a panel dataset should in general be expected to correlate among individuals, implying that correcting for heteroskedasticity is not enough. Therefore, all standard errors presented in the subsequent sections are not only robust, but also clustered at the firm level and therefore in accordance with the ideas of Stock and Watson (2008).

[13] In an OLS framework, heteroskedasticity can simply be defined as $Var(\epsilon_i|\boldsymbol{b}_i) = \sigma_i^2$, where ϵ_i denotes the error term, $\boldsymbol{b}_i$ the vector of regressors and i an index variable (Greene, 2012).

5 Results

Building on the previous discussion, the present section presents the core results of this paper. After showing some preliminary relations between the variables of interest, regression results are summarised for the full and a restricted sample, before robustness checks are performed.

5.1 Preliminary Evidence

As a first step, this subsection tests for causality between the variables of interest and relies on the ideas of Granger (1969) which were outlined in Section 4.2. However, the panel structure of the available dataset requires the incorporation of further contributions of Holtz-Eakin et al. (1988) as well as Nair-Reichert and Weinhold (2001). Specifically, for each pair of variables, the onestep difference GMM estimator of Arellano and Bond (1991) with time fixed effects is applied. Referring to Equation 18 in Section 4.2 above, J is set 1 due to the considerable amount of missing values in the available dataset.

As pointed out by Roodman (2009), the number of instruments required for a GMM estimation increases quadratically in the panel's time dimension. Consequently, a large amount of instruments can be expected, which is likely to bias the coefficients of instrumented regressors as a result of over-fitting them[14].

What is more, as long as the amount of instruments outnumbers the parameters, the condition of exogeneity can be evaluated with the *Hansen test of over-identifying restrictions*. The test's null hypothesis assumes that all instruments are valid and therefore that the second stage residuals are not correlated with any specific set of them (Roodman, 2009) (Wooldridge, 2013). If the amount of instruments gets large, however, the Hansen test loses power dramatically and implausible *p-values* of 1.00 are generated (Bowsher, 2002) (Roodman, 2009).

These considerations raise the question of the appropriate number of instruments. Roodman (2009) states that the literature does not provide a clear recommendation with regard to this issue and offers the amount of individual units as an "arbitrary rule of thumb" (Roodman, 2009, p. 99) for the instrument count. Considering the summarised concerns, the models presented in this study aim at holding the number of instruments small by either restricting the amount of lags for instrumenting endogenous variables to two or considering more lags, but collapsing the instruments to one single column. Furthermore, Hansen p-values are systematically reported in order to detect implausible test statistics.

In Table 4, Granger (1969) causalities between the *investment rate* and all explanatory

[14] Specifically, should the count of instruments equal the amount of observations, the first-stage regression produces a perfect fit and $\widehat{\tilde{b}}$ equals $\tilde{b}$. Consequently, the IV-results perfectly match those of OLS, which are biased by assumption (Roodman, 2009).

variables[15] are reported. Within this framework, the *investment rate* evaluated at time t serves as the dependent variable and is explained by its lag as well as by the lagged values of the respective *column variable*. As pointed out in Section 4.2, the GMM estimator is required in this dynamic environment as it permits previous error terms to be correlated with the current realisation of the dependent variable. The respective *column variable* is, however, regarded as exogenous, but nevertheless not utilised as an external instrument in the first differenced equation[16].

Referring to the coefficients and test statistics in Table 4, interpretation patterns are presented based on *Column 1*. This model explains the current *investment rate* by its lagged value as well as by the lagged and logarithmised *price index* and reveals that the two regressors significantly Granger (1969) cause the dependent variable. Furthermore, as has been outlined above, the applied estimation strategy controls for unobserved firm as well as time fixed effects. In addition, the number of observations amounts to 204 and the instrument count to 36, while the Hansen test p-value of 0.82 does not raise concern. Finally, the bottom two lines in *Column 1* summarise tests for possible autocorrelation in the idiosyncratic error term. Section 4.2 outlined that the requirement for exogeneity in a GMM setting can only be fulfilled provided that serial correlation among the instruments' and instrumented variables' disturbance terms is not an issue. As pointed out by Roodman (2009), autocorrelation of first order in levels corresponds to autocorrelation of second order in differences[17]. Therefore, serial correlation statistics are reported as of degree 2. Furthermore, if significant autocorrelation of degree g is detected[18], GMM instruments are restricted to lags $g+1$ and longer following Roodman (2009). In *Column 1*, second order autocorrelation is insignificant and therefore, the *investment rate* at *t-1* is instrumented by its previous values, lagged once and twice.

Analogously, the same logic can be applied in order to interpret the results summarised in the remaining columns. This leads to the observation that apart from the logarithmised *price index*, the *cash flow rate*, the *regulatory indicator for market structure* as well as the logarithmised *tangible fixed assets* are found to Granger (1969) cause the *investment rate* at a significance level of 10%. Accounting for the caveats associated with Granger (1969) causalities, the coefficients are not interpreted quantitatively in this preliminary analysis. It should be noted, however, that all their signs go in reasonable directions[19].

[15]For *revenues*, only Δ *log revenues* are considered.

[16]Modelling the *column variable* differently does not change the general conclusions presented here. Detailed results are available upon request.

[17]Let ϵ_t be the error term at time t. Then, $\Delta\epsilon_t = \epsilon_t - \epsilon_{t-1}$ and $\Delta\epsilon_t$ as well as $\Delta\epsilon_{t-1}$ which share the term ϵ_{t-1} are negatively correlated by construction. Consequently, correlation between ϵ_{t-1} and ϵ_{t-2} can only be evaluated informatively by examining $\Delta\epsilon_t$ together with $\Delta\epsilon_{t-2}$ (Roodman, 2009).

[18]This corresponds to a p-value lower than 0.05.

[19]Certainly, the effects of the logarithmised *price index* and the *regulatory indicator for market structure* are not clear from a theoretical standpoint. What is more, empirical papers identify contradicting results, see with regard to the former variable Kilian (2008) for the US energy sector as well as Gugler et al. (2013) for the EU electricity sector and concerning the latter Alesina et al. (2005) for OECD infrastructure sectors, Nardi (2012) for the EU electricity sector and Esposito et al. (in press) for the EU railway sector.

Table 4: Simple Granger (1969) causalities. Estimated with GMM, containing firm as well as time fixed effects. Instrument lags appropriately defined and restricted to two. Estimation implemented in Stata using *xtabond2* (Roodman, 2009). Table adapted from *stargazer* (Hlavac, 2015). Robust standard errors clustered at the firm level in parenthesis.

	Dependent variable:		
	Investment Rate$_t$		
	(1)	(2)	(3)
	log Price Index	Δ log Revenues	Cash Flow Rate
Investment Rate$_{t-1}$	0.459***	0.558***	0.114
	(0.094)	(0.082)	(0.179)
Column Variable$_{t-1}$	−0.638**	−0.021	0.271**
	(0.263)	(0.084)	(0.132)
Firm Fixed Effects	Yes	Yes	Yes
Time Fixed Effects	Yes	Yes	Yes
Number of Observations	204	110	114
Number of Instruments	36	18	21
Hansen Test p-value	0.818	NA	0.040
Diff. Autocorr. Test (2) p-value	0.109	0.205	0.029
Diff. Autocorr. Test (3) p-value	0.054	0.141	0.292
	(4)	(5)	(6)
	Share Renewables (without Hydro)	Share Renewables (Total)	log Load
Investment Rate$_{t-1}$	0.149	−0.270	0.450***
	(0.156)	(0.278)	(0.105)
Column Variable$_{t-1}$	−2.523	0.567	−0.936
	(3.058)	(2.747)	(0.708)
Firm Fixed Effects	Yes	Yes	Yes
Time Fixed Effects	Yes	Yes	Yes
Number of Observations	183	183	164
Number of Instruments	30	29	36
Hansen Test p-value	0.207	0.140	0.996
Diff. Autocorr. Test (2) p-value	0.022	0.117	0.242
Diff. Autocorr. Test (3) p-value	0.104	0.106	0.207
	(7)	(8)	(9)
	log Long Term Interest Rate	Regulation (Entry)	Regulation (Public Ownership)
Investment Rate$_{t-1}$	−0.143	0.101	0.460***
	(0.248)	(0.174)	(0.171)
Column Variable$_{t-1}$	−0.022	0.009	0.050
	(0.094)	(0.020)	(0.062)
Firm Fixed Effects	Yes	Yes	Yes
Time Fixed Effects	Yes	Yes	Yes
Number of Observations	190	169	169
Number of Instruments	32	31	33
Hansen Test p-value	0.854	0.734	0.633
Diff. Autocorr. Test (2) p-value	0.043	0.023	0.050
Diff. Autocorr. Test (3) p-value	0.128	0.060	0.104
	(10)	(11)	(12)
	Regulation (Vertical Integration)	Regulation (Market Structure)	log Tangible Fixed Assets
Investment Rate$_{t-1}$	−0.082	0.486***	0.099
	(0.279)	(0.150)	(0.209)
Column Variable$_{t-1}$	0.146	0.061*	−0.304***
	(0.086)	(0.033)	(0.109)
Firm Fixed Effects	Yes	Yes	Yes
Time Fixed Effects	Yes	Yes	Yes
Number of Observations	169	159	204
Number of Instruments	29	33	34
Hansen Test p-value	0.748	0.788	0.868
Diff. Autocorr. Test (2) p-value	0.126	0.118	0.009
Diff. Autocorr. Test (3) p-value	0.056	0.084	0.159
Note:			*p<0.1; **p<0.05; ***p<0.01

Table 5: Simple (reverse) Granger (1969) causalities. Estimated with GMM, containing firm as well as time fixed effects. Instrument lags appropriately defined and restricted to two. Estimation implemented in Stata using *xtabond2* (Roodman, 2009). Table adapted from *stargazer* (Hlavac, 2015). Robust standard errors clustered at the firm level in parenthesis.

	Dependent variable:		
	Column Variable$_t$		
	(1)	(2)	(3)
	log Price Index	Δ log Revenues	Cash Flow Rate
Investment Rate$_{t-1}$	-0.362^{*}	1.456	0.340
	(0.210)	(0.935)	(0.214)
Column Variable$_{t-1}$	0.754^{***}	-0.236^{**}	-0.741^{***}
	(0.114)	(0.103)	(0.035)
Firm Fixed Effects	Yes	Yes	Yes
Time Fixed Effects	Yes	Yes	Yes
Number of Observations	207	110	112
Number of Instruments	39	15	18
Hansen Test p-value	0.871	NA	NA
Diff. Autocorr. Test (2) p-value	0.743	0.227	0.094
Diff. Autocorr. Test (3) p-value	0.744	0.309	0.988
	(4)	(5)	(6)
	Share Renewables (without Hydro)	Share Renewables (Total)	log Load
Investment Rate$_{t-1}$	0.116	0.003	-0.280
	(0.076)	(0.111)	(0.178)
Column Variable$_{t-1}$	0.934^{***}	0.811^{***}	0.291^{**}
	(0.150)	(0.154)	(0.128)
Firm Fixed Effects	Yes	Yes	Yes
Time Fixed Effects	Yes	Yes	Yes
Number of Observations	186	186	163
Number of Instruments	27	27	38
Hansen Test p-value	0.107	0.035	0.955
Diff. Autocorr. Test (2) p-value	0.548	0.409	0.695
Diff. Autocorr. Test (3) p-value	0.225	0.429	0.665
	(7)	(8)	(9)
	log Long Term Interest Rate	Regulation (Entry)	Regulation (Public Ownership)
Investment Rate$_{t-1}$	0.173	8.442^{*}	-0.341
	(0.606)	(4.668)	(0.544)
Column Variable$_{t-1}$	-0.168^{***}	0.826^{***}	0.539^{**}
	(0.052)	(0.055)	(0.268)
Firm Fixed Effects	Yes	Yes	Yes
Time Fixed Effects	Yes	Yes	Yes
Number of Observations	193	147	147
Number of Instruments	39	33	33
Hansen Test p-value	0.403	0.854	0.991
Diff. Autocorr. Test (2) p-value	0.497	0.482	0.409
Diff. Autocorr. Test (3) p-value	0.242	0.850	0.795
	(10)	(11)	(12)
	Regulation (Vertical Integration)	Regulation (Market Structure)	log Tangible Fixed Assets
Investment Rate$_{t-1}$	-0.945	2.392	0.031
	(0.724)	(2.025)	(0.349)
Column Variable$_{t-1}$	0.550^{***}	0.622^{***}	0.445^{***}
	(0.052)	(0.134)	(0.146)
Firm Fixed Effects	Yes	Yes	Yes
Time Fixed Effects	Yes	Yes	Yes
Number of Observations	147	137	205
Number of Instruments	31	31	38
Hansen Test p-value	0.833	0.475	0.906
Diff. Autocorr. Test (2) p-value	0.978	0.288	0.140
Diff. Autocorr. Test (3) p-value	0.459	0.720	0.071
Note:			$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

Interestingly, the significance of the lagged *investment rate* strongly depends on the lag structure of its instruments. In *Columns 1, 2, 6, 9* and *11*, where the test for autocorrelation in differences permits instrumenting the time-displaced *investment rate* with lags 2 and 3, its previous value is positive and significant. However, the instrument set has to be lagged longer in the remaining columns and the significance disappears.

Finally, the p-values of the Hansen test are plausible in general. An unexpectedly high statistic can only be found in *Column 6*, while no p-value is available in *Column 2* due to the small number of instruments.

The issue of reverse causality is addressed by Table 5, where the respective *column variable* is predicted by lagged realisations of the *investment rate* and itself. Illustrated again on the basis of *Column 1*, the logarithmised *price index* at time *t* serves as the dependent variable and the *investment rate* as well as the logarithmised *price index* at *t-1* as regressors. At the 10% significance level, both coefficients are significantly different from zero, indicating that reverse causality matters. As before, the number of observations and instruments as well as p-values of the Hansen test and tests for serial correlation in the residuals are reported in the bottom panel of *Column 1*.

Apart from the logarithmised *price index*, potential reverse causation is only identified for the *regulatory indicator of entry*. Consequently, this issue is minor in the present analysis, but nevertheless motivates to instrument these variables in the context of the proposed GMM approach.

To summarise the remaining results, all *column variables* are significantly predicted by their previous values. Moreover, all autocorrelation tests permit to instrument the lagged dependent variable with its immediately preceding realisations. Finally, the Hansen test statistics are reasonable in general, although not available for *Columns 2* as well as *3* and somewhat critical in *Columns 5, 6, 9* and *12*.

5.2 Regression Results from the Entire Sample

This subsection goes one step further and presents regression results of Equation 14, Equation 15 and their extensions outlined in Section 4.1 by considering the entire dataset available. For this purpose, the fixed effects estimator is applied, before GMM approaches follow.

Fixed Effects Estimation As outlined in Section 4.2, the fixed effects estimation proposed here includes the lagged dependent variable in order not to suffer from omitted variable bias. Nevertheless, the regression results have to be interpreted with caution as a possible bias arises out of the small amount of time periods available. Therefore, error correction mechanisms are exclusively addressed with GMM techniques.

Applying the fixed effects estimator on the relationships of interest yields the results presented in Table 6 which reports coefficients and their respective standard errors. Furthermore, the number of observations, two goodness-of-fit measures[20] as well as the F statistic for the regression[21] are summarised in every column.

To begin with, *Column 1* presents the base model, where the current *investment rate* is explained by lagged values of itself and the logarithmised *price index*, the change in logarithmised *revenues* as well as the previous *cash flow rate*. Subsequently, *Column 2* introduces the current *share of renewables* excluding hydroelectric power, before the remaining columns successively introduce lagged values of the logarithmised *load* and *long term interest rate* as well as those of the *regulatory indicators*.

Turning to the specific estimates yields several notable results. First of all, the lagged *investment rate* is highly significant in all specifications and takes values between 0.5 and 0.7. This implies that, ceteris paribus, a rise in the *investment expenditure per unit of (lagged) capital* by one standard deviation in the current period raises the succeeding *investment rate* by roughly 0.6 standard deviations. These results constitute a first indication for path dependencies in the electricity sector and are in accordance with the findings of Alesina et al. (2005), Lyon and Mayo (2005), Cambini and Rondi (2010), Gugler et al. (2013), Cullmann and Nieswand (2016), Poudineh and Jamasb (2016) as well as Cambini and Rondi (2017).

In addition, the lagged *cash flow rate* is also found to be a significant predictor in all specifications, taking values between 0.2 and 0.3. Again, the positive sign corresponds to the expectations and matches with the results of Cambini and Rondi (2010) as well as Cambini and Rondi (2017). Quantitatively, a rise in the contemporary *cash flow rate* by one standard deviation increases the subsequent *investment rate* by around 0.35 standard deviations. As discussed in Section 4, the identified relationship can, however, not only be linked with capital market imperfections, but also with the firms' expectations.

The final variable discovered to significantly predict the *investment rate* is the logarithmised *price index*, albeit this holds for only half of the specifications at the 10% significance level, which does not allow general conclusions. Interestingly, the positive correlation from Table 3 in Section 3 has however changed to a negative relationship.

Turning to the *share of renewables* and thereby to the variable of main interest, no

[20]The R^2 is defined as

$$1 - \frac{SSR}{SST},$$

while the adjusted R^2 imposes a penalty for every additionally added independent variable and is given as

$$1 - \frac{\frac{SSR}{n-l-1}}{\frac{SST}{n-1}},$$

provided that n denotes the number of observations, l the amount of explanatory variables, SST the sum of squares of the dependent variable and SSR that of the residuals. Building on this, the R^2 and adjusted R^2 in Table 6 are defined as the time variation in the dependent variable which is explained by the time variation in the regressors (within R^2 and within adjusted R^2) (Wooldridge, 2013).

[21]The null hypothesis of this test statistic is that a model's explanatory variables are jointly insignificant (Wooldridge, 2013).

Table 6: Fixed effects estimation of the *investment rate*, containing firm as well as time fixed effects. Implemented in R using the package *plm* (Croissant et al., 2016). Table adapted from *stargazer* (Hlavac, 2015). Robust standard errors clustered at the firm level in parenthesis.

	Dependent variable:			
	Investment $Rate_t$			
	(1)	(2)	(3)	(4)
Share Renewables (without Hydro)$_{t-1}$		−0.055	−0.212	−0.230
		(0.257)	(0.445)	(0.285)
Investment $Rate_{t-1}$	0.600***	0.600***	0.597***	0.615***
	(0.094)	(0.087)	(0.099)	(0.097)
log Price $Index_{t-1}$	−0.208*	−0.205*	−0.227*	−0.214
	(0.119)	(0.105)	(0.133)	(0.145)
Δ log $Revenues_t$	−0.041	−0.040	−0.081	−0.080
	(0.037)	(0.037)	(0.057)	(0.048)
Cash Flow $Rate_{t-1}$	0.208***	0.208**	0.210**	0.219**
	(0.073)	(0.094)	(0.080)	(0.088)
log $Load_{t-1}$			0.031	
			(0.170)	
log Long Term Interest $Rate_{t-1}$				−0.004
				(0.029)
Firm Fixed Effects	Yes	Yes	Yes	Yes
Time Fixed Effects	Yes	Yes	Yes	Yes
Observations	133	132	117	123
R^2	0.361	0.361	0.358	0.365
Adjusted R^2	0.140	0.138	0.080	0.120
F Statistic	13.860*** (df = 4; 98)	10.980*** (df = 5; 97)	7.522*** (df = 6; 81)	8.433*** (df = 6; 88)

	Dependent variable:			
	Investment $Rate_t$			
	(5)	(6)	(7)	(8)
Share Renewables (without Hydro)$_{t-1}$	−0.183	−0.182	−0.153	−0.153
	(0.295)	(0.297)	(0.307)	(0.313)
Investment $Rate_{t-1}$	0.512***	0.512***	0.502***	0.524***
	(0.104)	(0.103)	(0.114)	(0.102)
log Price $Index_{t-1}$	−0.244	−0.235*	−0.220	−0.258*
	(0.148)	(0.140)	(0.148)	(0.135)
Δ log $Revenues_t$	−0.002	−0.006	−0.005	−0.001
	(0.028)	(0.027)	(0.026)	(0.026)
Cash Flow $Rate_{t-1}$	0.275***	0.275***	0.274***	0.279***
	(0.068)	(0.067)	(0.068)	(0.070)
Regulation $Entry_{t-1}$	−0.003			
	(0.016)			
Regulation Public $Ownership_{t-1}$		−0.151		
		(0.216)		
Regulation Vertical $Integration_{t-1}$			0.054	
			(0.035)	
Regulation Market $Structure_{t-1}$				−0.010
				(0.019)
Firm Fixed Effects	Yes	Yes	Yes	Yes
Time Fixed Effects	Yes	Yes	Yes	Yes
Observations	113	113	113	112
R^2	0.333	0.334	0.337	0.343
Adjusted R^2	0.042	0.044	0.047	0.053
F Statistic	6.494*** (df = 6; 78)	6.520*** (df = 6; 78)	6.595*** (df = 6; 78)	6.704*** (df = 6; 77)
Note:				*p<0.1; **p<0.05; ***p<0.01

significant impact on the *investment rate* can be found. Moreover, the coefficients of the changes in logarithmised *revenues*, the lagged logarithmised *load* and *long term interest rate* as well as the time-displaced *regulatory indicators* neither prove themselves significant.

As has been outlined above, the fixed effects estimations only constitute a first impression of the underlying relationship between the variables of interest. In order to provide a profound analysis, more advanced estimation techniques are discussed below.

General Methods of Moments Estimation Results from the onestep difference GMM estimator including time fixed effects are summarised in Table 7 and Table 8. The former table does not contain error correction terms, while the latter takes these mechanisms explicitly into account. Furthermore, both estimation approaches consider the reverse causality issues detected in Table 5 and therefore regard not only lagged values of the *investment rate*, but also those of the *price index* and the *regulatory indicator for entry* as endogenous. What is more, the amount of instrument lags in Table 7 is again restricted to two in order not to give rise to the problem of too many instruments. In addition, the remaining regressors are assumed to be completely exogenous and therefore utilised as additional instruments[22].

Turning to the results outlined in Table 7 and comparing them with those from Table 6 shows that the obtained coefficients for the lagged *investment rate* and *cash flow rate* are very robust to the different estimators. Again, preceding values of the *investment rate* and of the *cash flow rate* impact the current *investment rate* significantly positively. Even the size of the coefficients is comparable, leading to an interpretation analogous to the fixed effects results summarised above[23].

In addition, the *regulatory indicator for public ownership* is found to negatively influence the *investment rate* at the 10% significance level. This means that a more private ownership structure of the most dominant players in the electricity sector is in line with enhanced investment spending.

Again, the *share of renewables* which constitutes the main variable of interest is not found to significantly influence the *investment rate*, although the respective coefficients exhibit a negative sign in all models. What is more, the *price index* loses its significance in all specifications, but keeps its unequivocal negative sign. Besides, neither the coefficient associated with Δ *log revenues* nor those with lagged values of the logarithmised *load* and *long term interest rate* or of the remaining *regulatory indicators* demonstrate significance.

Finally, the p-values of the Hansen test statistics do not indicate problems with the applied set of instruments, even though they are unexpectedly high in *Columns 3* and *5*.

[22] As shown in Section 5.4 below, a softening of this assumption does not alter the general messages developed here.

[23] An exception with regard to the size of the coefficients can be found in *Column 4*, where the tests for autocorrelation do not permit the use of lagged values of order two as GMM instruments. Nevertheless, the general pattern with regard to the coefficients' signs and significance is confirmed.

The final set of regressions concerning the unrestricted sample is summarised in Table 8. The models presented here correspond to those in Table 7, but are supplemented with the error correction terms from Equation 14. Again, the lagged explanatory variables *investment rate*, logarithmised *price index* as well as the *regulatory indicator for entry* are permitted not to behave completely exogenously. In addition, the same permission is given to the lagged and logarithmised *tangible fixed assets* as this variable is by definition a component of the *investment rate*. As before, the remaining set of variables is, however, modelled as completely exogenous.

An immediate consequence of the necessarily generous allowance of endogeneity patterns lies in a strong rise in the required instruments. In order to overcome the problem of too many instruments which has been discussed above, the strategy pursued here builds on the recommendation of Roodman (2009) by collapsing the available instrument set into one single column[24]. This approach is comparable with Holl (2012) and permits to increase the maximum amount of lags used as instruments (Roodman, 2009) which was set to nine in the regressions presented in Table 8[25].

Turning to the regression results, current values of the *investment rate* are again well predicted by and depend positively on their lagged realisations, even if the coefficients' size

[24]To provide an example, let $h_{i,t}$ be a variable which is instrumented by its lags of order two and further, where i denotes a specific individual and t a point in time. Then, the common way of representing the instruments looks as follows.

$$\begin{bmatrix} 0 & 0 & \dots & 0 & 0 \\ h_{i,t-2} & 0 & \dots & 0 & 0 \\ 0 & h_{i,t-3} & \dots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & h_{i,t-T} & 0 \end{bmatrix}$$

Consequently, the amount of required instruments equals $T-1$ and the following set of moment conditions must be satisfied for each $t \geq 3$ in order to fulfil the condition of instrument exogeneity.

$$\sum_i h_{i,t-2}\epsilon_{i,t} = 0,$$

where $\epsilon_{i,t}$ constitutes the error term. As an alternative, is is possible to collapse the available sequence of instruments into one single column, leading to

$$\begin{bmatrix} 0 \\ h_{i,t-2} \\ h_{i,t-3} \\ \vdots \\ h_{i,t-T} \end{bmatrix},$$

This single column requires only one moment condition to be fulfilled, namely

$$\sum_{i,t} h_{i,t-2}\epsilon_{i,t} = 0$$

and therefore reduces the instrument count dramatically (Roodman, 2009).

[25]The general implications of the estimates are robust to various lag structures. Further results are available upon request.

Table 7: General methods of moments estimation of the *investment rate* without error correction terms, containing firm as well as time fixed effects. Instrument lags appropriately defined and restricted to two. Implemented in Stata using *xtabond2* (Roodman, 2009). Table adapted from *stargazer* (Hlavac, 2015). Robust standard errors clustered at the firm level in parenthesis.

	Dependent variable:			
	Investment $Rate_t$			
	(1)	(2)	(3)	(4)
Share $Renewables_t$		−0.359	−0.524	−0.774
		(0.372)	(0.435)	(0.559)
Investment $Rate_{t-1}$	0.526^{***}	0.507^{***}	0.522^{***}	0.247^{*}
	(0.098)	(0.105)	(0.094)	(0.136)
log Price $Index_{t-1}$	−0.196	−0.162	−0.163	0.013
	(0.133)	(0.135)	(0.127)	(0.229)
Δ log $Revenues_t$	0.034	0.034	−0.003	−0.029
	(0.031)	(0.032)	(0.032)	(0.026)
Cash Flow $Rate_{t-1}$	0.234^{***}	0.232^{***}	0.230^{***}	0.164^{**}
	(0.049)	(0.049)	(0.050)	(0.072)
log $Load_{t-1}$			−0.069	
			(0.132)	
log Long Term Interest $Rate_{t-1}$				0.003
				(0.003)
Firm Fixed Effects	Yes	Yes	Yes	Yes
Time Fixed Effects	Yes	Yes	Yes	Yes
Number of Observations	108	108	94	101
Number of Instruments	37	38	39	39
Hansen Test p-value	0.796	0.806	0.997	0.706
Diff. Autocorr. Test (2) p-value	0.458	0.454	0.432	0.050
Diff. Autocorr. Test (3) p-value	0.098	0.122	0.120	0.119

	Dependent variable:			
	Investment $Rate_t$			
	(5)	(6)	(7)	(8)
Share $Renewables_t$	−0.052	−0.318	−0.458	−0.349
	(0.452)	(0.462)	(0.484)	(0.470)
Investment $Rate_{t-1}$	0.354^{**}	0.418^{***}	0.415^{***}	0.448^{***}
	(0.174)	(0.118)	(0.119)	(0.110)
log Price $Index_{t-1}$	−0.204	−0.166	−0.159	−0.196
	(0.155)	(0.139)	(0.150)	(0.141)
Δ log $Revenues_t$	0.026	0.037	0.041	0.047
	(0.035)	(0.036)	(0.037)	(0.039)
Cash Flow $Rate_{t-1}$	0.240^{***}	0.249^{***}	0.251^{***}	0.252^{***}
	(0.075)	(0.080)	(0.082)	(0.081)
Regulation $Entry_{t-1}$	0.007			
	(0.024)			
Regulation Public $Ownership_{t-1}$		-0.482^{*}		
		(0.286)		
Regulation Vertical $Integration_{t-1}$			0.002	
			(0.099)	
Regulation Market $Structure_{t-1}$				0.016
				(0.021)
Firm Fixed Effects	Yes	Yes	Yes	Yes
Time Fixed Effects	Yes	Yes	Yes	Yes
Number of Observations	89	89	89	88
Number of Instruments	44	34	34	34
Hansen Test p-value	0.938	0.569	0.568	0.447
Diff. Autocorr. Test (2) p-value	0.254	0.372	0.363	0.478
Diff. Autocorr. Test (3) p-value	0.397	0.511	0.451	0.212
Note:				*p<0.1; **p<0.05; ***p<0.01

Table 8: General methods of moments estimation of the *investment rate*, including error correction terms, containing firm as well as time fixed effects. Collapsed instrument lags appropriately defined and restricted to nine. Implemented in Stata using *xtabond2* (Roodman, 2009). Table adapted from *stargazer* (Hlavac, 2015). Robust standard errors clustered at the firm level in parenthesis.

	Dependent variable:			
	Investment Rate_t			
	(1)	(2)	(3)	(4)
Share Renewables_t		0.248	0.598	0.342
		(0.652)	(0.812)	(0.737)
Investment Rate_{t-1}	0.380**	0.383**	0.326***	0.314**
	(0.180)	(0.179)	(0.125)	(0.156)
log Tangible Fixed Assets_{t-1}	−0.317**	−0.330**	−0.345**	−0.334**
	(0.128)	(0.143)	(0.169)	(0.140)
log Revenues_{t-1}	0.076	0.068	0.018	0.071
	(0.069)	(0.068)	(0.077)	(0.088)
log Price Index_{t-1}	−0.148	−0.162	−0.120	−0.134
	(0.112)	(0.134)	(0.104)	(0.202)
Δ log Revenues_t	0.037	0.033	0.002	0.018
	(0.031)	(0.034)	(0.040)	(0.043)
Cash Flow Rate_{t-1}	0.153***	0.154***	0.171***	0.156***
	(0.033)	(0.031)	(0.027)	(0.026)
log Load_{t-1}			0.278	
			(0.183)	
log Long Term Interest Rate_{t-1}				0.000
				(0.004)
Firm Fixed Effects	Yes	Yes	Yes	Yes
Time Fixed Effects	Yes	Yes	Yes	Yes
Number of Observations	108	108	94	101
Number of Instruments	37	38	39	39
Hansen Test p-value	0.864	0.877	0.838	0.845
Diff. Autocorr. Test (2) p-value	0.057	0.065	0.248	0.024
Diff. Autocorr. Test (3) p-value	0.065	0.070	0.161	0.197

	Dependent variable:			
	Investment Rate_t			
	(5)	(6)	(7)	(8)
Share Renewables_t	−0.299	−0.317	−0.310	−0.282
	(0.640)	(0.652)	(0.614)	(0.643)
Investment Rate_{t-1}	0.229	0.242*	0.243*	0.279*
	(0.156)	(0.141)	(0.146)	(0.142)
log Tangible Fixed Assets_{t-1}	−0.315**	−0.320**	−0.333**	−0.317**
	(0.152)	(0.152)	(0.152)	(0.145)
log Revenues_{t-1}	0.058	0.066	0.066	0.069
	(0.080)	(0.067)	(0.069)	(0.067)
log Price Index_{t-1}	−0.174	−0.182	−0.212	−0.208
	(0.141)	(0.148)	(0.155)	(0.141)
Δ log Revenues_t	0.033	0.040	0.039	0.041
	(0.044)	(0.032)	(0.032)	(0.032)
Cash Flow Rate_{t-1}	0.167***	0.165***	0.168***	0.166***
	(0.030)	(0.030)	(0.031)	(0.031)
Regulation Entry_{t-1}	0.009			
	(0.028)			
Regulation Public Ownership_{t-1}		0.067		
		(0.256)		
Regulation Vertical Integration_{t-1}			−0.051	
			(0.090)	
Regulation Market Structure_{t-1}				0.009
				(0.016)
Firm Fixed Effects	Yes	Yes	Yes	Yes
Time Fixed Effects	Yes	Yes	Yes	Yes
Number of Observations	89	89	89	88
Number of Instruments	37	38	38	38
Hansen Test p-value	0.992	0.892	0.957	0.501
Diff. Autocorr. Test (2) p-value	0.038	0.032	0.031	0.035
Diff. Autocorr. Test (3) p-value	0.124	0.109	0.129	0.123

Note: *p<0.1; **p<0.05; ***p<0.01

decreases and the significance disappears entirely in *Column 5*. These results appear as a reasonable consequence of including the *tangible fixed assets* error correction term whose coefficients are, as in Gugler et al. (2013), negative and significant in all specifications. Since the remaining error correction term for *revenues* is never found to significantly determine the *investment rate*, the models' coefficients establish a stable equilibrium as expected. Furthermore, the *cash flow rate* acts as the only remaining variable identified as a significant predictor. Again, the respective coefficients assume positive, albeit smaller, values in all models. This implies that neither the *share of renewables* nor the other included variables are found to significantly influence the *investment rate*.

Finally, the p-values of the Hansen test statistics take reasonable values, but raise slight concerns in *Columns 5* as well as *7* and the instrument lags are defined appropriately in all specifications.

To summarise, the estimation approaches conducted in this subsection indicate that the current *investment rate* positively depends on lagged values of itself as well as on the *cash flow rate*. In addition, a significant and balancing error correction mechanism can be identified with regard to *tangible fixed assets*. What is more, some specifications certify a negative impact of the previous logarithmised *price index* as well as the *regulatory indicator for public ownership*.

The lagged *share of renewables* is never found to significantly affect the *investment rate*. Therefore, the following subsection develops an explanatory approach for this observed pattern and carries out further investigations.

5.3 Regression Results from the Restricted Sample

A possible concern with regard to the regression results presented in Section 5.2 follows from the observation that the proportion of *solid bio fuels* in the measure *share of renewables* varies considerably not only between, but also within countries as illustrated by Figure 6 that shows the respective differences in percentage points. As can easily be seen, substantial variations occur in Croatia, Estonia, Lithuania, Romania, the Slovak Republic and Slovenia. This observation is formally confirmed by Table 9 which shows that the respective standard deviations for this set of countries are relatively high and take absolute values well above 0.1.

Obviously, the estimation approaches pursued in Section 5.2 are not able to control for these variations. The coefficients of the *share of renewables* have therefore to be regarded as biased should the *investment rate* react differently to various compositions of renewable energy sources[26]. In order to overcome this issue, those six countries which exhibit a standard deviation of the annual differences in the ratio of *solid bio fuels* to all

[26]In this framework, *solid bio fuels* that can be regarded as a base load component as outlined in Section 3 above are taken into account.

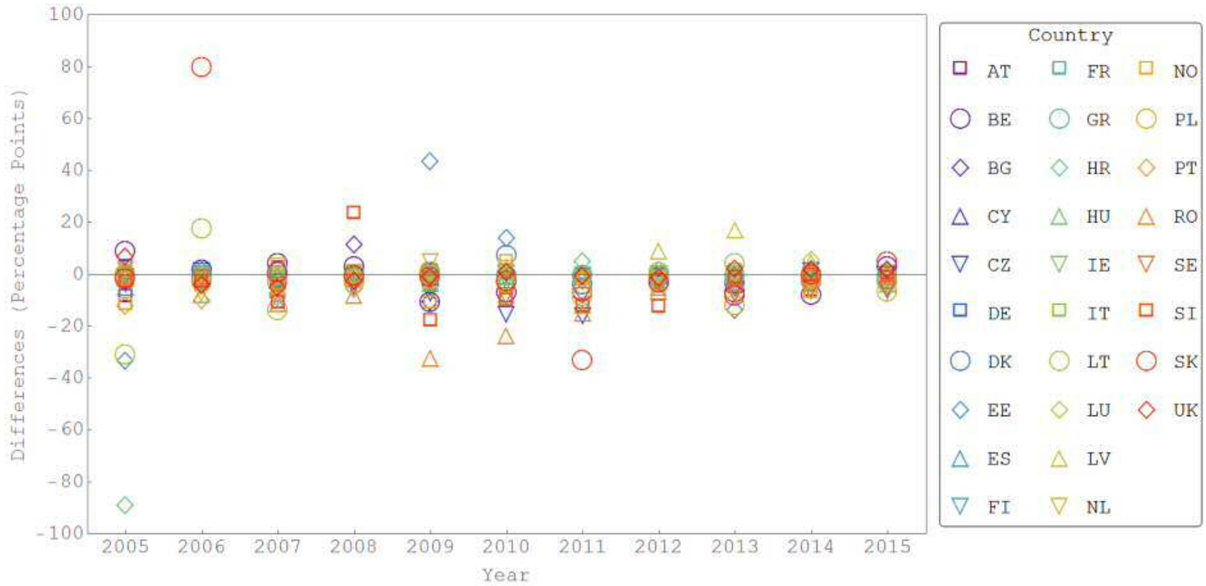

Figure 6: Annual differences in the ratio of *solid bio fuels* to all other *renewables* except for hydroelectric sources (Eurostat, 2017a). Illustrated in Mathematica.

renewables (except for hydroelectric sources) exceeding 0.1 are excluded from the sample.

Regression results based on this restricted set of countries are presented in Table 10. The models summarised here correspond to Table 9, but restrict the number of GMM instruments to six due to the smaller amount of observations available.

Now, the coefficients of the lagged *share of renewables* are highly significant in almost all specifications and take values between 0.8 and 1.2. Quantitatively, this implies that a rise in the current *share of renewables* by ten percentage points raises next period's *investment per unit of (lagged) capital* by around one standard deviation. This is substantial in absolute terms, as illustrated by Table 11 for a selected set of five countries. Based on the year 2015, a 10 percentage point rise in the *share of renewables* elevates grid investments in Austria by 126 Million, in Germany by 613 Million, in France by 1.5 Billion and in Italy by 1.0 Billion euro.

Table 9: Standard deviations of the annual differences in the ratio of *solid bio fuels* to all other *renewables* except for hydroelectric sources (Eurostat, 2017a). Bold numbers indicate standard deviations larger than 0.10. Implemented in R. Table adapted from *stargazer* (Hlavac, 2015).

AT	BE	BG	CY	CZ	DE	DK	EE	ES	FI	FR	GR	HR	HU
0.04	0.06	0.05	0.00	0.06	0.01	0.03	**0.19**	0.01	0.02	0.02	0.00	**0.27**	0.04
IE	**IT**	**LT**	**LU**	**LV**	**NL**	**NO**	**PL**	**PT**	**RO**	**SE**	**SI**	**SK**	**UK**
0.01	0.02	**0.12**	0.02	0.06	0.04	0.05	0.04	0.04	**0.11**	0.03	**0.11**	**0.27**	0.03

Turning to the remaining variables, the coefficients of the lagged *investment rate* and *cash flow rate* as well as the error correction term for logarithmised *tangible fixed assets* exhibit signs and significance comparable with Table 9. For this restricted set of countries, even the error correction term of logarithmised *revenues* is positive and significant in almost all columns, but still produces a stable model. Moreover, around half of the

Table 10: General methods of moments estimation of the *investment rate*, including error correction terms, containing firm as well as time fixed effects. Collapsed instrument lags appropriately defined and restricted to six. Countries excluded: Croatia, Estonia, Lithuania, Romania, the Slovak Republic and Slovenia. Implemented in Stata using *xtabond2* (Roodman, 2009). Table adapted from *stargazer* (Hlavac, 2015). Robust standard errors clustered at the firm level in parenthesis.

	Dependent variable:			
	Investment Rate$_t$			
	(1)	(2)	(3)	(4)
Share Renewables$_t$		0.817**	1.200**	0.539
		(0.412)	(0.488)	(0.474)
Investment Rate$_{t-1}$	0.259*	0.295**	0.372***	0.369***
	(0.155)	(0.130)	(0.112)	(0.103)
log Tangible Fixed Assets$_{t-1}$	−0.377***	−0.385***	−0.542***	−0.468***
	(0.142)	(0.138)	(0.164)	(0.120)
log Revenues$_{t-1}$	0.167*	0.141**	0.109	0.240***
	(0.092)	(0.072)	(0.087)	(0.076)
log Price Index$_{t-1}$	−0.195	−0.289*	−0.203	−0.163
	(0.165)	(0.161)	(0.158)	(0.245)
Δ log Revenues$_t$	0.061*	0.041	0.014	0.025
	(0.037)	(0.031)	(0.062)	(0.048)
Cash Flow Rate$_{t-1}$	0.151***	0.152***	0.175***	0.152***
	(0.012)	(0.014)	(0.014)	(0.012)
log Load$_{t-1}$			0.393***	
			(0.149)	
log Long Term Interest Rate$_{t-1}$				0.001
				(0.003)
Firm Fixed Effects	Yes	Yes	Yes	Yes
Time Fixed Effects	Yes	Yes	Yes	Yes
Number of Observations	88	88	74	81
Number of Instruments	28	29	30	30
Hansen Test p-value	0.360	0.217	0.933	0.922
Diff. Autocorr. Test (2) p-value	0.270	0.222	0.819	0.197
Diff. Autocorr. Test (3) p-value	0.187	0.162	0.746	0.705

	Dependent variable:			
	Investment Rate$_t$			
	(5)	(6)	(7)	(8)
Share Renewables$_t$	0.993***	1.057***	0.821***	0.962***
	(0.300)	(0.297)	(0.292)	(0.327)
Investment Rate$_{t-1}$	0.578***	0.489***	0.543***	0.487***
	(0.180)	(0.173)	(0.190)	(0.171)
log Tangible Fixed Assets$_{t-1}$	−0.540***	−0.519***	−0.554***	−0.522***
	(0.063)	(0.082)	(0.073)	(0.082)
log Revenues$_{t-1}$	0.156*	0.151*	0.184**	0.153*
	(0.081)	(0.078)	(0.077)	(0.079)
log Price Index$_{t-1}$	−0.401***	−0.427***	−0.441***	−0.420***
	(0.136)	(0.131)	(0.132)	(0.127)
Δ log Revenues$_t$	0.051	0.047	0.067	0.049
	(0.044)	(0.041)	(0.041)	(0.042)
Cash Flow Rate$_{t-1}$	0.078***	0.083***	0.083***	0.081***
	(0.030)	(0.028)	(0.025)	(0.029)
Regulation Entry$_{t-1}$	NA			
	NA			
Regulation Public Ownership$_{t-1}$		−0.180		
		(0.287)		
Regulation Vertical Integration$_{t-1}$			−0.122**	
			(0.046)	
Regulation Market Structure$_{t-1}$				0.004
				(0.017)
Firm Fixed Effects	Yes	Yes	Yes	Yes
Time Fixed Effects	Yes	Yes	Yes	Yes
Number of Observations	74	74	74	74
Number of Instruments	28	29	29	29
Hansen Test p-value	0.099	0.101	0.379	0.267
Diff. Autocorr. Test (2) p-value	0.947	0.739	0.868	0.675
Diff. Autocorr. Test (3) p-value	0.122	0.115	0.231	0.108
Note:		*p<0.1; **p<0.05; ***p<0.01		

specifications assert a negative influence of the lagged and logarithmised *price index* and even changes in the logarithmised *revenues* border with significance.

Table 11: Additional investments in power transmission networks resulting from a 10% increase in the *share of renewables (no hydro)*. Figures based on the year 2015 and stated in Million euro. Implemented in R. Table adapted from *stargazer* (Hlavac, 2015).

AT	**DE**	**FR**	**IT**
126.3	613.2	1545.2	1014.2

With regard to the lagged additional variables, two of them are found to significantly influence the current *investment rate*. First of all, logarithmised values of the *load* positively affect this variable which is in line with Lyon and Mayo (2005). Specifically, a rise in the time-displaced *load* by one percent rises the *investment rate* by around 3.8 standard deviations. Secondly, more deregulation in the field of *vertical integration* increases investment spending. However, all coefficients of the other variables stay insignificant and the *regulatory indicator for entry* has to be dropped due to its lack in variability. Finally, the lags for the GMM instruments are again chosen in view of the autocorrelation tests and the p-values of the Hansen test statistic are all insignificant, albeit unexpectedly high in *Columns 3* and *4*.

To conclude, this restricted sample of countries with a stable share of *solid bio fuels* yields significantly positive coefficients for the main variable of interest which implies a considerable effect of renewable energy resources on power grid investment. What is more, the effects of the remaining explanatory variables appear reasonable from a theoretical standpoint and are supported by empirical investigations.

5.4 Robustness Checks

In order to increase the validity of the results presented so far, they are subjected to a series of robustness checks in this subsection.

To begin with, Table 12 repeats *Columns 1* and *2* from Table 7 as well as Table 8, but treats all explanatory variables as endogenous. Consequently, the amount of required instruments raises considerably which is addressed by adequately defining, restricting and collapsing them. Turning to the regression results, the coefficients and their levels of significance remain almost unchanged which implies that the general conclusions are not sensitive to the changes made with regard to the endogeneity assumption. A notable exception can however be found in *Column 3*, where the variables describing logarithmised *revenues* positively affect the *investment rate*. This pattern can also be found in Table 10 and is in line with the expectations from Section 4.1.

In addition, it is worth examining if the regression results depend on a different definition of the *share of renewables*. Therefore, Table 14 replicates *Column 2* of Table 7 as well as Table 8, where hydroelectric power is added to the *share of renewables* and all instru-

Table 12: General methods of moments estimation of the *investment rate*, permitting that all explanatory variables are endogenous, containing firm as well as time fixed effects. Instrument lags appropriately defined, restricted and collapsed. No sample restrictions undertaken. Implemented in Stata using *xtabond2* (Roodman, 2009). Table adapted from *stargazer* (Hlavac, 2015). Robust standard errors clustered at the firm level in parenthesis.

	Dependent variable:			
	Investment Rate$_t$			
	(1)	(2)	(3)	(4)
Share Renewables$_t$		0.092		0.761
		(0.627)		(0.762)
Investment Rate$_{t-1}$	0.439***	0.432***	0.301***	0.326***
	(0.134)	(0.164)	(0.092)	(0.097)
log Tangible Fixed Assets$_{t-1}$			−0.264**	−0.281***
			(0.117)	(0.106)
log Revenues$_{t-1}$			0.121*	0.017
			(0.065)	(0.079)
log Price Index$_{t-1}$	−0.153	−0.096	−0.313	−0.231
	(0.184)	(0.177)	(0.237)	(0.164)
Δ log Revenues$_t$	0.025	0.074	0.125**	0.080
	(0.055)	(0.060)	(0.051)	(0.065)
Cash Flow Rate$_{t-1}$	0.238***	0.245***	0.206***	0.199***
	(0.030)	(0.040)	(0.039)	(0.033)
Firm Fixed Effects	Yes	Yes	Yes	Yes
Time Fixed Effects	Yes	Yes	Yes	Yes
Number of Observations	108	108	108	108
Number of Instruments	37	32	31	35
Hansen Test p-value	0.851	0.391	0.185	0.573
Diff. Autocorr. Test (2) p-value	0.296	0.479	0.124	0.122
Diff. Autocorr. Test (3) p-value	0.134	0.268	0.124	0.088
Note:	*p<0.1; **p<0.05; ***p<0.01			

Table 13: General methods of moments estimation of the *investment rate*, containing firm as well as time fixed effects. *Share renewables* comprises hydroelectric power. Instrument lags appropriately defined, restricted and collapsed. No sample restrictions undertaken. Implemented in Stata using *xtabond2* (Roodman, 2009). Table adapted from *stargazer* (Hlavac, 2015). Robust standard errors clustered at the firm level in parenthesis.

	Dependent variable:	
	Investment $Rate_t$	
	(1)	(2)
Share $Renewables_t$	−0.157	0.333
	(0.301)	(0.567)
Investment $Rate_{t-1}$	0.515***	0.393**
	(0.104)	(0.180)
log Tangible Fixed $Assets_{t-1}$		−0.331**
		(0.140)
log $Revenues_{t-1}$		0.065
		(0.067)
log Price $Index_{t-1}$	−0.182	−0.168
	(0.136)	(0.126)
Δ log $Revenues_t$	0.033	0.034
	(0.030)	(0.032)
Cash Flow $Rate_{t-1}$	0.233***	0.155***
	(0.049)	(0.031)
Firm Fixed Effects	Yes	Yes
Time Fixed Effects	Yes	Yes
Number of Observations	108	108
Number of Instruments	38	38
Hansen Test p-value	0.745	0.828
Diff. Autocorr. Test (2) p-value	0.447	0.067
Diff. Autocorr. Test (3) p-value	0.110	0.065
Note:	*p<0.1; **p<0.05; ***p<0.01	

ment lags are properly defined, restricted and collapsed. With regard to the regression results, all coefficients and their respective standard errors remain virtually unaffected and the *share of renewables (total)* is not found to significantly predict the *investment rate*.

Finally, Table 14 performs the same regressions as Table 10, but again replaces the *share of renewables (hydro)* by the *share of renewables (total)*. Interestingly, the significance of this predictor remains, while the size of its coefficient decreases in all models. This implies that even if hydroelectric power is considered, an increasing *share of renewables* leads to a rising *investment rate* in the restricted set of countries. Concerning the remaining explanatory variables, their coefficients and significance levels permit the same conclusions as outlined in Section 5.3 above.

To conclude, the robustness checks performed in this subsection support the results derived previously and therefore strengthen their validity.

Table 14: General methods of moments estimation of the *investment rate*, including error correction terms, containing firm as well as time fixed effects. *Share renewables* comprises hydroelectric power. Collapsed instrument lags appropriately defined and restricted to six. Countries excluded: Croatia, Estonia, Lithuania, Romania, the Slovak Republic and Slovenia. Implemented in Stata using *xtabond2* (Roodman, 2009). Table adapted from *stargazer* (Hlavac, 2015). Robust standard errors clustered at the firm level in parenthesis.

	Dependent variable:			
	Investment Rate$_t$			
	(1)	(2)	(3)	(4)
Share Renewables$_t$		0.721**	0.816**	0.470
		(0.348)	(0.404)	(0.374)
Investment Rate$_{t-1}$	0.259*	0.292**	0.375***	0.377***
	(0.155)	(0.121)	(0.109)	(0.095)
log Tangible Fixed Assets$_{t-1}$	−0.377***	−0.387***	−0.538***	−0.478***
	(0.142)	(0.139)	(0.170)	(0.119)
log Revenues$_{t-1}$	0.167*	0.146**	0.137	0.249***
	(0.092)	(0.074)	(0.088)	(0.076)
log Price Index$_{t-1}$	−0.195	−0.274*	−0.183	−0.160
	(0.165)	(0.165)	(0.172)	(0.253)
Δ log Revenues$_t$	0.061*	0.052	0.029	0.032
	(0.037)	(0.032)	(0.063)	(0.049)
Cash Flow Rate$_{t-1}$	0.151***	0.152***	0.174***	0.151***
	(0.012)	(0.013)	(0.015)	(0.013)
log Load$_{t-1}$			0.385**	
			(0.151)	
log Long Term Interest Rate$_{t-1}$				0.001
				(0.003)
Firm Fixed Effects	Yes	Yes	Yes	Yes
Time Fixed Effects	Yes	Yes	Yes	Yes
Number of Observations	88	88	74	81
Number of Instruments	28	29	30	30
Hansen Test p-value	0.360	0.612	0.956	0.974
Diff. Autocorr. Test (2) p-value	0.270	0.225	0.481	0.181
Diff. Autocorr. Test (3) p-value	0.187	0.149	0.804	0.731

	Dependent variable:			
	Investment Rate$_t$			
	(5)	(6)	(7)	(8)
Share Renewables$_t$	0.732***	0.768***	0.569***	0.683***
	(0.212)	(0.201)	(0.207)	(0.220)
Investment Rate$_{t-1}$	0.551***	0.462***	0.517***	0.459***
	(0.162)	(0.155)	(0.167)	(0.153)
log Tangible Fixed Assets$_{t-1}$	−0.525***	−0.510***	−0.541***	−0.511***
	(0.063)	(0.085)	(0.075)	(0.085)
log Revenues$_{t-1}$	0.164**	0.160**	0.191**	0.162**
	(0.081)	(0.079)	(0.079)	(0.081)
log Price Index$_{t-1}$	−0.401***	−0.422***	−0.441***	−0.416***
	(0.140)	(0.133)	(0.137)	(0.131)
Δ log Revenues$_t$	0.064	0.063	0.078*	0.064
	(0.043)	(0.041)	(0.041)	(0.042)
Cash Flow Rate$_{t-1}$	0.085***	0.090***	0.090***	0.088***
	(0.027)	(0.025)	(0.023)	(0.026)
Regulation Entry$_{t-1}$	NA			
	NA			
Regulation Public Ownership$_{t-1}$		−0.125		
		(0.269)		
Regulation Vertical Integration$_{t-1}$			−0.122***	
			(0.047)	
Regulation Market Structure$_{t-1}$				0.002
				(0.016)
Firm Fixed Effects	Yes	Yes	Yes	Yes
Time Fixed Effects	Yes	Yes	Yes	Yes
Number of Observations	74	74	74	74
Number of Instruments	28	29	29	29
Hansen Test p-value	0.084	0.097	0.393	0.293
Diff. Autocorr. Test (2) p-value	0.877	0.660	0.811	0.606
Diff. Autocorr. Test (3) p-value	0.123	0.106	0.254	0.107

Note: *p<0.1; **p<0.05; ***p<0.01

6 Policy Implications and Conclusions

This paper aims at examining if the increasing importance of renewable energy sources in electricity generation stimulates investment in European power transmission networks. It is therefore located in the rapidly growing body of literature which analyses the welfare implications of this relatively novel energy source from a theoretical and empirical perspective.

The introduced error correction models build on Neoclassical investment theory which is augmented by capital constraints, future expectations, output prices, capacity considerations, interest rates and the regulatory environment. Within this framework, the proportion of renewable generation in total electricity output which enters the models in two different types constitutes the variable of main interest.

Regression results are obtained from Granger (1969) causalities, ordinary least squares techniques and general methods of moments procedures. While the variable of main interest is not found to significantly influence investment spending when the full set of transmission system operators is considered, a slight and justified sample restriction leads to the conclusion that a rising share of renewable energy sources substantially increases investment in power transmission networks. What is more, evidence indicates that power transmission investment is characterised by path dependencies and determined by an operator's cash flow.

The most obvious implication which can be derived from these results is that renewable energy policies must not only address generation capacities, but also consider power transmission networks. In this regard, the European Commission (2010) states:

> "Europe is still lacking the grid infrastructure which will enable renewables to develop and compete on an equal footing with traditional sources. Current projects of large-scale wind parks in the North and solar facilities in the South need corresponding power lines capable of transmitting this green power to the areas of high consumption. Today's grid will struggle to absorb the volumes of renewable power which the 2020 targets entail (...)." (European Commission, 2010, p. 10).

The present paper identifies evidence that the increasing share of renewables indeed stimulates investment behaviour, but does neither answer if the additional expenditures suffice to ensure a stable grid that satisfies the stochastic nature of most renewable energy sources nor which policy framework leads to the most efficient power grid nor who should bear the investment cost. Rather, these questions pave the way for future research.

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