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REGULAR ARTICLE

Public policies for a sustainable energy sector: regulation, diversity and fostering of innovation

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Abstract Many industrialized countries have introduced environmental policy measures in order to reduce negative externalities linked to economic activities. These policy actions produce different effects on the economic system depending on the regulatory tools adopted and the specific objective of public intervention. The impact on innovation is particularly difficult to predict, especially with regard to the direction of technological change. As a case study, we have chosen the energy sector, in which the strong interrelations between socio-economic and technological dimensions may exacerbate the negative consequences of implementing conflicting policies. The aim of this paper is to show how the lack of strong coordination between different public policies implemented in the energy sector may lead to an incoherent policy mix with negative effects on the development and diffusion of environmentally-friendly energy technologies. We have adopted a gravity equation model based on bilateral export flows of technologies for production and consumption of renewable energies and energy-saving technologies for OECD countries. Our key findings show that alternative measures of public support in the energy sector have been producing contrasting effects on the international competitiveness of energy technologies.

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1 Introduction

Over the last decades, many industrialized countries have introduced several policy measures in order to reduce the environmental impact of economic activities. The effects produced by these policy actions on the economic system are difficult to predict and depend on the different regulatory tools adopted and the specific objective of the public intervention. The impact assessment of environmental regulations on compliance innovation is particularly difficult, especially with regard to the direction of technological change.

Many empirical studies have analyzed the effects that environmental polices produce on innovation and competitiveness by adopting alternative hypotheses and different empirical models. Two main streams of literature can be identified in this field. The first is oriented toward the investigation of the effects of environmental regulation on international competitiveness and, indirectly, on a possible induced technical change, whereas the second one is specifically devoted to the quantification of the direct impacts on innovation performance (see Kemp 2000 for an extensive review). Such contributions address this issue through either firm level or country level analyses.

In the literature, more stringent environmental regulations has been traditionally seen as potentially harmful to the productivity and competitiveness of the national industry, since they lead to higher costs faced by firms (Antweiler et al. 2001; Bommer 1999; Brock and Taylor 2005; Copeland and Taylor 2003, 2004; Levinson and Taylor 2004). However, building on seminal contributions by Schumpeter (1947) on the *creative response* of economies in adapting to changes in conditions and on the extensive literature on the induced-innovation hypothesis first advanced by Hicks (1932), it has been argued that the introduction of severe environmental regulations can stimulate green innovations and increase the export competitiveness of environmental technologies (Porter and van der Linde 1995). The argument, in its strongest formulation, is that the introduction of a new regulation pushes firms to innovate, so that the whole economy and hence its competitiveness is benefited (Porter and van der Linde 1995). In this paper, we refer to a *narrow* version of the Porter hypothesis as defined by Jaffe and Palmer (1997, p. 610), which they summarize in this way: "if one country adopts stricter environmental regulations than its competitors, the resulting increase in innovation will enable that country to become a net exporter of the newly developed environmental technologies".[1]

[1] We would like to thank one anonymous referee for helping us to clarify this point.

The empirical studies on the Porter hypothesis have not been completely successful in finding robust support for this argument. Moreover, they are mainly based on specific industries rather than broad sectors or economic systems (Albrecht 1998; Murty and Kumar 2003; Wagner 2003, 2006). Analogously, the main contributions addressing the impact of environmental regulation on technological innovation using patent data (e.g., Jaffe and Palmer 1997; Lanjouw and Mody 1996; Popp 2002) have not found unanimously robust evidence on the effect of stringency of environmental policy expressed in terms of the compliance costs paid by private firms (pollution abatement and control expenditures). Nevertheless, more recently, there has been increasing empirical evidence to support the argument that stringent environmental policies lead to technological innovation in general (Hascic et al. 2008), and specifically in the energy sector (Markard and Wirth 2008; Walz et al. 2008). In the same venue, relevant results have been provided by Johnstone et al. (2008) specifically for the renewable energy sector where a set of alternative policy types (e.g., R&D, investment incentives, tax and tariff incentives, voluntary programmes) has been used as covariates to explain the innovation capacity (quantified by the number of patent applications) of OECD countries in the wind, solar, ocean, biomass, and waste energies.

While there is still debate on the relevance of the potential benefits of environmental regulation for technological change and market competitiveness (Jaffe et al. 1995, 2003, 2005), there is an increasing consensus that technology responses are not a mere reaction to regulatory pressure (Kemp 1997, 2000). The introduction of a new environmental regulation may well represent a stimulus for new research because it affects market condition by opening up new profit opportunities, but innovation systems should be equipped with adequate scientific and technological knowledge so that the economy can respond creatively to changes in external constraints (Antonelli 2008; Costantini and Crespi 2008a, b; but also Dosi et al. 1988; Rennings 2000; Fagerberg et al. 2005; Antonelli and Quatraro 2010). In this respect, the use of an appropriate mix of technology policies and environmental policies emerges as a crucial factor in directing economic systems towards sustainable paths of economic growth (Kemp 2000; van den Bergh and Kemp 2006).

The aim of this paper is to investigate this issue further, showing how the lack of strong coordination between public policies for environmental purposes may lead to an incoherent policy mix with contrasting forces and impacts, producing a reduced overall benefit in terms of sustainable development. In order to do this, we will focus our analysis on the energy sector since, as we will show in the next paragraph, it represents a case in which the strong interrelations between the socio-economic and technological dimensions may exacerbate the negative consequences of implementing conflicting policies.

In particular, two specific issues related to the energy sector are addressed in the analysis: (1) the impact on the export dynamics of energy technologies generated by broad environmental regulation policy and specific innovation policies; (2) the conflicting impacts on export competitiveness of energy technologies of different policies due to the distortive potential of the enforced policy mix.

The rest of the paper is structured as follows: Section 2 provides the background framework for the empirical analysis, Section 3 describes the econometric strategy, while Section 4 gives details on the dataset, Section 5 reports the main empirical results, and Section 6 summarizes the main conclusions from the analysis and provides some policy recommendations.

2 Analytical background

Recently, a significant body of literature has emphasized the shortcomings of the standard normative economic theory of environmental policy, as developed in the seminal work of Baumol and Oates (1988), in explaining the patterns of environmental innovation and, above all, in guiding policy-makers in the setting of an optimal policy mix.

In particular, Rammel and van den Bergh (2003) emphasized that traditional economic approaches are inappropriate for dealing with the dynamics of structural and adaptive changes in economic systems. This is in line with a growing body of literature analyzing the potential of evolutionary economics to explain sustainable development and environmental policies (Kemp 1997; Norgaard 1994; van den Bergh and Gowdy 2000; van den Bergh 2003; van den Bergh et al. 2007; Nill and Kemp 2009). According to these contributions, an evolutionary foundation of sustainable development policies should account for concepts such as adaptive behaviors, evolutionary potential, diversity, path-dependence and lock-in. Within this framework of analysis, the notion of *transition policy* has emerged which goes beyond the traditional policy approaches in the fields of environment, energy and technology, encompassing elements of all these policy fields, involving technology policy, development of knowledge at individual and public levels, behavioral change and alterations in organizations (including networks) as well as institutions (including markets) (Kemp 1997; Rotmans et al. 2001; van den Bergh et al. 2007). *Transition policy* can be defined as the stimulation and management of learning processes, involving different actors and multiple dimensions, preserving the variety of policy and technological options and motivated by a long-term policy objective (Rotmans et al. 2001). In this evolutionary context, policy and institutions appear different from the view point of traditional economics (Metcalfe 1995). A key difference is represented by the emphasis given to diversity as opposed to efficiency. The diversity of options is regarded in this framework as essential for creatively adapting to changing circumstances and preferences through selection processes and innovations. As a consequence, public policies must be directed not towards predetermined results but towards improving the way in which variety selection and innovation processes operate (Metcalfe 1998). Consequently, policies and governments can try to influence or even mould transitions in systems of innovation, so that a credible *transition policy* seeks the integration of three main specific aspects: environmental regulation, unlocking policy preserving diversity and fostering of innovations (van den Bergh et al. 2007).

The notion of transition policy is of particular relevance in the energy sector.

First, there is a strong need in the energy system for regulatory strategies to force technological regime shifts. Time-scales of half a century are in fact estimated for major changes in this sector and this justifies the importance of analyzing transition and learning processes (Rennings 2000).

Second, in energy and transport systems, a carbon lock-in seems to be particularly difficult to discard, where progress in environmental-friendly technologies should be supplemented by changes in consumer behavior and the institutional framework (Unruh 2000, 2002). In the energy sector, network economies emerge due to the strong interrelations between technological systems and users, thus producing a continued refinement of the dominant design which can define a technological trajectory typically affected by lock-in and path-dependence effects (Unruh 2000). An example of an unsustainable system, fossil-based energy supply, is particularly interesting for our purpose. Old and recent attempts to produce substantial changes in consumption and production technology patterns have met strong resistance in agent behaviors, particularly in socio-economic systems with a uniform and widely diffused dominant design. Strategies aimed at creating a diversity of alternative options increase the possibility of future sustainable changes only if a transition policy framework is followed.

Third, the energy sector can be interpreted as a good example of a complex adaptive system (Mayumi and Giampietro 2001). Since every successful adaptation is only a temporary solution to changing selective conditions, maintained diversity allows for a repertoire of alternative options and increases the possibility that altered conditions can be successfully met through pre-adaptations and further evolution. The existing trade-off between efficiency and diversity in the energy sector (which is one of the major causes of path dependence and lock-in), can be explained by the fact that energy appraisals are pervasive and diffused and an optimal policy mix is heavily dependent on specific circumstances such as natural resources availability, consumer behavior, productive structure and others. The diffusion of carbon-free energy forms and energy-saving technologies is a typical example of the necessary coexistence of alternative solutions to fossil fuel energies. Energy is used by different agents (consumers and producers) at different scales (from micro to large plants) and in different socio-economic systems. Flexibility seems to be the only response to such a complexity.

These characteristics of the energy sector explain the existence of several different public policies that aim to escape the carbon lock-in. Nonetheless, in the absence of strong coordination between all public policies implemented in the energy sector, the final outcome could be a non-optimal policy mix with contrasting forces and impacts. Environmental policies can in fact produce transitional conflicting results and this is exactly the case for public support for biofuels, as we will show in our empirical investigations. Different policies produce different effects on the direction of technological change since, in some cases, they act in favor of a specific technological path in new energy technologies, limiting the pace of innovation and the diffusion of alternative technologies. This is particularly true when we consider the complex available set of technological and policy choices to cope with climate change and energy consumption.

The low coordination in energy policies has been a common trend in industrialized countries as a consequence of the adoption of a set of multiple niche strategies regarding different economic sectors in the absence of a coherent transition policy framework. Even if these strategies have been positively gauged by the new strategic niche management approach (see among others Kemp et al. 1998; Hoogma et al. 2002; Nill and Kemp 2009), the simultaneous adoption of several niche strategies in the same sector could lead to public support policies with conflicting effects.

A further complexity comes from the fact that the same policy action can be used for different purposes, thus increasing uncertainty in the end. This is evident when energy policies claim to pursue a reduction in greenhouse gas emissions and an improvement in security of energy supply (Costantini et al. 2007). This double outcome should be found in relation to policies supporting both energy efficiency and the production of renewable energy.

A more evident conflict should emerge when existing (scarce) resources have to be allocated to different purposes. If the energy strategy of one country is more favorable to the development of energy-saving technologies, R&D efforts in this field can crowd out resources from the investments in renewable energy sources, and vice versa.[2] Moreover, to the extent that energy conservation is more successful, the transition to renewable energy sources will be slower, since energy conservation will reduce the urgency for a shift towards a system based on sustainable energy sources (van den Bergh et al. 2007, p. 58). Finally, the deployment of renewable energy technologies, which are characterized by high unit costs of installation and exploitation, involves vast investment in R&D activities and supporting infrastructures in the absence of which renewable technologies have little chance of becoming competitive. However, entrepreneurs have little incentive to divert finance towards radical innovation activities as long as there are opportunities to acquire rents from incremental improvements and the recombination of existing (mature) technologies. The crucial question is, therefore, how many scarce resources should be diverted from other energy technologies (including energy

[2]On 23 January 2008, the European Commission put forward an integrated proposal for Climate Action, including a directive that sets an overall binding target for the European Union of 20% renewable energy by 2020 and a 10% minimum target for the market share of biofuels by 2020, to be observed by all Member States. Moreover, the Commission declared that further efforts to improve energy efficiency are required, reducing energy consumption by 20% by 2020. As stated in the document, the EU goal of saving 20% of energy consumption by 2020 through energy efficiency is a crucial part of the European energy and climate policy because it is one of the key ways in which CO_2 emission savings can be made. This is a clear example of a multiple set of policies which could lead to conflicting goals.

efficiency) towards renewable technologies while ensuring security of energy supply (Safarzynska and van den Bergh 2008).[3]

Another relevant example of potentially contrasting effects of policy actions is represented by biofuels. In general, when environmental disutilities arise from a locked-in technological system, the solutions sought are those that minimize changes to the system or leave the overall infrastructural system unaltered. This partly explains the efforts to expand the biofuel market as a non-radical solution to the carbon lock-in. The diffusion of biofuels blended with fossil fuel will help to use the existing network, while minimizing the financial and psychological costs of a transition to completely different transport systems. In this sense, it is also easier to justify the huge costs associated with biofuels production in industrialized countries where biofuel marginal production costs are somewhat higher than fossil fuel production costs (Schmidhuber 2006, among others). In this case, higher production costs should compensate for those financial and psychological costs that accompany a radical change in the technological regime of the transport sector.

Moreover, for policy makers constrained by a carbon lock-in but forced by the Kyoto Protocol to provide incentives for carbon-saving alternatives, niches become an attractive policy target. As markets grow, scale effects can substantially improve technology, leading to big gains (Unruh 2002). This is exactly the justification given to first-generation biofuels, which is based on the idea that the market must be created even if it is not environmentally and economically sustainable because scale effects will lead to the discovery of new (second and third-generation) technologies for producing biofuels that are more efficient and less harmful to eco-systems.

However, the creation of a protected niche such as the biofuel market in order to escape from the fossil-based dominant fuel system could be counterproductive if it diverts resources from the other new energy technologies, thus reducing the portfolio investment in different alternative solutions. This negative result rests on two characteristics of the biofuels sector: the agricultural lobbies are strong enough in advanced economies to determine another lock-in situation with biofuels as the dominant but not the best environmentally-friendly design, and blending biofuels with fossil fuels represents a risk minimizing solution in terms of required investments for the adaptation of existing infrastructures (rather than a radical change in the entire distribution framework).[4] In this respect, while biofuel production seems to be an appealing sector to solve problems both for energy security and climate change, it should be taken into account that—mainly because of pressures by agricultural lobbies in industrialized countries—it represents a sector in which subsidies are pervasive and extensive (Costantini et al. 2010). This has important implications in terms of the cost effectiveness of this instrument

[3]This aspect will be specifically addressed in the empirical section of the paper.

[4]The adaptation process for biofuels with blending shares is quite similar to the substitution between leaded and unleaded gasoline, as described in Schwoon (2006).

and the achievement of energy and environmental goals. As biofuels are just one of the existing alternative technologies currently available for addressing energy and environmental goals, the huge bulk represented by biofuel support policies may not be neutral in terms of technical progress generation in the renewables and energy-saving technologies. Such strong orientation of the policy framework can indeed produce serious consequences in terms of reduced variety of alternative technologies, leading to possible lock-in effect in inferior technologies such as those for the production of first generation biofuels.

Following this line of reasoning, in the empirical analysis, we will provide evidence on the relevance of the three dimensions outlined above as characterizing a transition policy framework that is environmental regulation, unlocking policies preserving diversity and fostering of innovations. We claim that, while environmental regulation can, in general, produce positive effects on competitiveness via inducement effects on innovation, a strongly oriented policy framework (as in the case of energy policies dominated by the public support for biofuels) has the potential to direct technological change on specific paths. This has to be taken into account when designing public policies, since it may imply a potential failure in the objective of preserving diversity in alternative technologies. Finally, we will try to assess the relevance of the third dimension relative to the fostering of innovations since, as suggested in previous studies (Costantini and Crespi 2008a, b), we believe that environmental policies and technology policies should be integrated in order to produce a significant impact on technological competitiveness in the energy sector.

For the purpose of our analysis, we have not adopted a direct innovation approach (as, for instance, in the patent count analysis developed by Hascic et al. 2008, and Johnstone et al. 2010), but we have chosen a gravity equation framework drawn from the international economics literature, since it constitutes a theoretically and statistically robust basis for analyzing the impact of public policies on environmental technologies (Costantini and Crespi 2008a, b). Moreover, there are two specific reasons for this choice. The first is that public support policies for production and consumption of biofuels have been introduced very recently, not before the year 2000. If we had adopted the patent count methodology developed by Hascic et al. (2008) and Johnstone et al. (2008), we would have been forced to build a dataset for a longer time period in order to expand the number of observations (as, for instance, from 1985, when data on environmental expenditures were provided) and would have lost the statistical robustness of our covariates related to biofuel policies.

Second, the final scope of our paper is to issue some policy advice related to the capacity of environmental policies to reinforce international competitiveness, as claimed by the recent revision of the Lisbon Agenda for the EU in which sustainability goals were addressed as an example of win–win policies that produce environmental protection and economic development. If the effects related to public support policies related to biofuels divert investments and reduce competitiveness of energy-saving and renewable energy technologies, this could imply a noticeable conflict between policy actions, especially in the European Union.

We are conscious that working at national rather than at firm level strongly reduces the ability to understand specific agent behavior. Nonetheless, it is widely accepted that national systems of innovation have emerged as a proper unit of analysis (Freeman 1987; Lundvall 1988; Nelson 1993) which is particularly appropriate for studies on environmental technologies where, as we try to demonstrate, the combination of domestic environmental regulation and national innovation policies can play a significant role.

3 Econometric strategy

Gravity models are used for a number of different purposes, ranging from a traditional assessment of trade potentials associated with regional or global trade agreements to more specific studies oriented towards the analysis of the existence of trade creation or diversion related to the stringency of domestic environmental regulation. A number of econometric studies (Ederington and Minier 2003; Grether and De Melo 2003; Harris et al. 2002; Jug and Mirza 2005; Levinson and Taylor 2004; Mantovani and Vancauteren 2008) suggest that stringent domestic environmental regulations have a negative effect on total trade, giving empirical evidence of the existence of a pollution haven hypothesis.

By contrast, other studies have shown that strict environmental regulations do not have a univocal (negative) impact on international competitiveness (Mulatu et al. 2004; van Beers and van den Bergh 2003). Moreover, when the narrow version of the Porter hypothesis is investigated (Jaffe et al. 2003; Lanoie et al. 2007), a gravity model applied to specific sectors, such as environmental technologies, gives opposite results, affirming the positive role of domestic regulation in inducing firms to be more competitive in international markets (Costantini and Crespi 2008a, b).

Here we have adopted a gravity equation model based on bilateral export flows of technologies for the production of renewable energies and energy efficiency. The model used in this context is in line with many other empirical studies which focus on the effects of environmental regulation on trade flows, and it allows two major achievements to be made.

The first is that this methodology allows an empirical model to be built by using data for several countries and many years and for specific sectoral environmental policies, whereas most previous empirical studies on innovation and adoption of environmental technologies have focused on one single country.

Second, by using a gravity equation, the role of distinct environmental policies on the international competitiveness of environmental-friendly energy technologies can be investigated. Since export flows could be considered a measure of the competition strength at international level (in the form of comparative advantages), the gravity model can therefore be used to understand whether different public environmental regulation policies have unidirectional effects on the competitiveness of new energy technologies. If coexistent policies have contrasting effects on the dynamic of competitiveness, this should be interpreted as a clear sign of a non-optimal policy mix.

The first theoretical explanation of a gravity model has shown that the deterministic gravity equation can be derived from a trade-share-expenditure system model (Anderson 1979). The basic empirical formulation explaining bilateral trade flows between countries in a panel context takes the general form of:

$$X_{ijt} = e^{(\alpha_{it}+\delta_{jt}+\tau_{ijt}+\gamma D_{ij})} G_{ij}^{\beta_0} Y_{it}^{\beta_1} Y_{jt}^{\beta_2} Z_{it}^{\beta_3} Z_{jt}^{\beta_4} T_{ijt}^{\beta_5} \tag{1}$$

where X_{ijt} is the trade flow from origin i to destination j at time $t = 1, \ldots, T$, for N country pairs. α_{jt} and δ_{jt} represent the country specific time-variant effects, for reporters and partners respectively, whereas τ_{ijt} represents country-pair time-variant effects. D_{ij} stands for all possible dummy variables representing for instance contiguity, common language or free trade agreement effect, while G_{ij} represents the geographical distance between trading partners. Y_{it} and Y_{jt} are the relevant economic sizes of the two locations measured as the gross domestic product and/or the population of the two partners. Z_{it} and Z_{jt} are all other explanatory variables, such as the role of specific policies and market conditions.[5]

In the estimation of the gravity equation, the main problem is to take into account the unobservable multilateral resistance factors implied by the theory. The literature proposes three different approaches: the use of a price index to measure the price effects in the gravity equation, as in Baier and Bergstrand (2001), the use of non-linear least squares to solve a system of simultaneous equations, as proposed in Anderson and van Wincoop (2003), and, finally, the representation of multilateral resistance terms with country-pair time-variant effects, as in Baldwin and Taglioni (2006). As shown by Feenstra (2002), only the last two approaches lead to consistent estimates. However, the former of these is only applicable to cross-section data, thus causing a loss in the capacity to fully explain the dynamics of trade patterns (Baldwin and Taglioni 2006). Consequently, the use of a fixed effects estimator is preferable, allowing any other unobservable variables omitted in the trade costs component to be swept out. This choice requires Eq. 1 to be estimated in its log-linear form:

$$\begin{aligned} \ln\left(X_{ijt}\right) = {} & \alpha_{it} + \delta_{jt} + \tau_{ijt} + \gamma D_{ij} + \beta_0 \ln\left(G_{ij}\right) + \beta_1 \ln\left(Y_{it}\right) + \beta_2 \ln\left(Y_{jt}\right) \\ & + \beta_3 \ln\left(Z_{it}\right) + \beta_4 \ln\left(Z_{jt}\right) + \varepsilon_{ijt} \end{aligned} \tag{2}$$

This log-linear transformation allows considering the MRTs represented by exporting and importing countries' effects (respectively α_{it} and δ_{jt}) and a

[5]Four points highlight the importance of the resistance term in trade flows: (1) the existence of transport costs; (2) the time elapsed during shipment, mainly for perishable goods; (3) the production costs related to the synchronization of multiple inputs in the production process; (4) the increase with distance of communication and transaction costs.

country-pair time-variant trend variable, calculated as the interaction between temporal trends and fixed effects for country pairs (τ_{ijt}).

When using Eq. 2, the log-linear transformation leads to some problems that need to be solved. The very first issue is how to treat the dependent variable related to bilateral trade flows when there are several zero trade flow values. When such zero trade flows are considered in a log-linear form, they automatically disappear from the dataset. Among the alternative solutions proposed within the recent literature,[6] we have adopted the approach where the dependent variable is expressed as $ln(1 + X_{ijt})$, where X_{ijt} is the value of bilateral trade flows and the constant elasticity relationship is preserved (Martin and Pham 2008).[7] We are aware that this method may imply some biased results for the border effect caused by the role of firm heterogeneity in explaining the decision to trade with a specific partner, as recently emphasized by Helpman et al. (2008). Nonetheless, this bias tends to disappear when trade flows under investigation are related to narrowly defined sectors, as the existence of zero trade flows are often randomly distributed and less persistent over time with respect to a broader sector-based or total trade flows estimation.

There are some contributions suggesting to treat persistency over time with dynamic panel estimators (Bun and Klaassen 2002), when autocorrelation of the residual term is a concern. Relying on the fact that a Wooldridge test on our dependent variables accepts the null hypothesis of absence of autocorrelation, we have excluded the necessity to specifically treat time persistency with dynamic estimators and lagged dependent variables.

In the same venue as for trade flows, using the log-linearization of Eq. 2 may reduce observations when there are explanatory variables with recurrent zero values as for our tariffs and policies variables. In order to maintain the number of observations, we have replaced zeros with ones also for our covariates, as suggested by Nahuis (2004).

Finally, since the gravity equation is derived as a reduced form model, correlation rather than causation can be estimated. This specific issue has been addressed both in the standard gravity literature for trade policy (Baier and Bergstrand 2007) and in the pollution haven applications (Mantovani and Vancauteren 2008), where the proposed solution is to use an instrumental variable estimator. According to this literature, we have adopted an econometric strategy based on proper instrumental variables in order to control for possible endogeneity problems. In particular, our main concern was with

[6] For extensive discussions on this issue, see Olper and Raimondi (2008), Santos Silva and Tenreyro (2006) and Westerlund and Wilhelmsson (2009).

[7] When replacing zeroes with ones in a regression, care must be taken that units are chosen appropriately. The key is to make certain that, whatever the units of measure, the equivalent of one is added so that the log–linear transformation preserves the variance in the original data. In order to check for robustness of our results, we have compared our main model with estimations from a Heckman two-stage procedure. Our findings are consistent and robust in respect of treating zero flows in a probit equation.

the possible endogeneity of regulation variables, since environmental and energy regulation may be strictly related to the present state of technology. Consequently, we adopted a 2SLS estimator, where environmental and energy policies and public R&D energy expenditures are considered endogenous. The instruments adopted are chosen with the aid of innovation literature in the energy sector, as energy price and per capita energy consumption (Adeyemi and Hunt 2007; Johnstone et al. 2010; Newell et al. 1999; Popp 2002, 2006).

4 Dataset description

The exporting countries for this analysis (our *i* countries in the gravity equation) are 20 OECD countries: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Japan, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, the United Kingdom and the United States. The sample for *j* importing countries includes 148 countries (including OECD countries), and the time period analyzed goes from 1996 to 2006. The full sample therefore covers a total of 32,560 observations ($= 20 \times 148 \times 11$), of which 28,160 ($= 20 \times 128 \times 11$) are bilateral cross-border observations and 4,400 ($= 20 \times 20 \times 11$) are intra-country trade observations (all equal to zero).

We have adopted a log-linear formulation for the gravity equation in a panel context described by the following equation:

$$\ln \mathbf{ENEXP}_{ijt} = \alpha_{it} + \delta_{jt} + \tau_{ijt} + \beta_1 \ln \mathbf{GRAV}_{ijt} + \beta_2 \ln \mathbf{REG}_{it} + \beta_3 \ln \mathbf{BIOF}_{it} + \beta_4 \ln \mathbf{RDENE}_{it} + \beta_5 \mathbf{DUMMIES}_{ijt} + \varepsilon_{ijt} \tag{3}$$

where MRTs effects are given by α_{it} and δ_{jt} and the country-pair time trend is captured by τ_{ijt}.

The vector of dependent variables collects the bilateral export flows from country *i* to country *j* at time *t* of three different aggregations: (1) technologies for renewable energies $RENWEXP_{ijt}$with the exclusion of those related to biofuels; (2) technologies for energy-saving $ENSAVEXP_{ijt}$; (3) the sum of the two previous variables $ENEXP_{ijt}$. All data for the export flows are extracted from the COMTRADE database (UNCTAD) based on the Harmonised Commodity Description and Coding System (HS 1996). The HS product codes related to technologies for renewable energies and energy efficiency are defined by Costantini and Crespi (2008a, b) by selecting the codes explicitly associated with technologies for producing renewable energies and energy-saving from the classification of environmental goods and services proposed by OECD (Steenblik 2005), with the help of a specific study on European trade flows of energy technologies provided by the Italian Research Institute for New Technologies, Energy and the Environment (ENEA 2007).

The variables included as independent covariates are aggregated into five groups, as reported in Table 1. This choice is functional for the interpretation of the econometric results focusing on different aspects of our framework and evaluating the role of all the drivers here considered, separately and together.

Table 1 Definition of variables

Variable[a]	Definition	Source
Dependent variables		
$ENEXP_{ijt}$	Total bilateral export flows in renewable energies and energy-saving technologies (constant 2000$ PPP) from countries i to countries j	UNCTAD-COMTRADE
$RENWEXP_{ijt}$	Bilateral export flows in renewable energies technologies (constant 2000$ PPP) from countries i to countries j	
$ENEFFEXP_{ijt}$	Bilateral export flows in energy-saving technologies (at constant 2000$ PPP) from countries i to countries j	
Standard gravity (GRAV)		
$GDP_{i,j,t}$	Natural logarithm of GDP (constant 2000$ PPP) country i and j	World Bank (2007)
$POP_{i,j,t}$	Natural logarithm of total population of country i and j	
$LAND_j$	Natural logarithm of land area of country j (sq. km)	
$DIST_{ij}$	Bilateral geographic distances	CEPII (2006)
COL_{ij}	Existence of colonial relationships between country i and j (dummy variable)	
$CONT_{ij}$	Geographic contiguity between country i and j (dummy variable)	
Environmental and energy regulation (REG)		
$ENVREG_{it}$	Sum of public and private costs for environmental protection expressed as % of GDP	OECD, EUROSTAT (2006)
$POLRENW_{it}$	Number of policy actions promoting renewable energy sources (solar, solar PV, wind, geothermal, etc.)	IEA/JRC Global Renewable Energy Policies and Measures Database
$POLENEFF_{it}$	Number of policy actions promoting energy efficiency (R&D, incentives, subsidies, education, etc.)	
Public support for biofuels (BIOF)		
$AHSBF_{it}$	Applied MFN tariff ad valorem for biofuels, weighted with import flows (%)	UNCTAD-TRAINS
$MANDBF_{it}$	Fuel mandate, targets of blending shares of total consumption (%)	GSI
$EXCBF_{it}$	Value of excise tax reductions for bioethanol and biodiesel (US$ per litre of biofuel)	OECD (2008)
$POLICYBF_{it}$	Arithmetic mean of AHSBF, MANDBF, and EXCBF (%)	
Public support to RD in the energy sector (RDENE)		
$RDENE_{it}$	Ratio of public R&D expenditure in the energy sector on total R&D (%)	OECD-IEA

Table 1 (continued)

Variable[a]	Definition	Source
$RDENEFF_{it}$	Ratio of public R&D expenditure in energy efficiency on public R&D expenditure in the energy sector (%)	
$RDRENW_{it}$	Ratio of public R&D expenditure in renewable energies (excluding biomass) on public R&D expenditure in the energy sector (%)	

[a]Symbols for the identification of countries and time period must be interpreted as follows: *ijt* represents the bilateral interaction between exporting and importing countries with a temporal dimension, *ij* represents the bilateral interaction between exporting and importing countries without a temporal dimension, *i*, *j*, *t* represents the value of the variable for country *i* and *j* respectively, with a temporal dimension, *it* represents the value of the variable for country *i* with a temporal dimension

The first group (*GRAV*) collects the variables included in a standard gravity equation model. Income (*GDP*) and population (*POP*) for countries *i* and *j* allow us to address the role of the mass of the trading partners (both exporters and importers), whereas geographic variables refer to the bilateral geographic distances (*DIST*) between the trading partners following the calculations provided by CEPII (Mayer and Zignago 2006), and the total land area as a dimensional variable of the importing country (*LAND*). In addition, we have tested the role of two dummy variables: the existence of past colonial relationships (*COL*) assuming value 1 if there are colonial relationships, and the geographic contiguity (*CONT*) assuming value 1 if the two trading partners are neighboring.[8]

The second group refers to measures of environmental and energy regulation for the *i* exporting countries (*REG*). A quantitative assessment of environmental regulation is represented by the total costs sustained by government and private firms in order to support different policies for environmental protection. This overall stringency variable allows us to examine the role of environmental regulation as a general driver of international competitive advantages. It consists of a sum of three different costs: the current environmental protection expenditures, both of the public and the private sectors as a percentage of GDP (see Costantini and Crespi 2008a, b; Hascic et al. 2008); the share of environmental tax revenues on GDP; the amount of public investments in R&D on environmental protection as a percentage of GDP. All these measures of environmental regulation are taken from OECD National Accounts Statistics and EUROSTAT National Environmental Accounts.

A quantification of existing regulatory measures promoting energy efficiency and renewable energy sources follows the proposal of Johnstone and

[8]In this paper, we have adopted simple distances as a distance measure for which only one city is necessary to calculate international distances. The simple distances are calculated following the great circle formula, which uses latitudes and longitudes of the most important city (in terms of population) or its official capital (Mayer and Zignago 2006).

Hascic (2008). The Global Renewable Energy Policies and Measures Database provides data on policies applied in over 100 countries in support of renewable energy and energy efficiency from the early 1970s until now. The database includes several different measures, ranging from R&D public support to market incentives or regulatory vs. voluntary approaches, thus making it impossible to quantify the relevance of each action exactly. Hence, we have adopted the same approach as Johnstone and Hascic (2008) by building a composite policy variable akin to an index that mainly reflects differences in the strength of policy approaches across countries and over time. It is constructed as the annual cumulative number of policies still in place for each *i-th* country, both for renewable energy excluding bioenergies ($RENWPOL$) and energy efficiency ($ENEFFPOL$) separately.

The disadvantage of this approach is that it does not distinguish between individual policy instruments. While there are likely to be important differences between instruments in terms of the "stringency" of the measures introduced, this shortcoming is unavoidable for any cross-comparative analysis in which multiple instruments are included. This means that we cannot distinguish between market-based and regulatory measures and we cannot investigate specific final energy sectors (such as industry, transport or services). Nonetheless, there is a significant advantage related to the fact that this composite policy variable can be lagged, allowing the analysis of dynamic issues which is essential to a gravity model approach.[9]

The third dimension is specifically related to public support for the biofuel sector. In this work, we have considered specific policy measures chosen with two criteria: policy actions should be implemented in the whole sample of exporting countries, thus reducing possible biases in the estimation results due to lack of data; policy measures should be attributed from an easily recognizable starting date. Therefore, we have modelled three types of public support policies:

1. Tariffs imposed on international imports flows of biofuels—as the sum of ethanol and vegetable oils for producing biodiesel—are from the UNCTAD-TRAINS database ($AHSBF$), all expressed in terms of MFN (Most Favored Nation) applied duties in *ad valorem* equivalent. We have taken the MFN applied tariffs and not the bound duties in order to reduce the biases related to the possibility that bound tariffs for protected sectors

[9] As far as concerns may arise when a unilateral variable is included in a gravity context – where mainly bilateral relationships are taken into account – we have considered some proxies of the environmental regulatory system as well as the technological innovation system of the importing countries, as suggested by Costantini and Crespi (2008a, b) and Spatareanu (2007), such as the reduction in main pollutant emissions, the total RD expenditures, or the level of technological capabilities. While the j countries sample is substantially reduced, the statistical robustness of these variables is weak. As far as j countries' fixed effects are considered in the model, we may affirm that they represent the best proxy for the environmental regulatory framework and the innovation capacity.

are inflated for the sake of advantages in the WTO negotiations process.[10]

2. Fuel mandates (*MANDBF*) expressed as a percentage target relative to the specific corresponding fossil fuels (gasoline for ethanol and diesel for biodiesel). In this case, we have considered only one policy measure related to all biofuels (expressed as a simple average of the mandates for two separate targets) because differences between ethanol and biodiesel are minimal.
3. Excise tax reductions favoring bioethanol and biodiesel consumption. In this case, we have taken the average values of tax reduction (US$ per litre) for ethanol and biodiesel (*EXCBF*). Data for this policy measure and fuel mandates are provided by the International Institute for Sustainable Development's Global Subsidies Initiative (GSI).
4. Lastly, we have built a synthetic policy measure (*POLICYBF*) in order to assess more generally the impact of public support for biofuels on the competitive advantages of the other clean energy technologies. Our variable is taken from the arithmetic mean of *AHSBF*, *MANDBF* and *EXCBF*, all expressed in percentage terms.

The fourth dimension includes the public efforts in R&D specifically for the energy sector. More precisely, we have considered three different specifications: (1) the share of public R&D expenditure in the energy sector on total R&D (*RDENE*); the share of public R&D expenditure in energy efficiency on total public R&D expenditure in the energy sector (*RDENEFF*); the share of public R&D expenditure in renewable energies on total public R&D expenditure in the energy sector (*RDRENW*). The last two variables allow us to investigate the specific impact of R&D efforts in these fields (energy efficiency and renewable energies, excluding biomass) on our dependent variables.

Finally, we have tested the effects related to dummies traditionally included in gravity equations for impact assessment associated with geographical aggregation, such as participation in regional and trade agreements or specific economic areas.

In order to implement a 2SLS estimator, we have instrumented the technology covariates with three variables, as suggested by Johnstone et al. (2010): (1) the energy price, expressed as the average of energy prices for households

[10]The so-called phenomenon of the "water in tariffs" corresponds to a wide range between bind duties (those declared to WTO) and applied duties (faced by importing countries in the international trade). For further details, see Bouët et al. (2008). All tariffs are calculated as weighted averages of the *ad valorem* equivalent with the corresponding trade flow related to the following HS 1996 codes: 1205.00 (Rape or colza seeds, whether or not broken), 1507.10 (Crude oil, whether or not degummed), 1511.10 (Crude oil), 1512.11 (Crude oil), 1514.10 (Crude oil), 2207.10 (Ethanol), 2905.11 (Methanol).

and industry weighted with relative energy consumption; (2) the level of per capita electric power consumption; (3) the gross domestic expenditure on R&D as % of GDP (OECD, Main Science and Technology Indicators). The environmental and energy regulation variables have been instrumented with traditional 2-year lags (Fisher et al. 2003; Harris et al. 2002; Jug and Mirza 2005).

5 Empirical results

The first step of our analysis consists in the assessment of the role of the two major pillars we have considered in the previous paragraphs, i.e. the strength of the general environmental regulatory framework and the public efforts to promote technological innovation in the energy sector. We have tested several different formulations of our gravity equation by including different covariates and the results obtained are all consistent with our basic hypothesis. Table 2 shows the most significant results regarding both pillars. We have estimated all the equations by using an instrumental variable approach with a 2SLS estimator, as already explained in par. 3. We have adopted a "mixed" fixed-effects approach by using a random effect specification with properly designed countries and country-pairs dummies representing fixed effects, as recently suggested by Baldwin and Taglioni (2006).[11]

As we can see, the first estimation (Column 1) refers to the full dependent variable as the sum of all bilateral exports from our selected OECD countries to the j countries of technologies for renewable energies (excluding biomass) and energy efficiency. The coefficients of the covariates relative to the traditional gravity dimensions have the expected signs, where the higher the income level of the exporting countries, the higher the export capacity. This is explained by the gravity model literature, which assigns the effect of general domestic market size to GDP. The same applies to income levels in importing countries, but we can see that, in our model, this variable is less powerful in explaining export dynamics. The negative coefficients associated with population can be easily interpreted if we consider income per capita rather than the two separate variables. Even in this case, only population

[11] Recent studies addressing the role of environmental regulation (see Mantovani and Vancauteren 2008) in a gravity framework propose the adoption of a GSL-RE in order to correct autocorrelation and heterosckedasticity when working on general trade data. The dependent variable used in our paper is rather different from total export values and has statistical characteristics that lead to indifference when using a 2SLS or a GLS. We have computed the Hausman test on these two specifications, reaching the same conclusion as in Costantini and Crespi (2008a, b), i.e., that 2SLS is an efficient estimator with robust standard errors.

Table 2 The role of environmental regulation and specific public R&D on the export performance of countries in energy technologies

Dependent variable	Export of renewable energies and energy-saving technologies (RENWSAVEXP)	Export of renewable energies technologies (RENWEXP)	Export of energy-saving technologies (SAVEXP)
	(1)	(2)	(3)
GDPj	0.042	0.151***	−0.002
	(1.03)	(2.68)	(−0.04)
GDPi	2.710***	4.124***	5.103***
	(9.20)	(10.94)	(14.65)
POPj	−0.012	−0.154**	0.100
	(−0.21)	(−2.00)	(1.47)
POPi	−1.148***	−2.061***	−3.123***
	(−4.01)	(−5.63)	(−9.01)
DIST	−1.117***	−1.497***	−1.305***
	(−12.08)	(−12.34)	(−11.85)
COL	2.608***	3.510***	3.266***
	(9.92)	(10.62)	(10.05)
CONT	1.042***	0.968*	0.876*
	(2.53)	(1.84)	(1.81)
LANDj	−0.732***	−0.707***	−0.834***
	(−6.53)	(−4.94)	(−6.32)
ENVREGi	2.193***	1.013**	3.347***
	(8.80)	(2.26)	(11.52)
RDENEi	0.231**		
	(2.31)		
RDRENWi		0.503**	
		(2.27)	
RDENEFFi			0.606***
			(4.32)
OECD	7.209***	8.283***	7.506***
	(7.23)	(6.48)	(6.38)
YEAR DUMMIES	Yes	Yes	Yes
COUNTRY DUMMIES	Yes	Yes	Yes
Adj. R-sq	0.63	0.64	0.61
Obs	23,936	21,808	19,813

Z-statistics in parenthesis. ***p-values < 0.01, **p-values < 0.05, *p-values < 0.1

levels related to exporting countries have the expected coefficients with robust statistical significance, meaning that the higher the income per capita of the exporting countries, *ceteris paribus*, the higher the competitiveness in exporting energy technologies on international markets. The low statistical significance of coefficients associated with GDP and population for the *j* countries may be interpreted as a sign of a scarce influence of specific importing countries demand size.

When we consider the two separate dependent variables related to specific energy technologies (Columns 2 and 3), this result seems to be reinforced. With regard to the export flow of technologies for the production of renewable energy, it is worth noticing that the propensity to import technologies is positively influenced by the higher levels of income per capita of *j* countries. This result is reasonable enough if we consider the large differential in the production costs between traditional fossil fuel and renewable power plants. Typically, poor countries, with large energy supply constraints caused by lack of infrastructures, invest in enlarging energy production at the lowest cost with a preference for traditional fossil fuel technologies. This result could partially change if it were possible to investigate specific investment in micro-power plants where renewables are rather more economically viable, especially in developing countries, reducing the need for investment in expensive infrastructures. Indeed, this is an issue that needs to be investigated further. By contrast, the import propensity of energy efficiency technologies can increase due to frequent energy disruptions associated with poor infrastructures, where investments in energy saving could be more efficient than the reinforcement of existing infrastructures.

The other coefficients associated with the standard gravity variables are all statistically significant and consistent with other studies concerning both environmental regulation and general international trade issues. In this sense, particular emphasis should be given to the dimensions of the border effects related to geographic distance, contiguity and colonial relationships, which help to explain the influence of generally defined transactional costs on bilateral export flows.

The econometric estimates show that environmental regulation positively affects the international competitiveness in the export of energy technologies, as the positive and statistically significant coefficient for *ENVREG* demonstrates. This suggests that some narrow Porter-like effect actually operates. As coefficients in log-linear gravity models can be interpreted as elasticities, which means that raising compliance costs for environmental regulation relative to GDP by 1% will produce an increase in export flows of energy technologies of 2.2%. This evidence is more pronounced when we consider specific technologies for energy efficiency, where elasticity reaches a 3.3% level. We can partially explain this specific result by considering the fact that environmental taxes (including energy taxes) constitute a major component of our proxy for the general environmental regulation (*ENVREG*). In this respect, our results mainly reflect the fact that high energy taxes may represent a rather strong stimulus for the development of energy-saving technologies.

In order to derive a first indication on the role played by the second pillar of public support, we have considered the direct effect on export flows of energy technologies produced by public R&D expenditure in the energy sector. The first specification (Column 1) considers the general variable for public expenditure in the energy sector expressed as a percentage of the total R&D (*RDENE*). We found that it positively influences the aggregated dependent variable, with a positive and significant coefficient. Interestingly, if we divide R&D into energy efficiency and renewable energies, we can see that specific R&D resources have a significant impact on the differentiated flows of exports, with the former having the largest effect.[12] These results suggest that the specific efforts in building the innovative capacity of exporters in these fields strongly affect their competitiveness in the international market for energy technologies, with the specificity of R&D inputs emerging as a crucial element in shaping technological and market competitiveness of countries (Crespi and Pianta 2008).[13]

The subsequent step has been that of introducing an element of analysis related to the specific biofuel policies for creating a niche market. As we have already mentioned, there are several public policies that have recently been introduced especially by some OECD countries in order to foster the development of domestic consumption and production of biofuels. All these policies, apart from very recent and rare occasions, do not discriminate between the technological process adopted for the generation of bioethanol or biodiesel. As discussed in par. 2, it could be argued that the overall policy setting promoting biofuels may orient technological change in a specific direction and negatively affect the evolution of technologies in other branches of the energy sector. In order to test this hypothesis, we have tried to investigate whether the export dynamics of technologies for renewable energies (excluding those related to biofuels) and energy savings—intended as a measure of international technological competitiveness—have been negatively affected by public efforts to promote the biofuel market. In Table 3, we report results for a gravity equation where, in addition to the general environmental regulation and the public R&D in the energy sector, we have added four alternative variables representing public incentives to the domestic production and consumption of biofuels: Column 1 refers to a general policy mix, Column 2 is related to import tariffs on biofuels and raw materials, Column 3 shows the effects of an excise tax exemption for fossil fuels, and Column 4 represents the impact of demand-side policies expressed as mandates of fuel blending shares (see

[12] As we have explained in par. 3, we have adopted an instrumental variable approach by using a 2SLS estimator in order to treat both environmental and energy regulation and public support to R&D in the energy sector as endogenous variables. The endogenous variables are included in the equation without temporal lags, while we have considered the lagged values as instruments (two periods back). We have tested other specifications where the endogenous variables are included in the gravity equation with temporal lags, since it can be argued that the response to policies in terms of export dynamics may be not contemporary. In our opinion, considering lagged values in instruments gives a good response to this issue without losing information. For the sake of simplicity, we do not report these results in the text, but they are available upon request from the authors.

[13] In order to make the model consistent with the standard gravity literature, we have added a full set of year dummies (1996–2006) which have proven to be jointly significant in order to capture the effects related to temporal shocks. We have also included country fixed effects related to trading partners. Finally, we have also included several regional dummies, but the only one with statistically robust coefficients is related to the fact that importing countries are members of the OECD.

Table 3 The impact of biofuels policies on the export dynamics of energy technologies

Dependent variable	Export of renewable energies and energy-saving technologies (RENWSAVEXP)			
	(1)	(2)	(3)	(4)
GDPj	0.043	0.043	0.043	0.043
	(1.04)	(1.06)	(1.07)	(1.05)
GDPi	2.676***	2.223***	2.257***	2.550***
	(9.06)	(5.78)	(5.62)	(8.42)
POPj	−0.012	−0.012	−0.012	−0.012
	(−0.21)	(−0.21)	(−0.22)	(−0.21)
POPi	−1.107***	−0.683*	−0.700*	−0.987***
	(−3.85)	(−1.85)	(−1.82)	(−3.35)
DIST	−1.108***	−1.139***	−1.149***	−1.103***
	(−11.89)	(−11.33)	(−11.16)	(−11.22)
COL	2.597***	2.699***	2.724***	2.582***
	(9.81)	(9.13)	(8.99)	(9.27)
CONT	1.056***	0.991**	0.980**	1.062***
	(2.55)	(2.25)	(2.17)	(2.44)
LANDj	−0.732***	−0.733***	−0.733***	−0.731***
	(−6.49)	(−6.14)	(−6.00)	(−6.17)
ENVREGi	2.100***	2.164***	2.156***	2.147***
	(8.37)	(8.32)	(8.21)	(8.34)
RDENERTOTi	0.235**	0.453*	0.515**	0.194*
	(2.34)	(1.86)	(2.04)	(1.85)
POLICYBFi$_{(t-1)}$	−0.051***			
	(−4.30)			
AHSTOTi$_{(t-1)}$		0.015		
		(1.21)		
EXCBFi$_{(t-1)}$			−0.056***	
			(−5.14)	
MANDi$_{(t-1)}$				0.0128
				(1.51)
OECD	7.211***	−1.290	7.189***	7.213***
	(7.19)	(−1.58)	(6.64)	(6.85)
YEAR DUMMIES	Yes	Yes	Yes	Yes
COUNTRY DUMMIES	Yes	Yes	Yes	Yes
Adj. R-sq	0.63	0.63	0.63	0.63
Obs	23,936	23,936	23,936	23,936

Z-statistics in parenthesis. ***p-values < 0.01, **p-values < 0.05, *p-values < 0.1

par. 4 for details). In the following specifications, we have considered the impact of biofuel policies on the general dependent variable, because the overall effect on the technological competitiveness on international markets for energy technologies is what we are interested in. In order to account for the assumption that policies for biofuels support may divert investments from other technologies to escape the existing fossil-based dominant design, we have estimated the impact related to biofuels policies with one temporal lag, thus allowing for some transitory periods of adaptation to variations in the policy framework. Unlike environmental regulation policies, we have not treated biofuel policies as endogenously determined by export flows of other energy technologies due to the existence of a multiple set of different forces fostering the adoption of biofuels, as already described in the previous paragraphs.[14]

As shown in Table 3, the standard gravity variables are statistically significant and the expected signs, as well as the coefficients for environmental regulation (*ENVREG*) and R&D in the energy sector, are consistent with the results reported in Table 2. The coefficient associated with the biofuel policy mix (Column 1) is definitively negative and statistically significant. This result confirms our research hypothesis that niche strategies aiming at discarding carbon lock-in by selecting incremental innovations with pervasive and non-flexible policy interventions, as in biofuels, may be detrimental to technological competitiveness in the other sectors of energy technologies, especially those related to sustainability goals (renewables and energy efficiency), due to contrasting effects produced by different policy actions.

As a further step, we have tested the specific impacts related to different policy tools adopted by national governments. The results reported in Columns 2–4 clearly show that market-based instruments, in the form of a reduction of the energy tax imposed on biofuels (*EXCBF*), are the most influential in determining the track of specialization in the energy sector, with a negative and statistically significant coefficient. The coefficients associated with the variables related to fuel mandates and import tariffs are positive but not significant. As a partial explanation of these results, we should consider that both mandates and tariffs on imports of biofuels show a low statistical variance due to the strong homogeneity of data related to EU countries (i.e., 14 countries out of the 20 exporting countries analyzed here).

After checking for possible contrasting effects linked to biofuel policies, we have considered the two solutions to a carbon lock-in more specifically in terms of renewable energies and energy efficiency technologies. Adopting a transition management approach means that a flexible policy mix allows a gradual adaptation of the socio-economic system to new environmental challenges by guaranteeing the appropriate degree of diversity in the technological solutions. This leads to the need for a properly designed integrated strategy as in the case for a socio-technical system which is as complex as the energy sector. In a context of financial budget constraint, specific policies aiming at supporting the development and diffusion of energy-saving appraisals may divert resources from the investments in renewable energy technologies, and vice versa. While renewable energies may be considered as a more radical solution to the carbon lock-in, innovations in the field of energy saving often rely on existing technologies, mainly representing incremental innovations.

We have tried to model this intuition empirically and results reported in Table 4 seem to confirm this. Based on results obtained in Tables 2 and 3, Columns 1 and 2 report estimations of the impact of specific domestic policies

[14]The selection of one temporal lag for all the biofuel-related variables has been validated from a comparison of endogenous vs. independently defined variables and by including zero, one and two lags for each variable. Coefficients are definitely more significant and statistically robust, with one period back exogenous specification.

Table 4 Energy regulation and innovation

Dependent variable	Export of renewable energy technologies (RENWEXP)	Export of energy-saving technologies (SAVEXP)	Export of renewable energies technologies (RENWEXP)	Export of energy-saving technologies (SAVEXP)
	(1)	(2)	(3)	(4)
GDPj	0.149***	−0.001	0.087	0.002
	(2.61)	(−0.02)	(1.46)	(0.04)
GDPi	3.330***	3.910***	3.241***	3.516***
	(9.46)	(12.05)	(9.20)	(10.687)
POPj	−0.148	0.099	−0.165 **	0.115
	(−1.91)	(1.46)	(−1.97)	(1.63)
POPi	−1.426***	−2.156***	−1.370***	−1.848***
	(−4.10)	(−6.62)	(−3.93)	(−5.59)
DIST	−1.643***	−1.587***	−1.589***	−1.246***
	(−14.64)	(−14.61)	(−12.22)	(−9.20)
COL	3.440***	3.287***	3.516***	3.125***
	(10.96)	(10.11)	(11.09)	(9.67)
CONT	0.775	0.698	0.800	1.246***
	(1.55)	(1.45)	(1.60)	(2.58)
LANDj	−0.710***	−0.845***	−0.678***	−0.807***
	(−5.18)	(−6.40)	(−4.89)	(−6.06)
EXCBFi$_{(t-1)}$	−0.040***	−0.144***	−0.014	−0.143***
	(−2.83)	(−9.45)	(−0.94)	(−9.41)
POLRENWi	0.653***		0.929***	
	(4.00)		(5.01)	
POLENEFFi		0.084**		0.113***
		(2.31)		(3.16)
RDRENWi	0.225***		0.380***	
	(2.86)		(4.16)	
RDENEFFi		0.667***		0.609***
		(4.53)		(3.88)
RDENEFFi$_{(t-1)}$			−0.242***	
			(−5.17)	
RDRENWi$_{(t-1)}$				−0.055
				(−0.98)
OECD	8.183***	7.442***	8.229***	−0.988
	(6.67)	(6.33)	(6.60)	(−1.08)
YEAR DUMMIES	Yes	Yes	Yes	Yes
COUNTRY DUMMIES	Yes	Yes	Yes	Yes
Adj. R-sq	0.63	0.49	0.64	0.49
Obs	20,469	19,813	19,149	19,017

Z-statistics in parenthesis. ***p-values < 0.01, **p-values < 0.05, *p-values < 0.1

supporting energy efficiency and the diffusion of all forms of renewable energies (except for biomass) adopted in our 20 OECD exporting countries.

The results for the coefficients related to the standard gravity variables still confirm the positive role of income per capita of the exporting countries as a sort of willingness to pay (or demand-pulled) effect on environmental-friendly energy technologies.

Given the results shown in Table 3, we check the role of public support for biofuels by using the excise tax exemption as the most significant variable identified from previous estimates. The negative impact of biofuel policies on the export dynamics of energy technologies still holds for renewable energy technologies and energy efficiency. In contrast with estimates reported in Table 2, we have replaced the role of a generally defined measure of environmental regulation strength (*ENVREG*) with two specific policy variables strictly related to the export flows dynamics of the two energy technologies here considered (*POLRENW* and *POLENEFF*, respectively).[15]

As in the previous modelling approach, we have considered such policy variables and the public R&D expenditures (*RDRENW* and *RDENEFF*, respectively) as endogenous by instrumenting them with their correspondent lagged values (two periods back) and with energy prices and per capita energy consumption. In this case, we are interested in investigating the potential contrasting effects of several simultaneous energy policies and public R&D investments in these two energy technology fields more precisely.

This alternative specification does not significantly change our previous results and confirms the positive role of both regulation and public R&D expenditures on the international technological competitiveness in the energy sector. Nonetheless, energy-saving technologies export flows seem to be more (negatively) affected by biofuel policies than renewable energies. This evidence can be explained by the existence of a larger conflict related to the transport sector. Indeed, the investment efforts to produce biofuels as a viable and sustainable solution to the current fossil-based transport system may discourage the development of energy-saving appraisals for vehicles, which will indiscriminately reduce fossil fuels and biofuel consumption. Moreover, the combination of ethanol tariffs, blending mandates and direct support to biofuels producers in the form of tax credits can, in some cases, lower both the prices of ethanol and the gasoline with which it is blended, thereby encouraging the consumption of fossil fuels (Ewing and Msangi 2009), or discouraging the adoption of energy-saving technologies in the transport sector.

Finally, we have modelled the potential substitution effect related to alternative investment decisions for a fairly rigid overall public R&D budget by including both public R&D energy variables in each equation. The “correspondent” R&D variable (*RDRENW* for *RENWEXP* and *RDENEFF* for *SAVEXP* respectively) is endogenously modelled in the same way adopted in previous estimations, whereas the “opposite” R&D variable (*RDENEFF* for *RENWEXP* and *RDRENW* for *SAVEXP*, respectively) is modelled as an exogenous and lagged (one period back) variable.[16]

[15] We have dropped the variable related to general environmental regulation from equations due to potential multicollinearity with the specific energy policy variables.

[16] We have tested several alternative specifications for this point and our findings reveal that the opposite variable is not endogenously determined and that the one lag structure seems to be statistically more robust.

The results reported in Columns 3 and 4 of Table 4 indicate that some substitution effects may take place, since the “opposite” R&D variables have negative and, in the case of renewables, statistically significant coefficients in the two models. This result is consistent with what has been argued in par. 2 concerning a potential trade-off between the advancements in energy-saving and renewable energy technologies, that is, according to the extent that energy conservation is more successful and less expensive (due to its intrinsic incremental rather radical innovative content), the transition to renewable energy sources will be slower, since energy conservation will reduce the urgency for a shift towards a system based on sustainable energy sources.

6 Conclusions

In this paper, we have tested an empirical model based on a gravity equation in order to provide evidence of possible problems related to coordination failures between different environmental policies. As a case study for our analysis, we have focused on the energy sector, in which the strong interrelations between the socio-economic and technological dimensions may exacerbate the negative consequences of implementing conflicting policies.

In particular, two specific issues have been addressed: (1) the impact on the export dynamics of energy technologies generated by broad environmental regulation policy and specific innovation policies; (2) the conflicting impacts on export competitiveness of energy technologies of different policies due to the distortive potential of the enforced policy mix.

Our results show that environmental regulation is positively correlated and may affect international competitiveness in the export of energy technologies, providing evidence of the relevance of a narrow Porter-like effect. Nonetheless, from our empirical analysis, it clearly emerges that environmental policies should be supported by technology policies aimed at equipping innovation systems with adequate scientific and technological knowledge in order to respond creatively to changes in external constraints.

Moreover, by focusing on public support for the biofuel sector, we have been able to analyze the way in which the overall policy setting promoting biofuels may orient technological change in specific directions and negatively affect the evolution of technologies in other branches of the energy sector. This specific result raises the issue of the existence of potential negative effects related to the adoption of pervasive niche strategies on the objective of preserving diversity that should be a core element of a proper transition policy.

Finally, we found evidence of a possible trade-off between research efforts in renewables and energy-saving technologies. This aspect deserves further attention in future studies, but should be taken into account when designing the policy framework in the energy sector, since both environmental policies and innovation policies are capable of orienting the technological specialisation of economic systems.

The policy advice that can be drawn from this analysis is a strong warning on the implementation of public policies which can be difficult to remove in the future, generating lock-in effects and reducing diversity. The design of a balanced policy mix emerges as a crucial element for directing economic systems towards sustainable economic growth paths.

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