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Knowledge Accumulation from Public Renewable Energy R&D in the European Union: Converging or Diverging Trends?*

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Abstract

Bottom-up processes of policy convergence are increasingly discussed as a substitute for the absence of supranational energy policy coordination and harmonization in the EU. The overall objective of this paper is to analyse the development of government support to renewable energy R&D across EU countries over time: does the empirical evidence suggest bottom-up convergence? In order to answer this question, we first construct country-specific R&D-based knowledge stocks, and then investigate whether the developments of these stocks tend to converge or diverge across EU countries. A data set covering 12 EU Member States over the time period 1990-2012 is employed to test for the presence of conditional β-convergence using a bias-corrected dynamic panel data estimator. The empirical results are overall robust and suggest divergence in terms of public R&D-based knowledge build-up in renewable energy technology. This finding is consistent with free-riding behavior on the part of some Member States, and the presence of industrial policy motives in other States in combination with agglomeration effects in the renewable energy sector. Energy import dependence and electricity regulation are found to influence the growth of the R&D-based knowledge stock, and the deregulation of the EU electricity markets has tended to contribute to a lower speed of divergence.

Keywords: renewable energy sources, public R&D support, convergence, European Union.

JEL classification: O44, P18, Q04, Q55.

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1. Introduction

The EU's integration with regard to energy and climate policy currently lingers at a "halfway stage" between national and union-wide approaches. This is sometimes considered untenable, in that the EU would have to move towards more integration so as to avoid re-nationalization (e.g., Buchan and Keay, 2016, p. 81). Still, the ambitious official rhetoric about an evolving "Energy Union" (EU Commission, 2015) can be questioned as strong politico-economic obstacles against a centralization of energy policy decision-making at the EU-level remain (e.g., Strunz et al., 2015). In line with such a rather skeptic view, for instance, the renewable energy policies as well as their outcomes in the various EU Member States are heterogeneous with substantial capacity increases in some countries and far more modest developments in others (IEA, 2014). For these reasons, it is increasingly being discussed whether bottom-up processes of convergence may substitute for the absence of supranational harmonization (e.g., Kitzing et al., 2012; Strunz et al., 2017).

The field of renewable energy research and development (R&D) merits particular interest in this respect: both policy makers and researchers have been calling for a significant increase in public R&D commitments in the renewable energy field in order to comply with climate mitigation pledges (e.g., Witte, 2009; Del Río, 2004; Reichardt and Rogge, 2014). Over the last two decades public R&D support to renewable energy has increased rapidly in Europe as well as in the OECD area (IEA, 2016a). Nevertheless, while the EU has overall succeeded in developing and adopting new carbon-free technology (e.g., wind power, solar PV etc.), the Member States have more or less full discretion when it comes to government spending on renewable energy R&D. In practice therefore, public R&D efforts and innovation activities in the renewable energy sector have typically been concentrated to a few leading countries; new high-value technologies have been developed in a limited number of advanced economies such as Germany, Denmark etc. (Dechezleprétre et al., 2011).

Against this background, the paper addresses two issues regarding domestic public support to renewable energy R&D. First, is there empirical support for the conjecture that national policies converge, despite the currently observed heterogeneity in public R&D expenditures and the absence of strong supranational guidance? In order to answer this question, the paper analyses how knowledge accumulation following national public R&D support has evolved over time. Second, the paper aims to shed some light on the empirical drivers of public R&D convergence/divergence as well as the speeds at which this takes place.

While the contribution of this paper lies on the empirical side, the results may also help to underpin a later normative evaluation of the observed patterns. For instance, in the presence of divergence and this being mainly triggered by regional comparative advantages and/or heterogeneous policy preferences, convergence need not be economically preferable. Then again, if pioneering countries interpret divergence as evidence of free-riding from follower countries, underinvestment in public R&D may well result – making the overall EU energy and climate policy targets more difficult and costly to achieve (e.g., Corradini et al., 2015; Garrone and Grilli, 2010). Indeed, maintaining public acceptance for the financial burdens that consumers in Europe must carry under a period of uncertainty regarding the energy system transformation could be more difficult in the presence of diverging national efforts.

Methodologically, we need to account for the fact that public R&D expenditures may have long-term impacts on knowledge build-up and technological change. For this reason we construct country-specific R&D-based knowledge stocks acknowledging the presence of time lags and knowledge depreciation, and investigate whether the developments of these stocks tend to converge or diverge across the EU countries. Specifically, the empirical analysis relies on a growth path approach and tests for so-called conditional β-convergence, i.e., stating that countries with lower initial R&D-based stocks will experience higher growth rates in this stock and therefore catch-up with the leading countries. The reverse relationship indicates divergence in terms of publicly supported R&D-based knowledge build-up in the renewable energy field. Moreover, we focus on conditional β-convergence, thus implying that we allow for the presence of heterogeneous steady state levels across countries. The influences of a number of exogenous variables are analyzed, including energy import dependence and electricity regulation. Furthermore, the empirical analysis also identifies a few determinants of the speed of convergence or divergence.

The econometric investigation relies on a panel data set covering 12 EU Member States over the time period 1990-2012, and the data are analyzed using a bias-corrected dynamic panel data approach applied to a number of different model specifications. Several robustness tests are made, including expanding the country sample to include additional OECD (yet non-EU) countries.[1] The time period is also extended – to cover 1980-2012 – and robustness tests are conducted with respect to the various ways in which the R&D-based knowledge stock is constructed (e.g., depreciation rates, time lags).

[1] Breyer et al. (2010) report that up to 85-90 % of global energy R&D has been performed in OECD countries.

The remainder of the paper is organized as follows. In Section 2 we discuss the role of public energy R&D support, and elaborate on the arguments for and against convergence of public R&D efforts in the case of renewable energy. Section 3 outlines the methodological approach of the paper, and presents the details of the different model specifications and the econometric issues that need to be addressed. In Section 4 we present and discuss the data used, i.e., key definitions, sources and descriptive statistics. Particular attention is devoted to the data needed to construct the R&D-based knowledge stock. Section 5 outlines the model estimation results and provides interpretations, while Section 6 concludes the paper and identifies a number of implications as well as avenues for future research.

2. Public R&D Support to Renewable Energy: Divergence or Convergence?

The basic rationale for public support to R&D is well-established. A large body of literature has argued and shown that the free market can fail when it comes to providing the socially efficient amount of resources aimed at generating new technological and scientific knowledge (e.g., Nelson, 1959; Arrow, 1962). Due to spillovers, this knowledge often has strong public good characteristics, implying that private firms invest too little and providing the economic rationale for public R&D expenditures. What is more, at the international level such spillover effects may also impact on the level of public R&D support at the national level because some countries may free-ride on others' development efforts (e.g., Mansfield et al., 1977).[2]

Previous research has also indicated that this underinvestment problem may be particularly prevalent in the case of R&D targeting environmental technology and clean energy, this due to the particularly strong presence of knowledge spillovers across firms and countries in these sectors (e.g., Popp, 2005; Fischer, 2008; Peters et al., 2012; Dechezleprêtre et al., 2013). Moreover, uncertainties about the future returns to environmental R&D tend to be especially high, e.g., because of policy inconsistencies (Jaffe et al., 2002). From a public economics perspective, a higher provision of dual types of public goods, i.e., a cleaner environment following pollution abatement and improvements in new clean energy technology, by some countries could lead to shrinking incentives for other countries to pursue similar efforts. Overall, divergence in national public R&D expenditures may therefore point towards free-riding activities of countries. From a global social welfare perspective, public R&D support would therefore be too low in the aggregate. This may in turn call for a stronger coordination

[2] Close economic integration, through trade and geographical closeness, increases the likelihood that countries have access to more or less the same pool of knowledge, even considering the fact that technological knowledge is not always fully codified and remains tacit and informal.

of public R&D expenditures at a higher supranational level, such as the EU. In addition to underinvestment, maintaining public acceptance for the financial burdens associated with the energy system transformation could be more difficult in the presence of diverging government efforts.

Still, the presence of knowledge spillovers cannot alone explain convergence/divergence in terms of public renewable energy R&D efforts. For instance, in the presence of international R&D spillovers domestic public R&D becomes more 'efficient' and can be optimally reduced (Park, 1998). Free-riding reduces all countries' incentives to pursue own R&D, but this does not necessarily explain why there may be convergence or divergence (i.e., why some become forerunners and others lag behind). Overall, there is a case to be made for both convergence and divergence in terms of R&D-based knowledge build-up in the renewable energy sector.

An important reason why some countries choose to be forerunners may be found in green industrial policy motives (Rodrik, 2014), and in broader goals of economic development and job creation. Through public R&D the domestic industry is given a leg up in the international competition; a first-mover advantage in renewable energy technology development can perhaps even tilt the future path of technological development in a direction that is closer to a country's initial comparative advantage. The laggard countries instead see their competitive advantages materializing in other (i.e., non-energy) sectors. In other words, divergence may simply result from varying comparative advantages and heterogeneous political preferences.

Any diverging paths may be strengthened by the presence of so-called agglomeration effects. This means that clustering occurs in the same industry because proximity generates positive externalities (Head et al., 1995; Rosenthal and Strange, 2001). In the case of technological research, there will be increasing returns on investments in areas where other similar research activities already exist. Positive spillovers across complementary R&D activities also provide stimulus for agglomeration (e.g., Delgado et al., 2014). In other words, innovative firms in a particular industry will establish themselves geographically in countries and regions where other inventive companies in the same industry can be found. Researchers will, in turn, leave laggard countries and then instead take up employment in countries where there are larger economic returns on new ideas. Public R&D support to specific sectors or technologies may help to further support such self-reinforcing processes.

However, the presence of forerunning and laggard countries does not necessarily mean that some countries will refrain from investing in renewable energy R&D support. Countries need a minimum level of technological capability to be able to appropriate on the knowledge primarily developed in other countries. This demand for so-called absorptive capacity arises due to the desire to improve existing technologies and adapt them to the local conditions (Cohen and Levinthal, 1989, 1990; Hussler, 2004; Mancusi, 2008). Government support to R&D may therefore be needed to secure a country's ability to comprehend and make use of external knowledge.[3] In a similar vein, Jovanovic and MacDonald (1994) point out that innovations and imitations are only to some extent substitutes. The benefits derived from knowledge spillovers can increase with differences in know-how, but the catch-up of laggards is in most cases conditional on their absorptive capacity. In other words, knowledge spillovers are not equal for everyone and their magnitudes depend on domestic investments in R&D.

One argument for convergence is that from a pure mathematical perspective it can be assumed that laggard countries can grow faster (in percentage terms) than the more technologically advanced countries since growing from something small will tend to result in comparatively large growth rates. This will in turn lead to a catch-up with the more developed countries, at least in the long-run (Keefer and Knack, 1997). Disruptive inventions and failed public R&D programs can contribute to convergence in that a former pioneering country could become locked into a stagnant technology, and thereafter face little incentives to pursue significant future R&D. Generally, policy convergence seems to rely on a combination of both economic and political drivers (e.g., Strunz et al., 2017): economic drivers facilitate convergence of the broader political agenda (as in the "Environmental Kuznets Curve" literature), while political drivers lead countries to actually adopt similar public policies. For instance, agreements at the supranational level can push countries to reach certain targets. Most notably, in the EU the Renewable Energy Directive (2009/28/EC) provides such an example; even though this Directive does not stipulate how much should be spent on domestic government renewable energy R&D support, it may provide incentives to undertake such investments in all EU Member States.

In sum, the above indicates rationales for the presence of both convergence and divergence in terms of public R&D support to renewable energy knowledge build-up. The notion that the new knowledge generated has important public good characteristics in combination with technological cluster theory support the divergence hypothesis. Convergence may however result in the presence of, for instance, top-down policy targets at the supra-national (e.g., EU) level. In addition, the importance of absorptive capacity, and the subsequent need to promote

[3] According to Antonelli et al. (2011) and Boschma and Lammarino (2009), the diffusion of knowledge is more likely to occur when the competences and knowledge stocks of the inventors and the adopters are closely related, or in other words when there is a high level of technological proximity (Fischer et al., 2006).

domestic R&D in order to make use of the knowledge develop in other countries, tends to support the convergence hypothesis or at least a lower speed of divergence. Hence, it is *ex ante* ambiguous whether policy convergence or divergence can be expected.

3. Model Specification and Econometric Issues

3.1 A Neoclassical Conditional Convergence Model

Our discussion in Section 2 suggested that the issue of divergence or convergence in terms of public R&D efforts to renewable energy remains an empirical question. For this reason, we specify a so-called conditional β-convergence model. β-convergence refers to a process were one entity, a country, that is less endowed with something (e.g., technological knowledge) grows faster, in relative terms, than the more well-endowed entities and therefore catches up with these over time. In addition, *conditional* β-convergence implies that we allow for entities (countries) to converge to different steady-state levels rather than to the same level.

Since public R&D expenditures may have long-lasting impacts on knowledge build-up and on technological change it is useful to abstain from only addressing annual government support to renewable energy R&D. Instead we assume that previous public R&D expenditures add to a per capita knowledge stock (e.g., Ek and Söderholm, 2010; Krammer, 2009), y_{it}. We have:

$$y_{it} = (1-\delta)y_{i(t-1)} + R\&D_{i(t-x)} \tag{1}$$

where *i* indexes the sample countries, and *t* indexes time. This builds on a perpetual inventory model approach, where a certain share of the previous year's stock adds to this year's stock. This is in turn determined by the size of the depreciation rate of the stock, δ (where $0 \leq \delta \leq 1$). Moreover, $R\&D_{i(t-x)}$ denotes the per capita annual government support to public renewable energy R&D, *x* is the number of years it takes before these expenditures generate results and thus add to the knowledge stock. In other words, this formulation builds on the reasonable assumptions that: (a) public R&D support to renewable energy sources does not have an instantaneous effect on the generation of new knowledge; and (b) the acquired knowledge depreciates in that the effects of previous public R&D expenditures become outdated (see also Hall and Scobie, 2006).

For our purposes we are interested in the development of this R&D-based knowledge stock in per capita terms, and our test of β-convergence involves investigating how the initial level of this per capita stock is related to the growth rate of the same stock. Specifically, in a panel data setting, conditional β-convergence can be tested through a transformed Barro growth equation (Barro and Sala-I-Martin, 1995):

$$\ln(y_{it}/y_{i,t-\tau}) = \alpha + \beta_c \ln(y_{it-1}) + \beta X_{it} + \rho_i + \eta_t + \varepsilon_{it} \qquad (2)$$

where $ln(y_{it}/y_{i,t-\tau})$ is the growth rate in the public renewable energy R&D stock per capita over the time period $t - \tau$ ($\tau = 1$) and t. The first term on the right hand side of equation (2) is the logarithm of the initial level of the per capita knowledge stock, i.e., $\ln y_{i,t-\tau}$. A negative – and statistically significant – estimate of β_c implies support for the conditional β-convergence hypothesis (e.g., Strazicich and List, 2003), while a positive estimate suggests divergence in terms of R&D-based knowledge build-up in the renewable energy field. The magnitude of β_c will in turn indicate the speed of convergence or divergence. Furthermore, ρ_i represents country-specific fixed effects, η_t represents period-specific fixed effects, while ε_{it} is the error term.

For our purposes the vector X_{it} contains three exogenous, independent variables that may influence the growth rate of the stock, and help control for differences in steady states across countries (e.g., Barro and Sala-i-Martin, 1992; Barro, 2015). *First*, RIR_{it} represents the opportunity cost of public R&D, here measured by the real rate of return on long-term treasury bonds. We anticipate that increases in this real interest rate will have a negative effect on annual government support to renewable energy R&D, and thus also on the growth rate of the corresponding knowledge stock, $ln(y_{it}/y_{i,t-\tau})$.

Second, we also include a variable, EI_{it}, indicating the degree of energy import dependence in country i and time period t. Energy imports into the EU and the OECD countries are heavily dominated by fossil fuels such as oil and natural gas. It could therefore be expected that increased energy import dependence should have a positive impact on the willingness of governments to invest in public R&D support to renewable energy sources that can substitute for fossil fuel imports. In this paper we focus on the aggregate support to all renewables, but it should be clear that individual countries may respond differently with respect to the specific energy sources receiving most support (e.g., biomass in northern Europe, solar PV in southern Europe) (see also Appendix B).

Third, ER_{it} is a variable measuring the degree of regulation of the electricity sector where high values indicate a more regulated sector, e.g., with respect to the presence of public ownership, entry barriers, vertical integration etc. (see Section 4 for details). Many of the most important renewable energy sources, e.g., wind power, solar PV etc., have increasingly been penetrating the electric power sector. Still, at the same time previous research indicates that as the OECD and EU countries have deregulated the electricity sector, the respective national governments have tended to reduce the budget appropriations for energy R&D (e.g., Nemet and Kammen, 2007; Sanyal and Cohen, 2009). The rationale behind these findings is that the deregulation of the market makes electric utilities more cost conscious due to more intense competition and to less ability to pass on any cost increases to consumers. In addition, in the absence of direct government control, the utilities may also have less incentive to internalize the social benefits of knowledge generation in their decision-making (see further Section 2 as well as Smith and Urpelainen, 2013).

The empirical analysis also involves two alternative and more general, model specifications in which we include two interaction effects. Specifically, we allow the speed of convergence (or divergence), i.e., β_c, to vary depending on the energy import dependencies and the electricity regulation, respectively (see also Brännlund et al., 2015). The following alternative model specifications are therefore introduced:

$$\ln(y_{it}/y_{i,t-\tau}) = \alpha + \beta_c \ln(y_{it-1}) + \beta X_{it} + \mu \ln(y_{it-1}) \ln EI_{it} + \rho_i + \eta_t + \varepsilon_{it} \quad (3)$$

$$\ln(y_{it}/y_{i,t-\tau}) = \alpha + \beta_c \ln(y_{it-1}) + \beta X_{it} + \mu \ln(y_{it-1}) \ln ER_{it} + \rho_i + \eta_t + \varepsilon_{it} \quad (4)$$

In these specifications the speed of convergence will be determined by the terms $\beta_c + \mu EI_{it}$ and $\beta_c + \mu ER_{it}$, respectively. In the case of energy import dependence it can be hypothesized that countries with relatively high energy import dependencies have stronger incentives to develop alternative energy sources relatively quickly; μ should therefore have a negative sign, suggesting either a higher speed of convergence or, alternatively, a lower speed of divergence. The interaction variable between $\ln y_{i,t-\tau}$ and ER_{it} permits us to answer the following question: how will a given move from a regulated to a less regulated electricity market in countries that have invested relatively much in public renewable energy R&D affect the knowledge stock growth rate compared to the case where a corresponding move takes place in countries with less ambitious track records in terms of public R&D support to renewables?

Equations (2)-(4) represent our base specifications, i.e., models I-III, which are estimated using a panel data set comprising 12 EU countries over the time period 1990-2012. However, in order to test the robustness of the results we also consider an extended data sample in which five OECD, yet non-EU, countries are included. These model specifications are labeled models IV-VI. Furthermore, Appendix A presents the results from a number of additional robustness tests. These include an extension of the data samples to also embrace a more extended time period, i.e., 1980-2012. We also test whether the results are robust to different assumptions concerning the construction of the R&D-based knowledge stock, i.e., the time lag (x) and the depreciation rate (δ) (see Section 4 for details).

3.2 Econometric Issues

The main usefulness of a panel approach lies in it allowing for heterogeneity across countries in the sample (Islam, 1995). When using lagged dependent variables in traditional models, such as pooled OLS, fixed- or random-effects models, there is a substantial risk that these yield biased estimates due to correlation and endogeneity issues. Kiviet (1995) therefore proposed the use of a least squares dummy variable approach (LSDV) that has been corrected for bias. This has been found to be more efficient than the various instrumental variable (IV) and generalized method of moments (GMM) estimators, such as Arellano and Bond (1991) who adopt a two-step method in which lags of explanatory variables in levels are used as instruments. Moreover, the GMM estimators were originally designed for large cross-sectional units N and long time periods T. Kiviet (1995) however demonstrated that the bias-corrected LSDV approach has a relatively small variance compared to most IV and GMM estimators. In our case N is either 12 or 17 while T equals 22 or 32.

For the above reasons our dynamic panel data models are estimated using the bias-corrected LSDV approach. Specifically, we build on Bruno (2005a) in which the bias approximations are extended to accommodate unbalanced panels, and on Bruno (2005b) who introduces the routine *xtlsdvc* that implements this approach in the Stata statistical software. 200 bootstrap iterations were employed.

4. Data Sources, Definitions and Descriptive Statistics

The main data set consists of a balanced panel including 12 of the 15 first EU Member States during the period 1990–2012.[4] The early 1990s involved a number of important geopolitical changes, such as the reunification of Germany and the expansion of the EU. Sweden, Finland and Austria who all joined the EU in 1995 were not members from the starting year of the period. The early 1990s were also characterized by an increased focus on climate change, and

[4] These countries include Austria, Belgium, Denmark, Finland, France, Germany, Italy, Netherlands, Portugal, Spain, Sweden, and the United Kingdom (UK). Greece, Ireland and Luxembourg are not included due to a lack of data on renewable energy R&D expenditures prior to the year 2000.

many of the early support schemes to renewable energy were introduced (e.g., the German feed-in tariff for wind power). With the introduction of two renewable energy directives in 2001 and 2009, all EU Member States have implemented support schemes to promote the adoption of various renewable energy sources (e.g., feed-in tariffs, quota schemes, tendering procedures etc.). However, while this has led to some amount of policy convergence in terms of renewable energy shares and policy instrument choices (Strunz et al., 2017), EU Member States still have full discretion when it comes to deciding how much government expenditures should be spent on encouraging R&D in the renewable energy sector.

As was noted above, in order test the robustness of the empirical results we also extend the data set to include five OECD countries that are not EU Member States; these are Canada, Japan, Switzerland, Norway and the USA (see Models IV-VI). Moreover, for both country samples we also consider the results when relying on an extended time period, i.e., 1980-2012 (see Table A3 in Appendix A).

4.1 The Calculation of the R&D-based Knowledge Stock

The dependent variable, $\ln(y_{it}/y_{i,t-\tau})$, is the growth rate in the per capita knowledge stock of publicly funded renewable energy R&D,[5] and the initial (lagged) level of this stock is one of the independent variables. The data needed to calculate this stock in line with equation (1) were collected from the Energy Technology RD&D Statistics database of the International Energy Agency (IEA). These IEA data are known as possibly the best available data source of public R&D expenditures in the energy sector (Garrone and Grilli, 2010). They also permit us to distinguish between R&D support to renewable energy sources and other energy R&D (e.g., energy efficiency, nuclear, fossil fuels etc.). However, this does not mean that the data are free from problems (Bointner, 2014). For instance, some authors argue that the database represents an incomplete representation of public support to energy R&D (e.g., Arundel and Kemp, 2009). There are also issues with respect to the geographical coverage over time. For instance, Germany was reunified in 1991 but reports some missing data for the new *Bundesländer* (i.e., states formerly associated with the German Democratic Republic) prior to 1992. Also, all countries may not provide data on the R&D funded by regional governments (IEA, 2012).

[5] While the analysis in this paper focuses on the development of the R&D-based knowledge stock per capita, we also tested alternatives where the size of the stock (and its growth) was related to GDP unit as well as to total energy use. However, using these alternative specifications of the dependent variable generated similar results to those presented using the per capita approach.

Furthermore, in order to construct the knowledge stock variables, in the baseline case we assume a time lag of two years (x=2) and a depreciation rate of 10 percent (δ=0.10). Our choice of time lag is constrained by the limited data set. However, since Popp (2015) shows that the time lag between public R&D expenses and private energy patents can be extended, up to 5-6 years, we also consider an alternative estimation based on a five-year time lag (see Appendix A). Our choice of a ten percent knowledge depreciation rate builds on Griliches (1998) and Nordhaus (2002), and in part this reflects the relatively rapid development of renewable energy technology since the oil crises in the 1970s. Griliches (1998) suggests that an appropriate depreciation rate for private R&D spending would be higher, basically leaving hardly any of the R&D spent 10 years ago to the present day. Also the size of this parameter is, however, likely to be uncertain. For this reason we also employ alternative assumptions, and estimate models based on a 5 and 15 % depreciation rates, respectively (Appendix A).

The IEA provides public R&D data for renewable energy sources from the year 1974 and onwards. Although respective domestic R&D expenditures were low in this year, we need to account for the fact that there was some accumulation of public R&D spending also before 1974. In order to account for previous R&D expenditures an initial knowledge stock, K_0, is estimated as:

$$K_0 = \frac{R\&D_0}{g + \delta} \tag{5}$$

where $R\&D_0$ is the amount of public renewable energy R&D spending per capita in the first year available (1974), and g is the average geometric growth rate for each country´s R&D spending by country over the first ten-year period (e.g., Hall and Scobie, 2006; Madsen and Farhadi, 2016).

Figure 1 illustrates the results of the calculation of the public renewable energy R&D-based knowledge stock (per capita). The stock is reported for the time period 1990-2012 for the 12 EU Member States. It is evident from Figure 1 that in per capita terms the R&D-based knowledge stock differs across countries as well as over time. For some of the countries (e.g., Sweden) we see periods of decline, thus indicating that new spending on public R&D has not been able to offset the depreciation of the stock as well as any increases in the country's total population. Germany and Denmark represent the two countries that have had the highest knowledge stock per capita since 2000, in part reflecting their promotion of wind power and later on solar PV. Overall there appears to be an increased focus on government support of renewable energy R&D over time in most countries. This reflects in large parts a shift away from support to other energy sources (e.g., nuclear power). In total for our 12 EU countries, the public R&D budgets for renewables increased from 7 % of the total energy R&D expenses in 1980 to 25 % in 2012.

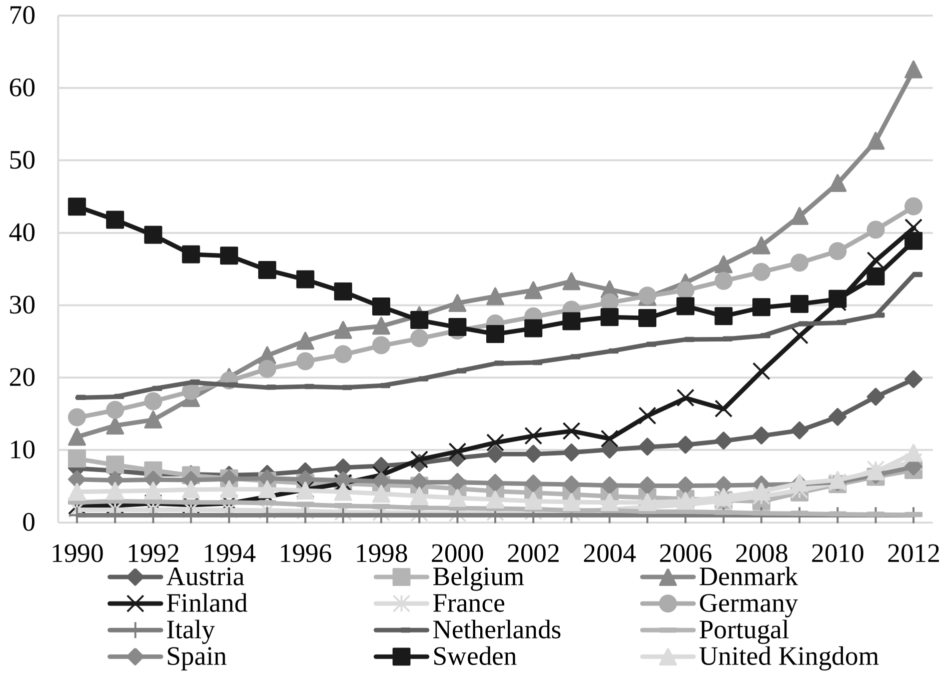

Figure 1: Renewable energy R&D support stock per capita, 1990-2012 (USD in 2014 prices and exchange rates).

Appendix B provides detailed information on how the selected countries prioritized among the different renewable energy sources: on average over the time period 2000-2012 (Figure B1) as well as in the single year 2012 (Figure B2). These figures show, for instance, that in the Nordic area (e.g., Finland and Sweden) a lion share of the R&D support has been spent on bioenergy, while Denmark and Germany have tended to prioritize wind power R&D. Solar PV tends to dominate public R&D support to renewables in southern Europe, e.g., in Italy.

4.2 The Independent Variables

Table 1 provides variable definitions and descriptive statistics for the per capita knowledge stock variables and the remaining independent variables used in the empirical investigation. The initial R&D-based knowledge stock enters the regression models in logarithmic form, but the descriptive statistics reported in Table 1 build on the original data. The real interest rate on government bonds (RIR_{it}) is used as a proxy for the opportunity cost of public R&D expenses. These rates were collected from the Statistical Data warehouse at European Central Bank (2016) and from the OECD statistical database (2016).

The variable addressing energy import dependence (EI_{it}) is defined as total primary energy use less domestic production, both measured in tons of oil equivalents. The information needed was obtained by examining the IEA's data series on total primary energy supply.[6] A negative value indicates that the country is a net exporter, and high positive values therefore suggest high energy import dependence. As was noted above, a country with a high level of energy imports is incentivized to invest in the development of renewables since this would reduce the country's exposure to international fuel price fluctuations and, possibly, supply shock interruptions caused by future political instability or resource constraints (e.g., Neuhoff, 2005; Rübbelke and Weiss, 2011).

Table 1: Variable Definitions and Descriptive Statistics

Variables	Definitions	Mean	S.D.	Min	Max
Dependent variable The growth rate in the knowledge stock of renewable energy R&D support per capita ($\ln(y_{it}/y_{i,t-\tau})$).	Knowledge stock calculated based on equation (1) and the parameter assumptions that are outlined in Section 4.1.	0.06	0.13	-0.10	0.99
Independent variables					
The initial public R&D-based stock (y_{it-1})	The one period lag of the knowledge stock, calculated based on equation (1) and the parameter assumptions that are outlined in Section 4.1.	12.13	1.34	8.15	15.45
Real interest rate (RIR_{it})	Rate-of-return in % on government bonds with 10-year maturity. Inflation adjusted	4.53	2.99	-2.77	16.75
Energy import dependence (EI_{it})	Energy use less production, both measured in tons of oil equivalents	9.36	152.87	-842.43	95.02
Electricity regulation (ER_{it})	The OECD PMR index of regulation in the electricity sector. Scaled between 6, the highest, and zero (0) the lowest.	4.01	1.78	0.87	6.02

[6] Energy use here refers to use of primary energy before transformation to other end-use fuels, which is equal to indigenous production plus imports and stock changes, minus exports and fuels supplied to ships and aircraft engaged in international transport.

Electricity regulation (ER_{it}) refers to the level of regulation of the sector in terms of public ownership, entry restrictions, vertical integration, price regulation of the wholesale market etc. We here employ OECD data on product market regulation (PMR) in the electricity sector. The electricity PMR contains annual data for several countries, and it ranges from 1 to 6. High values indicate the presence of a highly regulated sector while low values indicate liberalization. Since 1990 there has been a trend towards deregulation of electricity markets, and this has coincided with a significant decline in long-term R&D investment in the energy field (see also Jamasb and Pollitt, 2008).

5. Empirical Results

Table 2 presents the estimated coefficients for models I-VI, i.e., the models building on the time period 1990-2012, and where models I-III involve the EU 12 countries and models IV-VI the 17 OECD countries. For the EU 12 sample the results are overall robust and show a positive relationship between the initial levels of the R&D-based knowledge stock and the growth rate in this stock. This therefore indicates evidence of divergence across these EU countries in terms of public R&D knowledge build-up in the renewable energy sector. As was noted above, the presence of heterogeneous national preferences in combination with agglomeration effects may explain this result. Renewable energy industries tend to cluster in certain industries; this generates positive externalities (i.e., knowledge spillovers) due to geographical proximity (Head et al., 1995; Rosenthal and Strange, 2001). Governments are keen to support these industries, e.g., through public R&D support, as they may be viewed as essential vehicles for further economic growth and job creation.

The results also display that positive growth in the R&D-based knowledge stock is induced by higher energy import dependence. In other words, countries with high energy use levels and low levels of domestic production of energy generally have a stronger focus on public support to renewable energy R&D. However, we find no evidence of an interaction effect suggesting that the speed of β-divergence is affected by the magnitude of energy import dependence. In addition, in the EU 12 sample we find no statistically significant impact of changes in the real interest rate on the knowledge stock growth rate.

The results however illustrate a positive relationship between increases in electricity market regulations and the growth rate of the R&D-based knowledge stock. This effect is manifested in the interaction with the initial knowledge stock, i.e., the β_5 coefficient. For a given positive level of the knowledge stock, a more regulated electricity sector implies a higher growth rate in the stock made up of public expenditures to support renewable energy R&D. This result is consistent with previous research concluding that the deregulation of electricity markets has led to a decline in public energy R&D (e.g., Smith and Urpelainen, 2013). A higher degree of competition and less state control of operations will imply lower profit margins and less room for investments in long-term energy technology innovation.

Table 2: Conditional β-Convergence Model Results

Models	**I**	**II**	**III**	**IV**	**V**	**VI**
Coefficients	12 EU countries			17 OECD countries		
β_c Initial public R&D-based stock	0.394*** (0.068)	0.383*** (0.0685)	0.167** (0.065)	0.409*** (0.06)	0.409*** (0.0616)	0.083 (0.056)
β_1 Real interest rate	0.005 (0.003)	0.0058 (0.003)	0.0054 (0.003)	0.0053** (0.002)	0.0055** (0.002)	0.0056** (0.002)
β_2 Energy import dependence	0.0008** (0.0004)	0.0008** (0.0004)	0.0007* (0.0004)	0.0005*** (0.0001)	0.0006*** (0.00024)	0.0005*** (0.0001)
β_3 Electricity regulation	0.010 (0.007)	0.010 (0.00800)	0.011 (0.007)	0.012** (0.006)	0.012** (0.006)	0.012** (0.006)
β_4 Interaction – energy import dependence		0.0001 (0.001)			0.0002 (0.0002)	
β_5 Interaction – electricity regulation			0.068*** (0.019)			0.104*** (0.016)
Country dummies	Yes	Yes	Yes	Yes	Yes	Yes
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes
Number of Observations	252	252	252	362	362	362
Number of Countries	12	12	12	17	17	17
Number of Years	23	23	23	23	23	23
Iterations	200	200	200	200	200	200

Note: The standard errors are in parenthesis. Moreover, ***, ** and * denote statistical significance at the 1%, 5% and 10% levels respectively.

Furthermore, the model results also show that the higher the initial R&D-based knowledge stock, the higher the marginal impact of electricity regulation on the growth rate of this stock. Put differently, in countries that have invested a lot in public renewable energy R&D, a given move from a regulated to a less regulated electricity market would imply a larger decrease in the knowledge stock growth rate compared to a country with a less ambitious track record in terms of public R&D support. This also means, though, that the deregulation of European electricity markets over the last decades has helped slow down the speed of divergence in terms of the accumulation of government-funded R&D knowledge in the renewable energy field.

The results from models IV-VI show the corresponding results when the country sample is expanded, and it now also covers an additional five OECD countries that are not EU Member States. Table 2 illustrates that the results are overall robust. Also in this case there is evidence of divergence in terms of public R&D knowledge build-up in the renewable energy sector (with the exception of model VI where no statistically significant impact is reported). We also find positive relationships between both energy import dependence as well as electricity regulation on the one hand and the growth rate in the knowledge stock on the other. The electricity regulation effect is even more profound in the enlarged country sample, and also here we find evidence of an interaction with the initial level of the knowledge stock. The results from models IV-VI indicate a positive relationship between the real interest rate and the growth in the R&D-based knowledge stock; this is however unexpected since an increase in the opportunity cost of public R&D funds should imply that national governments would (ceteris paribus) be less willing to allocate funds to renewable energy R&D.

Appendix A contains a number of alternative model estimations testing whether the results are sensitive to different parameter assumptions and data samples. As was indicated above, there are uncertainties with respect to the construction of the R&D-based knowledge stock. *First*, while we assume a two-year time lag between public R&D expenditures and their addition to the domestic knowledge stock, Popp (2015) indicates that such lags may be more extended. For this reason we estimate six new models where this longer time lag has been employed to the stock. The results are displayed in Table A1 and they also indicate strong support for our finding of divergence in terms of public R&D knowledge build-up in the renewable energy field. In these estimations, though, there is only meagre evidence of a positive relationship between energy import dependence as well as electricity regulation on the one hand and growth in the R&D-based stock on the other. However, the results show the expected negative – and statistically significant – impacts of increases in the real interest rate.

Second, the size of the knowledge stock and any changes in it over time will also be affected by the assumed depreciation rate. Table A2 in Appendix A therefore reports results when the depreciation rate is assumed to be 5 and 15 %, respectively (in contrast to our base assumption of 10 %). These results are very similar to those reported in Table 2. For instance, there is clear evidence of divergence in all model specifications, and we find a positive and statistically significant impact of energy import dependence on the knowledge stock growth rate. These results also illustrate a positive relationship between electricity regulation and this growth rate, also here suggesting that the deregulation of the electricity markets has implied a slower speed of divergence.

Third and finally, Table A3 in Appendix A shows how our results in Table 2 are affected by expanding the data sample to cover the time period 1980-2012, i.e., also covering a period during which EU cohesion policies and renewable energy directives are likely to have had more modest influences on many of the countries in the sample. Also in this case there is strong evidence of divergence in terms of public R&D knowledge build-up in renewable energy technology. However, few of the other variables appear to have had any profound impact on the growth rate of the R&D-based knowledge stock, including energy import dependence and electricity regulation.

6. Concluding Remarks and Implications

This paper analysed the development of government support to renewable energy R&D across selected EU (and OECD) countries over time, and particular attention was devoted to the presence of conditional β-convergence. The empirical results suggested divergence in terms of public R&D-based knowledge build-up in the renewable energy sector, and these results were overall robust to various model specifications, variable constructions, and data samples. More pointedly phrased, there appears to be little reason to assume that public R&D-policies might converge without clear top-down signals for harmonization. Furthermore, the analysis showed that the deregulations of the European electricity markets have implied a lower speed of divergence in government support to renewable energy R&D.

How are we to interpret this overall divergence trend? To begin with, recall that, in general, convergence does not equate *good*, and divergence does not equate *bad*. While the empirical findings are consistent with free-riding behavior on the part of some EU Member States, they are also consistent with the presence of industrial policy motives and agglomeration effects. If ultimately driven by agglomeration benefits and heterogeneous policy preferences (i.e., the importance of domestic production, importance of regulating the power sector), divergence could appear economically preferable to convergence. Obviously, a comprehensive normative assessment is beyond the scope of the present paper. In any case, the above suggests that future research on public R&D support to environmental and green technology should in more detail address and study the complex – and sometimes conflicting – forces behind national governments' decisions to allocate funding to such R&D.

However, when we take the perspective of EU climate policy, there might be some reason for concern. With the finalization of the internal market being the main pillar of EU energy policy (one that gives the EU Commission substantial legal competences[7]), a hitherto neglected trade-off between this internal market agenda and climate policy comes into view: as deregulation lowers public R&D expenses, this might lead to convergence on a lower level of climate policy ambition.[8] Thus, underinvestment in public renewable R&D expenses could be an undesired side-effect of the internal market agenda. Such a trend would be amplified if the more ambitious countries suspect free-riding of laggards (no matter if it is actually free-riding that drives divergence). In the worst case, the transition to a zero-carbon energy system would become more cumbersome and more costly to achieve. As a remedy, international agreements on renewable energy R&D funding, i.e., analogous to internationally agreed emission targets for each country, might be contemplated. Such an agreement could, for instance, target an aggregate level of renewable energy R&D as a percentage increase from existing levels, and then impose a reasonable burden-sharing of R&D efforts across countries.

Then again, in the presence of strong green industrial policy motives, there is likely to be continued investment in public R&D support to renewable energy sources. Even if these efforts may be highly biased towards a few selected countries, there may be little concerns about free-riding and unfair burden-sharing already in a baseline scenario. In countries with high industrial policy motives, promoting renewable energy does not appear as a burden in the first place. In such cases the main challenges lie instead in designing institutional frameworks that can help counter the informational and political risks associated with green industrial policies (Rodrik, 2014); as a matter of fact, industrial policy motives are somewhat prominent within EU member states' energy policies, notably Germany (see Strunz et al., 2016).

In sum, the overall policy implication from the above analysis probably does not foster the case for harmonization and centralization within an "Energy Union" – unless free-riding-complaints should figure eminently in forthcoming climate and energy policy discussions.

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[7] This is exemplified by the EU Commission's „Guidelines on state aid for environmental protection and energy 2014-2020" (2014/C 200/01), which strongly impact on national renewable energy policies.

[8] More precisely, this may imply either slower divergence or convergence: the point is that reduced R&D efforts (particularly by forerunners) only insufficiently internalize spillover effects and do not correspond to the levels of public R&D support implied by the EU's climate pledges.

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Appendix A

Table A1: Conditional β-Convergence Model Results: 5-year Knowledge Stock Time Lag

Models	I (5-year lag)	II (5-year lag)	III (5-year lag)	IV (5-year lag)	V (5-year lag)	VI (5-year lag)
Coefficients	12 EU countries			17 OECD countries		
β_c Initial public R&D-based stock	0.447*** (0.047)	0.458*** (0.049)	0.451*** (0.046)	0.531*** (0.043)	0.533*** (0.044)	0.517*** (0.043)
β_1 Real interest rate	-0.007** (0.003)	-0.007** (0.003)	-0.008** (0.003)	-0.005*** (0.002)	-0.006*** (0.002)	-0.006*** (0.002)
β_2 Energy imports	0.0006** (0.0002)	0.0011** (0.0003)	0.0003 (0.0003)	-0.000 (0.00021)	-0.000 (0.0002)	-0.0001 (0.0002)
β_3 Electricity regulation	0.0027 (0.008)	0.0001 (0.009)	0.0019 (0.008)	-0.0013 (0.006)	-0.0018 (0.006)	-0.0021 (0.006)
β_4 Interaction – Energy import dependence		-0.000 (0.000)			-0.000 (0.000)	
β_5 Interaction – Electricity regulation			0.023 (0.016)			0.033* (0.018)
Country dummies	Yes	Yes	Yes	Yes	Yes	Yes
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes
Number of observations	252	252	252	362	362	362
Number of Countries	12	12	12	17	17	17
Number of Years	22	22	22	22	22	22
Iterations	200	200	200	200	200	200

Table A2: Conditional β-Convergence Model Results for the EU 12 Sample: 5 and 15 % Knowledge Stock Depreciation Rates

Models	I (5 %)	II (5 %)	III (5 %)	I (15 %)	II (15 %)	III (15 %)
Coefficients		12 EU countries			12 EU countries	
β_c Initial public R&D-based stock	0.432*** (0.06)	0.381*** (0.06)	0.151** (0.06)	0.338*** (0.07)	0.390*** (0.07)	0.173** (0.06)
β_1 Real interest rate	0.003 (0.002)	0.003 (0.002)	0.003 (0.002)	0.008* (0.004)	0.009* (0.005)	0.008* (0.004)
β_2 Energy imports	0.0006** (0.0003)	0.0006** (0.0003)	0.0005* (0.0003)	0.001* (0.0005)	0.001* (0.0006)	0.001 (0.0006)
β_3 Electricity regulation	0.007 (0.005)	0.007 (0.005)	0.007 (0.005)	0.014 (0.01)	0.013 (0.01)	0.015 (0.01)
β_4 Interaction – Energy import dependence		0.0007 (0.001)			-0.0009 (0.001)	
β_5 Interaction – Electricity regulation			0.062*** (0.013)			0.066** (0.028)
Country dummies	Yes	Yes	Yes	Yes	Yes	Yes
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes
Number of Observations	252	252	252	252	252	252
Number of Countries	12	12	12	12	12	12
Number of Years	22	22	22	22	22	22
Iterations	200	200	200	200	200	200

Table A3: Conditional β-Convergence Model Results: 1980-2012 Time Period

Models	I (1980-2012)	II (1980-2012)	III (1980-2012)	I (1980-2012)	II (1980-2012)	III (1980-2012)
Coefficients	12 EU countries			12 EU countries		
β_c Lagged dependent variable	0.463***	0.377***	0.429***	0.488***	0.483***	0.332***
	(0.057)	(0.061)	(0.059)	(0.047)	(0.047)	(0.048)
β_1 Real interest rate	0.004	0.004	0.004	0.004	0.003	0.004*
	(0.003)	(0.003)	(0.003)	(0.002)	(0.002)	(0.002)
β_2 Energy imports	0.0001	0.000	0.00012	0.000	0.000	0.000
	(0.0002)	(0.0002)	(0.0002)	(0.000)	(0.000)	(0.000)
β_3 Electricity regulation	0.003	0.005	0.003	0.003	0.003	0.002
	(0.006)	(0.006)	(0.006)	(0.005)	(0.005)	(0.005)
β_4 Interaction – Energy import dependence		0.0014*			-0.0001	
		(0.0007)			(0.0001)	
β_5 Interaction – Electricity regulation			0.008			0.039***
			(0.011)			(0.01)
Country dummies	Yes	Yes	Yes	Yes	Yes	Yes
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes
Number of Observations	372	372	372	516	516	516
Number of Countries	12	12	12	17	17	17
Number of Years	32	32	32	32	32	32
Iterations	200	200	200	200	200	200

Note: The standard errors are in parenthesis. ***, ** and * denote 1%, 5% and 10% levels respectively.

Appendix B

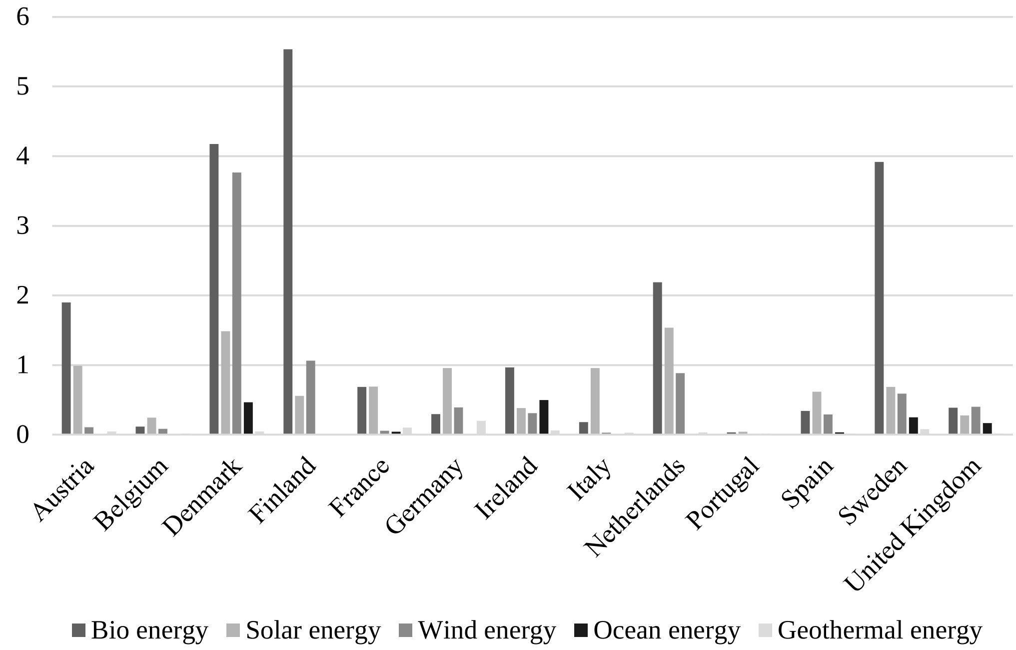

Figure B1: Per capita public R&D spending, average over the period 2000-2012 (USD in 2014 prices and exchange rates). Source: IEA Energy Technology RD&D Statistics database.

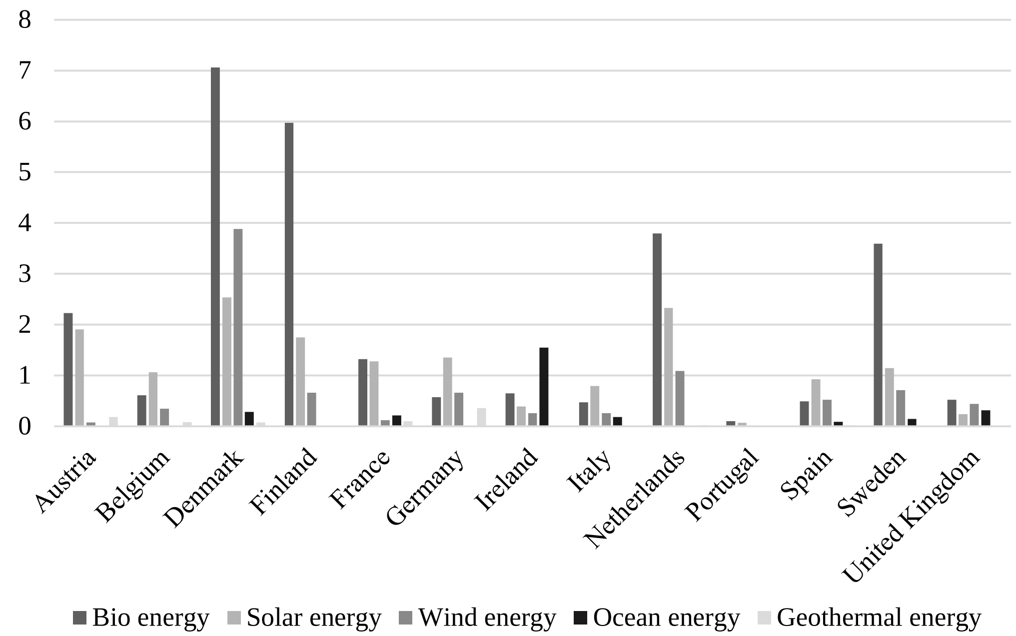

Figure B2: Per capita public R&D spending in 2012 (USD in 2014 prices and exchange rates). Source: IEA Energy Technology RD&D Statistics database.