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Towards renewable electricity in Europe:

An empirical analysis of the determinants of renewable electricity development in the European Union

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Abstract

The twenty-first century must see a decarbonisation of electricity production to mitigate the flow of greenhouse gas emissions into the atmosphere. This paper presents an econometric analysis of the factors that motivate the use of renewable energy in electricity production using panel data from EU Member States during the period 2000-2015. The research extends the literature in this area in several ways. Firstly, the econometric analysis is focused on the electricity sector rather than on the overall primary energy supply, which also includes the diverse heating and transport sectors. In addition, an alternative public policy variable is proposed using the tax and levy component of electricity bills. Furthermore, an alternative econometric approach is employed using a hybrid mixed effects estimator. The results of this analysis are found to be broadly as expected, with mixed fossil fuel price effects; electricity grid interconnection and higher levels of greenhouse gas emissions both motivate the development of renewable electricity. Policy implications are that policy support for fossil fuels should be ceased; electricity grid interconnections should be developed between countries; and furthermore, levies on retail electricity prices to fund RE support schemes are effective at promoting renewable electricity.

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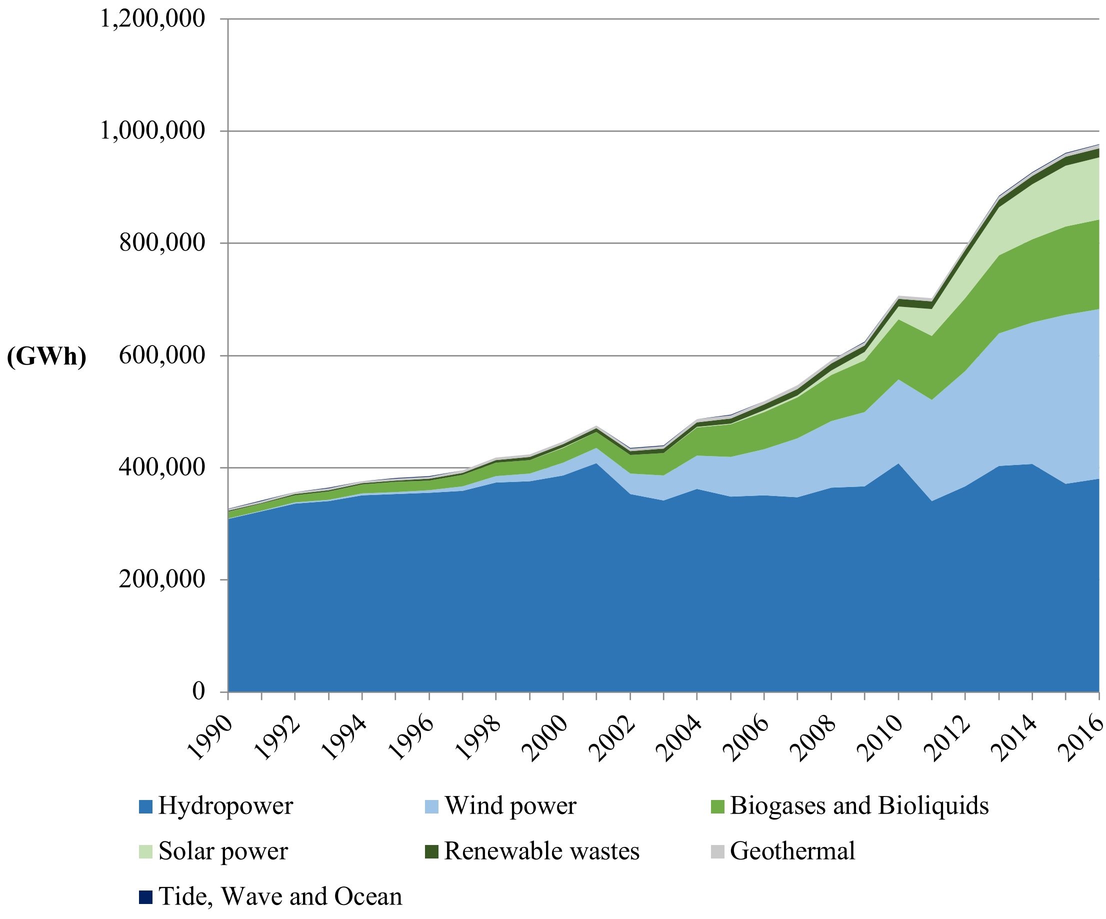
1. Introduction

Climate change is a threat to mankind and the most recent studies indicate that ‘global net human-caused emissions of carbon dioxide (CO_2) would need to fall by about 45 per cent from 2010 levels by 2030’ to limit the temperature rise to 1.5°C (IPCC, 2018). Decarbonisation of the electricity sector, which is still mostly based on fossil fuels, will play a vital role in achieving this goal (IEA, 2018). In the EU, the flow of greenhouse gas emissions has been gradually decreasing since 1990, yet far greater reductions are required to address the threat of climate change. Since 1997, the EU climate change framework has required Member States to meet mandatory targets for renewable energy (RE), energy efficiency improvements and CO_2 emissions. An EU-wide emissions trading scheme caps power sector and large industrial plant CO_2 emissions.

This paper presents an empirical analysis of the factors which encourage the development and use of RE in electricity production. Renewable electricity is crucial in its own right to reducing emissions, mainly due to its auxiliary nature in other consumption sectors; decarbonisation of the energy supply requires the electrification of both heating and transport, but this transition would clearly not be worthwhile if electricity production itself remained fossil fuel-based.

The OECD (2016) defines RE as the primary energy equivalent of hydropower (excluding pumped water storage), geothermal, solar, wind, tide and wave, bio-liquids and biogases, and the renewable fraction of municipal waste. Figure 1.1 illustrates the levels of electricity generated from each of these sources in the EU since 1990 (Eurostat, 2018a). Bio-fuels and particularly hydropower have traditionally contributed the bulk of RE to electricity generation, but Figure 1.1 also indicates that wind power and solar power are becoming increasingly important and have largely driven the increase in renewable electricity generation in the EU. Hydropower continues to generate the largest share of renewable electricity at 38 per cent in 2015, although wind power has seen its deployment quadrupled between 2004 and 2015 and now contributes a third of the EU’s renewable electricity, while solar photovoltaic reached 12 per cent of renewable electricity in 2015 (European Commission, 2017).

Figure 1.1: Gross electricity generation from renewable energy sources in the EU, 1990-2016



Source: Eurostat (2018a)

The European Commission (2017) states: ‘The promotion of renewable energy is an essential part of EU energy policy.’ The first RE target in 1997 required Member States to increase the contribution of RE to energy consumption to 12 per cent by 2010 (Klessmann *et al*., 2011). In 2001, the first renewable electricity target of 21 per cent by 2010 was set; this target was met mostly with hydropower. The generation of renewable electricity increased over the period 1990-2015 by 203 per cent. An increase of 4 per cent was observed for 2015 alone, with electricity generated from wind energy increasing by 19.3 per cent, indicating its increasing importance to electricity generation as a renewable source of energy (Eurostat, 2017). EU Member States were each required in 2009 to submit a National Renewable Energy Action Plan which set out 2020 targets for the share of RE in the three energy sectors. The Commission notes that the EU is ahead of its target trajectory for renewable electricity, with renewable sources contributing 28.3 per cent of the EU’s electricity production in 2015 (European Commission, 2017). A more specific and legally binding Renewable Energy

Directive, agreed on by the Commission in June 2018, provisionally sets a new target of 32 per cent by 2030 for the share of RE in the energy supply (European Commission, 2018).

Table 1.1 illustrates the shares of non-hydropower RE in electricity production for the sample of European countries included in our analysis for 2000 and 2015. Within the EU there is considerable divergence in terms of deployment shares of non-hydropower renewable electricity. For example, while all countries have observed some increase in renewable electricity, the highest share of RE in electricity generation in 2015 was boasted by Denmark with 60.7 per cent, whereas the corresponding figure for Ireland was 24.8 per cent and 6.1 per cent in France (World Data Bank, 2018a). Such a level of divergence poses questions on the influence of policy support in determining outcomes in RE deployment.

Table 1.1: Percentage contribution of renewable energy (excluding hydropower) to electricity production, 2000 and 2015

Country	**2000 (%)**	**2015 (%)**
Austria	2.67	16.49
Belgium	0.71	20.36
Bulgaria	0.00	6.31
Croatia	0.01	9.81
Czech Republic	0.72	9.68
Denmark	15.37	60.70
Estonia	0.15	14.14
Finland	12.46	19.10
France	0.57	6.13
Germany	2.40	27.43
Greece	0.84	17.63
Hungary	0.18	9.69
Ireland	1.43	24.80
Italy	2.47	23.40
Latvia	0.10	16.56
Lithuania	0.00	28.18
Luxembourg	11.61	23.52
Netherlands	3.16	12.28
Norway	0.20	1.88
Poland	0.16	12.69
Portugal	3.56	30.28
Romania	0.00	14.43
Slovak Republic	0.00	7.35

Slovenia	0.51	3.67
Spain	2.82	24.92
Sweden	3.14	16.30
United Kingdom	1.30	22.97

Source: World Data Bank (2018a)

This paper is motivated by the need to better understand the underlying factors driving RE deployment, particularly in the power sector. By 2050, the European Commission expects this sector to fully decarbonise through the generation of electricity from 'renewable sources such as wind, solar, water and biomass or other low-emission sources like nuclear power plants or fossil fuel power stations equipped with carbon capture & storage technology' (European Commission, 2018). Careful ex-post analysis of factors and policies that have proven successful in driving higher than average shares of renewable electricity can help policy makers and researchers design future policy pathways to decarbonise the electricity sector.

We follow Carley (2009) and Kilinc-Ata (2016) in excluding hydropower from our consideration of RE for two reasons. Firstly, Kilinc-Ata (2016) points out that hydropower is generally not eligible for subsidies under RE support policies. Secondly, as illustrated in Figure 1.1, hydropower is a more mature and established RE technology with much less scope for wider deployment in the EU; while hydropower's share of renewable electricity stood at 38 per cent in 2015, this figure has fallen from 74 per cent in 2004 (European Commission, 2017). Hydropower can only be developed by countries that are naturally endowed with mountain terrain allowing for falling or fast-moving water, and it can be argued that hydropower resources in EU countries are mostly already exploited. For the purposes of increasing the share of RE in electricity generation, it is thus more instructive to analyse the factors driving the development of RE sources other than hydropower. Despite RE being a priority of EU policy, once hydropower is excluded renewable sources still only make up a small percentage of electricity generation in the EU, at less than 20 per cent electricity generation.

Carbon emissions from fossil fuels represent unpriced externalities that can contribute to making RE relatively uncompetitive. In addition, during the early stages of diffusion of a new RE technology in a country, RE is typically more expensive relative to conventional fossil fuels. In such cases, public policy is clearly required to promote the development of RE. For example, van Ruijven and van Vuuren (2009) find that in the absence of climate policy, the preferred substitute energy source to natural gas in the electricity sector is coal, which is more carbon intensive. Borenstein (2012) argues that environmental externalities constitute the largest market failure in energy markets, and that the Pigouvian approach of pricing those externalities would be the most efficient method of eliminating that market failure. From a theoretical point of view, Menanteau, Finon and Lamy (2003) argue that price-based policies, such as feed-in tariffs (FITs), are more efficient than quantity-based policies, such as bidding systems or green certificate trading with quotas, for achieving a higher installed capacity of RE although a quantity-based approach would clearly be favoured from a cost-control perspective. An assessment of the impact of public policy is thus a crucial element of the literature on RE development.

The objective of this paper is to examine the factors contributing to the deployment of non-hydropower renewable sources of electricity. Our analysis is based on annual data from Member States of the EU between 2000 and 2015 and follows a panel data approach. This research offers three main innovations to contribute to existing literature. Firstly, the empirical analysis focuses solely on the contribution of RE to electricity production instead of to the total primary energy supply in the EU, thus omitting the heating and transport sectors. Secondly, an alternative measure of the extent of public policy support for RE, based on the tax and levy component of electricity prices, is proposed as a policy variable. Furthermore, a hybrid mixed effects model (Schunck, 2013; Allison, 2009) is employed instead of the fixed effects vector decomposition (FEVD) model used in the literature, which has been subject to criticism in econometrics literature. This research also serves as an update on previous research by utilising more recent data, a contribution which has been repeatedly highlighted in the literature as crucial in the relatively new and ever-evolving area of RE.

The remainder of this paper is organised as follows: a literature review of this topic is outlined in Section 2; Section 3 describes the data and methodology employed in the analysis; Section 4 reports and discusses the results of the empirical analysis; and finally, Section 5 concludes by suggesting policy implications of the analysis and areas requiring further research.

2. Literature review

The diversity in national shares of RE deployment in EU Member States and in their policy approaches has motivated a substantial literature on RE policy in recent years. Several empirical studies analyse the drivers of the deployment of RE in the overall energy supply (Aguirre and Ibikunle, 2014; Marques and Fuinhas, 2012; Johnstone, Hascic and Popp, 2010; Marques, Fuinhas and Manso, 2010). Some studies employ RE consumption, rather than deployment, as the dependent variable (Doytch and Narayan, 2016; Omri and Nguyen, 2014; Salim and Rafiq, 2012). Others again focus on the use of RE in electricity generation rather than the total energy supply, thus omitting RE in the heat and transport sectors in their analysis (Kilinc-Ata, 2016; Lin, Omoju and Okonkwo, 2016; Polzin, Migendt, Taube and von Flotow, 2015; Carley, 2009; Menz and Vachon, 2006).

Most of these empirical analyses adopt a panel data approach, generally using a fixed effect vector decomposition (FEVD) model (Aguirre and Ibikunle, 2014; Marques *et al.,* 2010; Carley, 2009) or a panel-corrected standard errors (PCSE) model (Polzin *et al.*, 2015; Marques and Fuinhas, 2012). Kilinc-Ata (2016) instead employs a fixed effects estimator, while Lin *et al.* (2016) opt for a time series approach using Chinese data. The FEVD approach is criticised in econometrics literature as being ‘illusory’, however (Greene, 2011; Breusch, Ward, Nguyen and Kompas, 2011); therefore, a contribution of this paper is to use a hybrid mixed effects model (Schunck, 2013; Allison, 2009) to fill this gap. Empirical studies on this topic predominantly analyse US data (Carley, 2009; Menz and Vachon, 2006), European data (Marques and Fuinhas, 2012; Marques *et al.*, 2010), or a combination of US, European and OECD data (Kilinc-Ata, 2016; Polzin *et al.*, 2015; Aguirre and Ibikunle, 2014). This paper updates the previous analysis of the determinants of European RE with a more recent time period of 2000-2015.

In specifying their estimation model, a range of parameters has been modelled with different results. Most studies find CO_2 emissions to have a significant and positive effect on the dependent variable (Aguirre and Ibikunle, 2014; Omri and Nguyen, 2014; Popp, Hascic and Medhi, 2011), although Marques and Fuinhas (2012) and Marques *et al.* (2010) find this effect to be negative. Aguirre and Ibikunle (2014) and Marques *et al.* (2010) suggest that CO_2 emissions can be included in models of RE deployment as a proxy for environmental concerns, although the link between emissions and environmental concerns is unclear. In addition, including an emissions variable is further complicated by causality issues stemming from the fact that the energy sector is itself a major contributor to CO_2 emissions and an increase in the use of RE at the expense of more traditional, carbon-intensive energy sources would be expected to reduce emissions, for example. Another common variable included in this literature is the dependency on energy imports, although the results are ambiguous. While Marques *et al.* (2010) argue that RE provides countries with an opportunity to develop an indigenous energy supply and thus increase energy security, Aguirre and Ibikunle (2014) find no significant effect, and Marques and Fuinhas (2012) find a negative effect. Some models include the potential of a country for RE in terms of solar, wind or biomass potential; Aguirre and Ibikunle (2014), for example, find that solar potential, but not wind potential, significantly and positively affects RE development. They suggest that these divergent results may be due to data limitations given the fact that the contribution of RE to the energy supply is not disaggregated between technologies in the paper’s dataset.

The findings on the influence of coal, oil and natural gas prices on RE development are mixed in the literature (Aguirre and Ibikunle, 2014; Marques and Fuinhas, 2012; Marques *et al.*, 2010). Aguirre and Ibikunle (2014) suggest that this may be due to fact that the models employed in the studies may not be equipped to detect any consistent price effect, as such effects tend to be over a longer time period than allowed for in the models. A more consistent result is a significant and positive wealth or income effect on RE deployment (Lin *et al.*, 2016; Salim and Rafiq, 2012; Marques *et al.*, 2010), which is unsurprising as higher levels of wealth imply increased scope to meet the higher initial costs of these technologies. A common result throughout the literature is that higher shares of fossil fuels in the energy supply lead to less RE development. Aguirre and Ibikunle (2014) and Marques *et al.* (2010), for example, suggest that this result indicates the presence of industrial lobbying on behalf of coal, oil and natural gas which constrains the development of RE. The interpretation of this result is questionable, however, as the share of fossil fuels would be expected to be negatively correlated with the share of RE in the energy supply; the result may simply be reflecting the fact that in many countries there is a nearly zero sum game between fossil fuels and RE in the energy mix.

Some studies include measures of trade openness and foreign direct investment (FDI) in their models of RE development. Results range from trade openness as a key driver of RE development (Omri and Nguyen, 2014), to the effect of FDI being dependent on the type of FDI and on the country’s income level (Doytch and Narayan, 2016), to trade openness and FDI having a negative effect on the dependent variable (Lin *et al.*, 2016). The effect of improving technology on RE deployment, using patent data as a proxy, is found to be positive but small relative to the effect of public policy (Popp *et al.*, 2011; Johnstone *et al.*, 2010).

In terms of estimating the impact of policy on RE deployment, researchers have generally included policy support as a variable in one of two ways: (i) the total number of policies in force, either aggregated or disaggregated into categories (Aguirre and Ibikunle, 2014; Marques and Fuinhas, 2012), and (ii) a dummy variable indicating the existence of a certain policy (Kilinc-Ata, 2016; Popp *et al.,* 2011). The overall effect of public policy that supports RE is generally found to encourage RE development (Marques and Fuinhas, 2012). When the RE policies are disaggregated, however, most policy types have an insignificant effect on the dependent variable (Aguirre and Ibikunle, 2014; Marques and Fuinhas, 2012; Popp *et al.*, 2011; Johnstone *et al.*, 2010; Carley, 2009). FITs appear to be the policy instrument most consistently favoured across studies (Polzin *et al.,* 2015; Kilinc-Ata, 2014; Popp *et al.,* 2011). It should be pointed out, however, that the insignificance of most policy categories may be a reflection of the use of imperfect policy variables, or the fact that some policies are only employed in a few countries. This paper contributes to the literature by attempting to better represent the level of RE policy support in our model by utilising a continuous variable of electricity taxes and levies as a proxy.

Finally, examples of more qualitative contributions to the literature on public policy directed at renewable electricity are found in Becker and Fischer (2013), Gan *et al.* (2007), van Rooijen and van Wees (2006), Wang (2006), Menz (2005), Bird *et al.* (2005) and Reiche and Bechberger (2004). These studies generally find that a package of different policy instruments, such as FITs, which is complemented with clear, credible and consistent policy objectives is the most effective policy approach for encouraging the use of RE.

3. Methodology

3.1 Data

We use annual data covering the EU-28 countries, with the exceptions of Cyprus and Malta, which have only recently begun to deploy renewable electricity due to the structural limitations of being small, island countries. Norway is added to the sample due to its high level of electricity grid interconnection with EU members Sweden and Denmark, and also due to its adherence to EU policy in the area of RE, to give a total of 27 countries. The period of analysis is between 2000 and 2015, beginning when RE started to become a serious EU policy objective and then exploiting the latest available data to give 432 observations.

The dependent variable is the natural log of the percentage contribution of RE to electricity production (World Data Bank, 2018a), excluding hydropower as discussed in Section 1. The relative price of other fuels, namely fossil fuels, may be expected to have an impact on the use of RE in electricity production and thus is included in the model. If the price of coal, for example, increases relative to the cost of RE, this may lead to a shift in competitiveness and an increase in the use of RE as a substitute for coal. Following Aguirre and Ibikunle (2014) and Marques *et al.* (2010), to capture any potential price effects the global prices of oil, coal and natural gas are sourced from the BP Statistical Review of World Energy 2017 (BP, 2017). As Aguirre and Ibikunle (2014) point out, however, any such price effects may be long-term due to the necessity for infrastructural change in order to substitute a fossil fuel with RE in electricity production. To account for this, we also include the prices of coal, oil and natural gas lagged by four years in our econometric analysis. Fuel prices are deflated to 2010 prices using the energy category of Eurostat's (Eurostat, 2018b) Harmonised Index of Consumer Prices (HICP) and are reported in US dollars.

We control for the structure of each country's economy by including GDP per capita (World Data Bank, 2018b), population growth (World Data Bank, 2018c) and the respective percentage contributions of aggregated fossil fuels (World Data Bank, 2018d), nuclear power (World Data Bank, 2018e) and hydropower (World Data Bank, 2018f). GDP per capita, measured in 2010 US dollars, is included as a macroeconomic control variable with the theory that a higher level of wealth can increase a country's capacity to develop RE. As populations of EU countries increase, it is also important to study the extent to which countries are able to meet the consequent rise in electricity demand with RE. In the short-term in particular, increases in electricity demand may be met by deploying marginal, fossil fuel-burning power plants which are both highly inefficient and carbon-intensive. The percentage contributions of other energy sources have also been included as variables capturing the structure of different economies in the literature. These variables would be expected to have a negative effect on the dependent variable, as an increase in the share of fossil fuels, nuclear or hydropower in electricity production must be at the expense of the share of other sources.

Imports (Eurostat, 2018c) and exports (Eurostat, 2018d) of electricity, measured in gigawatt-hours, are combined and included as total electricity flow in the model as a measure of the extent to which a country is interconnected with the electricity grids of neighbouring countries. The utilisation of variable RE sources such as solar and wind can be significantly improved with interconnection to neighbouring electricity systems. The availability of interconnectors to import electricity during periods of low renewable electricity production and to export excess renewable electricity in the absence of feasible storage could increase a country's capacity to incorporate RE into electricity production. This theoretically crucial feature of a country's electricity infrastructure has not yet received much attention in the empirical economics and policy literature and is therefore included in the model. Another measure of the interdependence of countries is trade openness, which is included using FDI in the literature. Doytsch and Narayen (2016) suggest that multinational companies use cleaner energy than domestic firms, and that higher levels of trade openness facilitate a greater transfer, and consequent diffusion, of new RE technology; therefore it may be informative to assess the extent to which this applies to EU countries, where many multinational companies originate and from where new RE technology is transferred. Following the literature, the net inflow of FDI is measured as a percentage of total GDP in our model and captures the relative importance of FDI to the economy (World Data Bank, 2018g).

We include greenhouse gas emissions (Eurostat, 2018e) as a proxy for the influence of environmental concerns on the development and use of RE, based on an argument by Aguirre and Ibikunle (2014) and Marques *et al.* (2010) that a high level of emissions may increase public acceptance of RE, or increase pressure on policy-makers to develop RE. To avoid problems of causality resulting from the electricity production sector itself making a significant contribution to a country's emissions, greenhouse gas emissions from the electricity production sector are excluded from our emissions variable, which is measured in tonnes per capita. We also lag this emissions variable by one year, as the level of emissions in one year may be expected to have an impact on the contribution of renewable electricity in the following year. A country's RE potential, assumed to be constant over time, is constructed using solar power potential (World Bank Group, 2018a) and wind power potential (World Bank Group, 2018b). The chosen measure for solar potential is the average global horizontal irradiation in a country, measured in kilowatt-hours per square metre. In the case of wind potential, the wind power available in the windiest tenth of the country in terms of area is measured in watts per square metre. As the dependent variable is not segregated between different RE sources other than to exclude hydropower, solar potential and wind potential are added to give one variable in the model in watts per square metre. It is generally expected that a higher level of RE potential would lead to a higher contribution of RE in electricity production, as more power is available for exploitation.

The impact of public policy designed to support RE on its use in the energy supply is discussed extensively in the literature, and some econometric models include various imperfect measures of this support, mainly using the number of policies in force. We propose an alternative approach to represent the extent of RE policy in EU countries. The Council of European Energy Regulators (2017) points out that there are two key tools employed by countries to finance RE support schemes: general taxation, and a levy component of electricity bills paid by consumers, with the latter approach being used by 20 out of 28 EU countries. A case study of the financing of RE support schemes through a levy on electricity prices in Ireland is presented in an online appendix to highlight this point. For the purposes of a public policy explanatory variable, we use the tax and levy component of electricity prices (Eurostat, 2018f) as a quantitative measure of the value of the policy support for RE rather than including dummy variables for different policy instruments or an accumulated number of active policies under various categories as is done by others. One drawback of this approach is that the support of RE is not the only use of the tax and levy component of electricity prices; other elements of this component include: (i) levies to fund capacity payments or the support of nuclear energy in some countries, and (ii) taxes such as value-added tax (VAT) and excise duty. To mitigate this drawback in the absence of more detailed data for our period of analysis, we deduct VAT and excise duty on electricity prices from the tax and levy value, and transform the resulting variable into its growth form. We assume implicitly that any increase in levies on electricity prices, once VAT and excise duties are excluded, is driven by an increase in the level of support afforded to RE during our period of analysis. These prices are also deflated to 2010 prices using the energy category of the HICP (Eurostat, 2018b) and converted to US dollars for consistency with our price variables. Table 3.1 provides the summary statistics for the variables in our model.

Table 3.1: Variables and descriptive statistics

Variable	**Description**	**Source**	**Observations**	**Mean**	**Standard deviation**	**Minimum**	**Maximum**
Renewable share	Contribution of renewable energy excluding hydropower to electricity production (%)	World Data Bank	432	7.43	8.63	0.00	60.70
Oil price	Crude oil price (2010 US$ per barrel) *	BP Statistical Review of World Energy 2017	432	68.59	21.94	36.28	99.90
Gas price	Natural gas price (2010 US$ per million btu) *	BP Statistical Review of World Energy 2017	432	6.82	2.05	3.54	10.98
Coal price	Coal price (2010 US$ per tonne) *	BP Statistical Review of World Energy 2017	432	78.87	25.65	47.20	150.18
Interconnection	Electricity imports plus electricity exports (GWh)	Eurostat	432	24127.11	22519.33	240.00	122298.00
Fossil fuel share	Contribution of fossil fuels to electricity generation (%)	World Data Bank	432	53.53	27.62	0.20	99.79
Nuclear share	Contribution of nuclear energy to electricity generation (%)	World Data Bank	432	19.90	23.60	0.00	82.24
Hydro share	Contribution of hydropower to electricity generation (%)	World Data Bank	432	18.49	24.00	0.04	99.51
Population growth	Population growth (%)	World Data Bank	432	0.18	0.79	-2.85	2.89
GDP	GDP per capita (2010 $)	World Data Bank	432	33813.43	23455.56	4011.10	111968.40

Emissions	Greenhouse gas emissions, excluding electricity production sector (tonnes per capita)	Eurostat	432	0.01	0.00	0.00	0.02
FDI	Foreign direct investment net inflow (% of GDP)	World Data Bank	432	6.86	16.28	-58.32	252.31
RE potential	Solar power potential plus wind power potential (W per m^2)	World Bank Group	27	704.88	269.99	404.23	1347.00
Tax	Growth of tax and levy component of electricity prices, excluding VAT and excise duty (2010 US$ per kWh) *	Eurostat	432	0.08	0.36	-0.84	4.17

*Deflated to 2010 prices using the Energy category of the Harmonised Index of Consumer Prices.

3.2 Methodology

As outlined in Section 2, Plumper and Troeger's (2007) fixed effect vector decomposition (FEVD) estimator is widely employed in the literature to empirically analyse RE development. However, this method is criticised in the econometrics literature as 'illusory'; time-varying covariates produce identical results using a three-stage FEVD estimator as a one-stage fixed effects (FE) estimator, and questions are raised on the ability of the estimator to provide robust estimated coefficients of time-invariant variables (Greene, 2011; Breusch, Ward, Nguyen and Kompas, 2011). This paper instead uses a hybrid mixed effects model (Schunck, 2013; Allison, 2009) which builds on Mundlak's (1978) correlated random effects model by adding specification flexibility. Unlike a traditional fixed effects model, which would allow for the consistent estimation of the effects of variables which vary within and between countries but which would not estimate the effects of variables which only vary between countries (i.e. time-invariant variables), this hybrid model allows for a decomposition of the effects of covariates between both types of variables. This method is considered appropriate given the potential significance of variables that vary across countries as well as within countries, such as greenhouse gas emissions, in addition to variables that only vary between countries, such as a country's RE potential which is assumed to be time-invariant. The model can thus be expressed as in Equation 3.1:

$$lnrenewable_{ij} = \alpha + \beta_1 Z_i + \beta_2 \left(X_{ij} - \bar{X}_i\right) + \beta_3 \bar{X}_i + u_i + \varepsilon_{ij} \tag{3.1}$$

In this model, $lnrenewable_{ij}$ is the dependent variable, the natural log of the contribution of RE (excluding hydropower) to electricity production for country i in year j. We follow Aguirre and Ibikunle (2014), Marques and Fuinhas (2012), Marques *et al.* (2010) and Carley (2009), in using the natural log of the contribution of RE to electricity production to measure RE development, as this avoids bias and inconsistency in estimates stemming from the skewed distribution of the dependent variable in level form. Alternative methods suggested (but ultimately overlooked) in the literature include measuring the replacement of traditional energy sources with RE in electricity production or measuring the total production of renewable electricity (Marques *et al.*, 2010). The problem of taking the natural log of a percentage which could have a value of zero is avoided by omitting Cyprus and Malta, two small, geographically isolated countries which have only recently begun to deploy renewable electricity compared with the rest of the EU.

The error term in Equation 3.1 has been decomposed into a time-constant county-specific effect, u_i, and an independent and identically distributed random error, ε_{ij}. RE potential, the variable which is constant over time and thus which does not vary within countries, is represented by Z_i. β_1 captures the standard random effect coefficient of RE potential in the model. X_{ij} represents a vector of all other variables in the model as they vary over time; these are oil price, gas price, coal price, interconnection, fossil fuel share, nuclear share, hydropower share, population growth, GDP per capita, emissions, FDI and growth in the share of taxes in electricity prices. β_2 captures the within-country effect of the X variables on the dependent variable, and β_3 captures the between-country effect of these variables on the dependent variable. Country-varying variables in the list of explanatory variables are specified in the model as deviations from the country mean, and the country means of the original X variables are then added to the model to capture between-country effects.

Additional models are also estimated to assess the robustness of the hybrid model's results, namely a panel-corrected standard errors (PCSE) model and a fixed effects (FE) model. Polzin *et al.* (2015), Aguirre and Ibikunle (2014) and Marques and Fuinhas (2012) all employ a PCSE model, which can avoid inefficient estimation of coefficients and biased standard errors for panel data. The PCSE model allows for the assumption that disturbances are heteroskedastic and contemporaneously correlated across panels for linear cross-sectional time series models. The model can be described as in Equation 3.2:

$$lnrenewable_{ij} = \alpha + \sum_{i=1}^{i} \beta_i X_{ij} + \varepsilon_{ij} \tag{3.2}$$

In Equation 3.2, as in the hybrid model, the dependent variable $lnrenewable_{ij}$ is the natural log of the contribution of RE (excluding hydropower) to electricity production for country i in year j. X_{ij} is a vector of all explanatory variables: oil price, gas price, coal price, interconnection, fossil fuel share, nuclear share, hydropower share, population growth, GDP per capita, emissions, FDI, RE potential and growth in the share of taxes in electricity prices. The PCSE estimator allows the error term ε_{ij} to be heteroskedastic, to be correlated across countries and to follow a first-order autoregressive process.

Kilinc-Ata (2016), meanwhile, utilises an FE estimator, arguing that the unobserved heterogeneity driving the share of RE in electricity production is relatively constant over time, and can thus be treated as fixed effects. The estimation model is described in Equation 3.3:

$$lnrenewable_{ij} = \beta X_{ij} + u_i + \varepsilon_{ij} \tag{3.3}$$

The dependent variable $lnrenewable_{ij}$ is once again the natural log of the contribution of RE (excluding hydropower) to electricity production for country i in year j, while X_{ij} represents a vector of all time-varying explanatory variables: oil price, gas price, coal price, interconnection, fossil fuel share, nuclear share, hydropower share, population growth, GDP per capita, emissions, FDI and growth in the share of taxes in electricity prices. As it is assumed constant over time, the RE potential variable is omitted from the FE estimator. The random country-specific unobserved effect is denoted by u_i, while ε_{ij} is an idiosyncratic error term. The FE estimator allows u_i to be correlated with the regressors X_{ij}, while assuming the idiosyncratic error ε_{ij} is uncorrelated with X_{ij}. Using a within FE estimator, estimates for the β coefficients are found by applying a mean-differencing transformation to Equation 3.3 which eliminates u_i; this allows for the consistent estimation of the β coefficients even if the regressors are correlated with the country-specific time-invariant unobserved effect, but does not allow for estimation of time invariant variables such as RE potential. The assumption that ε_{ij} is independent and identically distributed is relaxed to give cluster-robust standard errors.

This paper uses the Stata SE 15.0 statistical software package for the econometric analysis. Following Aguirre and Ibikunle (2014), we conduct several pre-estimation specification tests on the data. The Levin-Lin-Chu and Im-Pesaran-Shin tests examine the dataset for panel unit roots; both tests set the null hypothesis as all individual countries having a unit root. The Levin-Lin-Chu test sets homogeneity as the alternative hypothesis using residuals from a pooled OLS estimation, while the alternative hypothesis in the Im-Pesaran-Shin test is heterogeneity; this is done by averaging separate augmented Dickey-Fuller tests for each cross section in the data, allowing for different orders of serial correlation. Levene's test for equal variances then determines the presence of heteroscedasticity using a null hypothesis of homoscedasticity. Finally, serial autocorrelation is tested for using a Wooldridge test which sets no serial correlation as the null hypothesis, while a Pesaran test looks for cross sectional dependence, with cross sectional independence as the null hypothesis. Table 3.2 reports the results of these tests.

Table 3.2: Results of pre-estimation specification tests

Test	Test statistic
Levin-Lin-Chu for panel unit roots ($t*$)	-15.96***
Im-Pesaran-Shin test for panel unit roots ($\overline{W}_t$)	-4.95***
Levene test for equal variances (W_0)	10.10***
Wooldridge test for serial autocorrelation ($F(1, 28)$)	169.36***
Pesaran test for cross-sectional dependence	65.66***
*** denotes significance at the 1% level.	
** denotes significance at the 5% level.	
* denotes significance at the 10% level.	

The results of these specification tests are similar to the results reported in Aguirre and Ibikunle (2014). Both panel unit root tests, conducted using three lags, indicate stationarity by rejecting the null of unit roots. Levene's test for the equality of variances also rejects the null, implying the presence of heteroscedasticity. First-order autocorrelation is detected by the Wooldridge test, and the Pesaran test reports cross-sectional dependence.

4. Results and Discussion

The results from estimating the hybrid mixed effects model, the PCSE model and the FE model are reported in Table 4.1, while Table 4.2 presents point elasticities calculated at variable means based on the PCSE model.[1] Estimated coefficients for the hybrid model are segregated between standard random effects, within-country effects, and between-country effects. As illustrated in Table 4.1, the significance and direction of the coefficients are broadly similar between the hybrid and PCSE estimators, indicating robust results.

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[1] We calculate point elasticities based on the PCSE model instead of the hybrid model due to uncertainty in econometric literature on the interpretation of elasticities of within- and between-effects. Schunck (2013) provides some discussion on pitfalls in the application of hybrid models when including interactions.

Table 4.1: Estimation results from hybrid mixed effects model, PCSE model and FE model

ln(renewable share)	**Hybrid mixed effects coefficient**			**Panel-corrected standard errors coefficient**	**Fixed effect coefficient**
	Random effect	Within-country effect	Between-country effect		
Oil price $_t$		0.02***		0.02***	0.02***
		(0.01)		(0.01)	(0.01)
Oil price $_{t-4}$		0.06***		0.03***	0.06***
		(0.01)		(0.01)	(0.02)
Gas price $_t$		0.09		0.05	0.09**
		(0.07)		(0.05)	(0.04)
Gas price $_{t-4}$		-0.01		0.15**	-0.01
		(0.07)		(0.07)	(0.04)
Coal price $_t$		-0.01		-6.12×10^{-4}	-0.01**
		(0.00)		(0.00)	(0.00)
Coal price $_{t-4}$		-0.02***		-0.02***	-0.02***
		(0.01)		(0.01)	(0.00)
Interconnection $_t$		3.43×10^{-5} *	1.60×10^{-5} **	2.95×10^{-5} ***	5.43×10^{-5}
		(0.00)	(0.00)	(0.00)	(0.00)
Fossil fuel share $_t$		-0.01	-0.11***	-0.10***	-0.01
		(0.02)	(0.03)	(0.02)	(0.04)
Nuclear share $_t$		-0.05**	-0.12***	-0.11***	-0.05*
		(0.02)	(0.03)	(0.02)	(0.03)
Hydro share $_t$		0.06*	-0.11***	-0.10***	0.06

		(0.03)	(0.03)	(0.03)	(0.06)
Population growth $_t$		0.16	1.92***	-0.24	0.16
		(0.19)	(0.53)	(0.20)	(0.35)
GDP $_t$		1.14×10^{-5}	8.93×10^{-7}	5.06×10^{-5} **	1.14×10^{-5}
		(0.00)	(0.00)	(0.00)	(0.00)
Emissions $_{t-1}$		492.17***	-162.72*	171.89***	492.17***
		(96.13)	(92.40)	(59.47)	(172.15)
FDI $_t$		-3.12×10^{-3}	-4.75×10^{-3}	-6.80×10^{-4}	-3.12×10^{-3}
		(0.01)	(0.04)	(0.00)	(0.00)
RE potential $_t$	-9.82×10^{-4}			-1.16×10^{-3}	
	(0.00)			(0.00)	
Tax $_t$		0.25	5.40**	0.10	0.25
		(0.21)	(1.95)	(0.07)	(0.17)
Observations		432		432	432
Wald χ^2		505.42***		93.11***	
F-statistic					31.45***

Standard errors are reported in parentheses.

*** denotes significance at the 1% level.

** denotes significance at the 5% level.

* denotes significance at the 10% level.

Table 4.2: Point elasticities calculated at variable means with respect to dependent variable, based on PCSE model

ln(renewable share)	**Point elasticity at variable mean**
Oil price $_t$	1.30***
	(0.45)
Oil price $_{t-4}$	1.35**
	(0.51)
Gas price $_t$	0.24
	(0.26)
Gas price $_{t-4}$	-0.65**
	(0.29)
Coal price $_t$	-0.04
	(0.24)
Coal price $_{t-4}$	-1.34***
	(0.37)
Interconnection $_t$	0.55***
	(0.13)
Fossil fuel share $_t$	-3.96***
	(1.16)
Nuclear share $_t$	-1.73***
	(1.44)
Hydro share $_t$	-1.36**
	(0.48)
Population growth $_t$	-0.03
	(0.03)
GDP $_t$	1.32**
	(0.50)
Emissions $_{t-1}$	0.87***
	(0.31)
FDI $_t$	-3.61×10^{-3}
	(0.01)
RE potential $_t$	-0.63
	(0.67)
Tax $_t$	0.01
	(0.00)

Standard errors are reported in parentheses.

*** denotes significance at the 1% level.

** denotes significance at the 5% level.

* denotes significance at the 10% level.

In common with the literature on this topic, the results suggest mixed effects of fossil fuel prices on RE deployment (Aguirre and Ibikunle, 2014; Marques and Fuinhas, 2012; Marques *et al.*, 2010). As global prices are utilised in this paper, the hybrid model does not estimate between-country price effects. In terms of within-country effects, the effects of the price and lagged price of oil are significantly positive across all three estimators and are supported by a significant and positive elasticity. The effect of the lagged price of coal appears to have a negative effect, however, while the effects of the prices of natural gas are not significant, other than for the PCSE estimator where it is positive when lagged. Aguirre and Ibikunle (2014) do not find any significant price effects, and Marques *et al.* (2010) report oil prices as having a negative effect and gas prices as having a positive effect on RE deployment, the opposite of the results of this analysis; these studies do not include lagged prices, however. Our results suggest that RE is treated as a substitute energy source for oil, but not necessarily for natural gas, for the purposes of electricity production. In many countries, gas is a complement to RE, as it is used to fill the gaps in availability of the RE resource and therefore this result makes sense. Contrary to expectations, a rise in the price of coal appears to discourage the use of RE in the long term (four years) and may suggest a complementary relationship also, however the size of the effect is relatively small. As is pointed out by Aguirre and Ibikunle (2014), price effects on the share of RE in electricity production may be more long-term than is allowed for in their models. While our analysis lags the price variables by four years in an attempt to address this, it may be the case that over an even longer time period, more consistent results across the literature could emerge.

The econometric literature analysing determinants of RE development does not focus on the level of electricity grid interconnection. In this analysis, a positive coefficient for this variable, measured by combining electricity imports and exports, is estimated and is consistent across all estimators and supported by a significant elasticity of 0.55. This result is as expected, indicating that electricity grid interconnection positively impacts the incorporation of RE into electricity production. This can be explained by the need for a flexible supply of electricity to accommodate variable sources of power such as solar and wind. The ability of a country to export excess renewable electricity during periods of above average supply, and to import electricity during periods of below average supply, increases its capacity to incorporate RE into electricity production. Conversely, if a country's electricity grid is isolated from the grids of other countries, it is unable to develop renewable electricity for reasons of supply security and unfeasible electricity storage. This result offers a clear implication to policy makers: electricity grid interconnection between countries should be developed in order to maximise the potential use of renewable electricity.

One finding which is consistent throughout the literature is that higher shares of fossil fuels in the energy supply inhibits the development of RE (Aguirre and Ibikunle, 2014; Marques and Fuinhas, 2012; Marques *et al.*, 2010). This reflects the negative correlation between the share of fossil fuels and the share of RE, as an increase in RE's share must reduce the share of other energy sources. The impact of the fossil fuel variable, measuring the accumulated share of coal, oil and natural gas in electricity production, on RE share is large and significantly negative between countries, as is the point elasticity. It is suggested in the literature that this relationship indicates the prevalence of a fossil fuel industrial lobby which inhibits the development of RE in countries with high shares of fossil fuels in their energy supply, although there is no evidence in our econometric analysis to support this theory. As expected, a similar result is found for the share of hydropower in electricity production, and a negative coefficient is also found for the share of nuclear energy across all estimators, again reflecting the statistical relationship between these explanatory variables and the dependent variable.

In terms of national greenhouse gas emissions (excluding emissions from electricity production and lagged by one year), the positive results presented in Table 4.1 along with a significant elasticity of 0.87 concur with Aguirre and Ibikunle (2014), Omri and Nguyen (2014) and Popp *et al.* (2011) in indicating that higher levels of emissions in other sectors within countries encourage higher shares of RE in electricity production. Marques and Fuinhas (2012) and Marques *et al.* (2010) find that emissions have a negative effect on the use of RE, but it may be that in more recent years a greater level of concern in the EU regarding emissions has driven a shift towards RE. It may also be the case that the coefficients of emissions variables in previous studies do not account for the issues of causality if the emissions variable included emissions from electricity production. It should be noted that the hybrid model only finds this effect to be significant within countries; a sample incorporating countries outside the EU, with different beliefs, approaches to climate change or levels of emissions to EU Member States, may be required to find a significant effect between countries. However, the results do suggest that a country's level of emissions in other sectors matters to the development of RE.

Only our between-country hybrid model indicates a significant and positive effect of population growth on the use of RE. While Aguirre and Ibikunle (2014) do not find any significant effect of population growth on the dependent variable, this result can be viewed as slightly surprising as population growth requires greater production of electricity, which in the short term may be met by increasing the use of fossil fuel-based power plants. This between-country effect suggests that in the EU, larger countries have better developed RE power and that perhaps increases in electricity generation to meet rising populations may actually be met by RE sources. Public policy supporting renewable electricity, therefore, need not be concerned about growing populations in EU Member States. In terms of the macroeconomic control variable, the PCSE estimator indicates a significant positive effect of GDP per capita on the dependent variable, along with a significant elasticity of 1.32; this is unsurprising as a higher level of wealth increases a country's capacity to develop RE (Lin *et al.*, 2016; Salim and Rafiq, 2012; Marques *et al.*, 2010). The fact that this result is not reflected by the hybrid estimator may be due to our sample being confined to EU Member States; a sample including countries with substantially lower levels of wealth may produce more robust results for the wealth variable. Furthermore, no significant effect is found for the share of FDI in GDP. There is thus no evidence in our econometric analysis of EU Member States in support of the hypothesis outlined by Doytch and Narayen (2016), whereby FDI can facilitate a transfer of knowledge and a greater capacity for a country to diffuse new RE technology. Doytch and Narayen (2016) find this effect to be dependent both on the type of FDI and on a country's income level, which may explain why no significant effect is found among EU Member States in this research. EU countries are comparatively wealthier and more developed than other countries, and much of the FDI which facilitates a transfer of knowledge, innovation and technology in the area of RE originates in the EU.

We find no significant effect of RE potential (the combined wind and solar power potential) on the dependent variable. It may be that a more detailed breakdown of the dependent variable into specific RE sources is required to reveal the true effect of RE potential on the use of renewable electricity. On the basis of our results, however, the deployment of renewable electricity is not dependent on the solar and wind power potential of specific countries. This requires further investigation, as it seems counterintuitive that the level of RE potential would not influence RE deployment.

Finally, a significantly positive effect is found between countries for the policy variable, the growth of the tax and levy component of consumer electricity bills. Such a result would be hoped for as an indication of the overall success of public policy in encouraging the use of renewable electricity. The result suggests that increased levies on electricity bills, which we argue implies a greater level of public policy support for RE, encourages the use of renewable electricity. No significant effect is found within countries however, or for either the PCSE or FE estimators; this may indicate that between-country effects are masked by within-country effects in the latter estimators. Our hybrid estimator's between-country result concurs with Marques and Fuinhas (2012), who utilise the aggregate number of policies in force as a policy variable, in terms of overall policy effectiveness. Aguirre and Ibikunle (2014), who also use the number of active policies as a variable, find coefficients to be generally insignificant when disaggregating between different policies. Kilinc-Ata (2016), meanwhile, employs dummy variables for policy measures, finding certain policies such as FITs to be more effective at supporting RE. Based on our hybrid model estimation, we suggest an important policy implication that increasing levies on consumer electricity prices is an effective tool for promoting the development of renewable electricity.

5. Conclusions and Policy Implications

The twenty-first century must see a decarbonisation of electricity production for there to be any chance of reducing greenhouse gas emissions sufficiently to mitigate the adverse effects of climate change (IEA, 2017). This paper seeks to contribute to this goal by presenting an econometric analysis of the factors which motivate the use of RE in electricity production, using data from EU Member States between 2000 and 2015.

In addition to exploiting more recent data, an important contribution in itself in the evolving area of RE, this research offers three key innovations. Firstly, the econometric analysis is focused on the electricity sector rather than on the overall primary energy supply, which includes the diverse sectors of electricity, heating and transport. To this end, the contribution of RE to electricity production is utilised as the dependent variable, with the more mature and developed hydropower excluded to scrutinise newer RE technologies. Secondly, an alternative public policy variable is proposed by using the tax and levy component of electricity bills as a measure of the extent of public policy support for RE. This offers a more quantitative measure of support than dummy variables or the accumulated number of policies which are used in the literature. Furthermore, an alternative econometric approach is employed in place of the FEVD estimator favoured in the literature on this topic but criticised in econometric debates. A hybrid mixed effects estimator (Schunck, 2013; Allison, 2009) is used instead, which allows for the estimation of effects both within and between countries for panel data.

The results of this analysis are found to be broadly as expected. In line with the literature, the fossil fuel price effects on RE are mixed, while the shares of other energy sources in electricity production negatively affect the dependent variable. The theory that electricity grid interconnection increases a country's capacity to develop RE is supported by the results, while the hypothesis of FDI boosting RE development is not supported among the EU Member States in our sample. While the absence of any significant effect suggests that FDI does not boost renewable electricity development in EU countries, it also implies that increased FDI has no negative effect on the share of RE in electricity production; this result indicates that policy-makers in the EU need not be concerned about the effect of FDI on renewable electricity deployment.

In contrast to some contributions to the literature, higher CO_2 emissions in other sectors are found to motivate a shift towards RE. If the link between emissions levels and environmental concerns suggested by the literature is accepted (Aguirre and Ibikunle, 2014; Marques *et al.*, 2010), it could be inferred that policy-makers should clearly link the development of renewable electricity with a need to reduce greenhouse gas emissions to boost political will and public acceptance for RE projects. A positive effect is also found for the alternative public policy variable proposed by this paper, indicating that economic supports via electricity taxes or levies are broadly successful in supporting the deployment of renewable electricity.

These results suggest several key policy implications: given that one of the main reasons behind the need for the development of renewable electricity is to decarbonise the energy system, an obvious policy implication of these results is that for RE support schemes to be most effective, public policy support for fossil fuels should be ceased[2]; electricity grid interconnections should be developed between countries; EU policy-makers do not need to be concerned about the effect of FDI on renewable electricity development; and furthermore, increasing levies on consumer electricity prices to fund RE support schemes is effective at promoting renewable electricity.

This paper focuses specifically on the electricity sector rather than on the primary energy supply. A similar econometric analysis of the heating and transport sectors may also be worthwhile given the diversity between the characteristics of all three energy sectors, subject to data availability. Another potential avenue for further research is to further disaggregate

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[2] Such as the Public Service Obligation (PSO) levy supporting the generation of electricity from peat as well as from RE in Ireland, as discussed in Appendix A.

the contribution of RE into different technologies. We exclude hydropower from the dependent variable as it is generally excluded from support schemes and is at a much later stage of development than other RE technologies. However, the explanatory variables employed in this analysis may have different effects on solar power compared to wind power or biomass, and research using data which disaggregates these technologies may be insightful. Finally, this econometric analysis is based on data from EU Member States; subject to data availability, a similar analysis which incorporates countries at different stages of development, with different levels of wealth or with different beliefs or approaches to climate change may also prove instructive.

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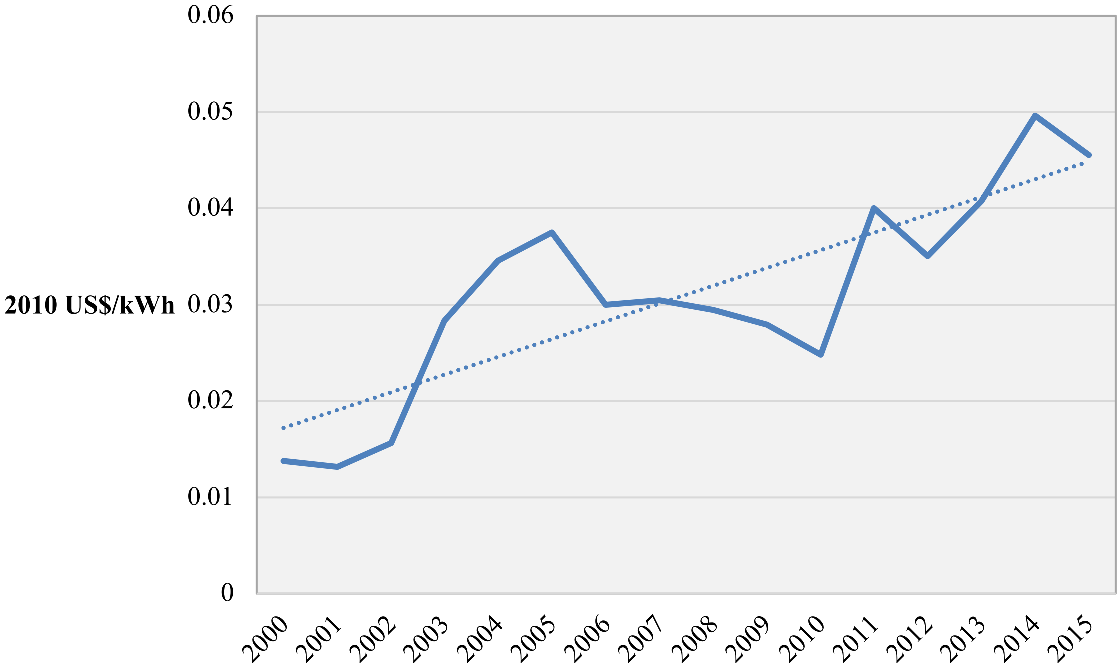
Appendix A: Case study – Public Service Obligation in Ireland

In Ireland, subsidies which support the use of RE in electricity production are funded by a levy on the electricity prices paid by consumers. A Public Service Obligation (PSO) levy is set annually by the Commission for Regulation of Utilities (CRU) and is charged to all electricity customers. According to the CRU (2017), the purpose of the PSO levy is to support national policy objectives in the area of RE, as well as the use of indigenous peat for reasons of supply security. The levy is utilised to pay the difference between a set price guaranteed to PSO-supported generators (i.e. generators which use RE or peat) and the market price, thus subsidising the use of RE and peat. Government policy sets the level of subsidy provided to PSO-supported generators, and the CRU then determines the size of the levy and administers its support schemes within its Government mandate. Electricity suppliers collect the levy from customers and then pass it on to EirGrid, Ireland's electricity transmission operator, which is responsible for paying out PSO-funded subsidies.

Several support schemes are financed by the PSO levy in Ireland. Long-term projects under an Alternative Energy Requirement (AER) scheme launched in 1995 for onshore and offshore wind are covered, along with three feed-in tariff (FIT) schemes. REFIT 1 was launched in 2006 to support electricity generation from wind power, hydropower, biomass and waste, and this was complemented in 2012 by REFIT 2 and 3. Two peat-burning plants, West Offaly and Lough Ree, are also covered by the PSO levy, although this support is set to be terminated at the end of 2019, leaving PSO support schemes to be directed solely on renewable electricity generation (CRU, 2017).

Figure A1 illustrates that the tax and levy component of electricity prices in Ireland has been gradually increasing since 2000, and it can be argued that this gradual increase is driven by increases in the PSO levy due to the exclusion of VAT and excise duty from the data. The CRU (2017) calculates that the PSO levy will increase by 20 per cent in 2018, with households paying €1.79 more per month on electricity bills than in the previous year: 'This increase is mainly due to a significant growth in the level of renewable generation expected to materialise in the next year'. The PSO levy for 2018 is calculated at €271.9 million, which is a significant increase from €92 million in 2012, and this supports 3,317MW of renewable electricity and 250MW of peat-fired electricity (CRU, 2017).

Figure A1: Tax/levy component (excluding excise duty) of electricity prices in Ireland, 2000-2016



Source: Eurostat (2018f)

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