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REGULAR ARTICLE

The impact of environmental regulation on innovation and international competitiveness

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Abstract
The purpose of this paper is to analyze the impact of environmental regulation on innovation and international competitiveness. We test the weak, narrow, and strong versions of Porter's hypotheses by looking at the impact of environmental regulation on exports both directly and indirectly through innovation and by introducing the role of pollution intensity in moderating the impact of stringent regulation on innovation and international competitiveness. Green policies are measured with the OECD Environmental Stringency Policy Index, distinguishing between market, non-market instruments, and technology support policies. Differently from previous papers, we adopt the technology gap approach to trade, which is suitable for relating environmental regulation to trade competitiveness and we apply the simultaneous-equation system econometric model with a moderating factor represented by pollution intensity. The results support the weak and strong versions of Porter's hypotheses and find that the positive impact of regulation on innovation and exports increases with a country's pollution intensity, suggesting that green policies, if properly coordinated, can represent a win–win strategy, fostering, at the same time, sustainability and international competitiveness.

Keywords Environmental regulation · Porter hypothesis · International competitiveness · Export model · Patents

JEL Classification Q56 · F41 · Q55

1 Introduction

Recently, the concern for reconciling economic growth and environmental goals has been growing. Fay (2012) coined the term *inclusive green growth* and almost all international institutions have been conducting studies and introducing programs oriented in this direction. At the European level, the European Green Deal and Next Generation EU are aimed at achieving sustainable growth while addressing the

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Extended author information available on the last page of the article

problem of climate change. Several instruments have been used to address environmental issues and the OECD has made an important effort to measure the adoption of different environmental policies distinguishing between market-based and non-market-based instruments, and technology support policies, and developing the Environmental Policy Stringency (EPS) index.

However, the regulatory instruments devised to foster the green transition have been a concern for firms and countries perceiving them as additional costs and a threat to their competitiveness. In periods of crisis, and more recently after the start of the war in Ukraine and the problems linked to the shortage and the increase in the price of gas and electricity, several countries, from Japan to the Netherlands, have been tempted to be more flexible in their environmental goals, even reopening or delaying the closure of coal power stations (Rawnsley 2022; Brown et al. 2023). But is there a real trade-off between environmental stringency and competitiveness or can the two goals be reconciled? The traditional vision of the existence of such a trade-off, which is at the basis of the Pollution Haven hypothesis, has been challenged by the vision of Porter and van der Linde (1995a), who have moved from a static representation of firms' profit maximization to a dynamic view of the impact of regulation on innovation and structural change. In this framework, environmental policies may be a stimulus for new products and processes (Porter's weak hypothesis), thanks above all to those based on market instruments (Porter's narrow hypothesis), and, through this channel, they may also positively affect firms' (and countries') competitiveness (Porter's strong hypothesis). While several studies have found support for the weak and narrow versions of Porter's hypotheses, the empirical tests of the strong version led to contrasting results.

Petroni et al. (2019), in surveying the main results of the literature, highlight the *fuzziness surrounding studies aimed at confirming or denying the validity of the strong version of the Porter hypothesis* (Petroni et al. 2019, p. 122). In particular, they argue that an increase in compliance costs causing more innovation is not a confirmation of the Porter hypothesis since more innovation does not necessarily overcome the compliance costs, possibly leading to lower profits. They also suggest looking at the role of moderating factors, namely pollution intensity and value appropriation, possibly affecting the relationship between environmental regulation and competitiveness. This paper addresses these issues by testing simultaneously the weak, narrow, and strong Porter hypotheses at the country level and the moderating impact of pollution intensity. We contribute to the literature in different ways. First, while there is growing literature testing the impact of regulation on international competitiveness with contrasting results, there is no contribution at the country level, which considers both the direct and indirect (through innovation) impact of regulation. Lanoie et al. (2008) is the only study testing simultaneously the weak and strong versions of the Porter hypothesis by allowing for a direct (cost increase) and indirect (through innovation) effect of regulation on business performance. They find that regulation increases R&D expenditures (positive evidence for the weak version of the Porter hypothesis) but that the net impact on business performance is negative (no evidence of the strong version). We adopt a similar approach to study the direct and indirect impact of regulation on countries' international competitiveness in the framework of the technology gap approach to trade (Soete 1981; Laursen and Meliciani 2002, 2010; Evangelista et al. 2015; Dosi et al. 2015) where innovation plays a central role for market share dynamics. In the case of countries' international competitiveness (export market shares), the mechanisms behind the direct effect of regulation are different from those operating at the firm level. In fact, while regulation increases production costs, it can also contribute to structural change towards sectors/products with a higher income elasticity of demand (Galindo et al. 2020; Guarini and Porcile 2016; Althouse et al. 2020) and with an ambiguous direct effect on countries' export shares. We argue that only a simultaneous equation approach allows for the disentanglement of the net effect of environmental protection stringency on competitiveness, i.e., to properly distinguish between the weak and strong version versions of the Porter hypotheses. Second, we distinguish between market-based and non-market-based regulation within the simultaneous equation model allowing us to test Porter's narrow hypothesis while considering the direct and indirect impact of the two types of regulation on international competitiveness. We also take into consideration the role of technology support policies. In this respect, we add to the literature that has tested the strong hypothesis without distinguishing between market-based and non-market-based instruments (Rubashkina et al. 2015; Costantini and Mazzanti 2012; Martínez-Zarzoso et al. 2019; Yang et al. 2020; Nie et al. 2021; De Santis et al. 2021). Third, we distinguish between the short and medium effect of regulatory measures. Porter argues that more stringent environmental policies will lead to innovations aimed at reducing inefficiencies, ultimately resulting in cost reductions. However, this process may take time. Ambec et al. (2013) criticize the methodology of many older studies that regress productivity at time 0 against the severity of environmental regulation at time 0, without allowing the necessary time for the innovation process. Lanoie et al. (2008), through a firm-level analysis, challenge this approach by introducing delays of 3 or 4 years, demonstrating that stricter regulations can lead to modest long-term gains in productivity in manufacturing sectors in Quebec. More recently, the country-level analysis of 14 OECD countries by Martínez-Zarzoso et al. (2019), using the panel quantile regression model, examines Porter's hypotheses in the short and long term. The results show that in the short term, more rigorous environmental policies are associated with an increase in the number of patent applications and total factor productivity (TFP) for the higher quantiles of the patent distribution and for all quantiles of TFP, respectively. In the long term, Environmental Performance Score (EPS) influences research and development, patents, and TFP across all quantiles. Therefore, more stringent environmental regulations promote cleaner production processes that could contribute to improving energy efficiency. We extend this approach to detect the short and medium impact of the stringency of regulation on international competitiveness.

Finally, to the best of our knowledge, this is the first paper to test whether the impact of regulation on international competitiveness may vary according to a country's pollution intensity. By estimating the net effect of the stringency of environmental regulation on international competitiveness for different levels of pollution intensity, we can shed light on the possibly different impact of such regulations across countries with important policy implications. Empirical analysis concerns OECD countries over the period 1990–2020 thanks to the availability of data and in particular those concerning the OECD composite index of green regulation recently updated (Kruse et al. 2022).

2 Conceptual framework: Green regulation, innovation, and international competitiveness

The controversial relationship between regulation and competitiveness finds two main theories in economic literature: the Pollution Haven hypothesis and the Porter hypothesis (Dou and Han 2019). In the "traditionalist" vision of the neoclassical environmental economy, the purpose of environmental regulation (ER) is to correct market failure, eliminating a negative externality by internalizing its costs in firms. According to this view, internalization involves additional costs for firms subject to regulation. All of this can have negative effects at both firm, sectoral and national level. This perspective originated the Pollution haven hypothesis (PHH), which states that the polluting industries may relocate to countries/regions with less environmental regulations, namely, Pollution Haven (Dou and Han 2019).

The first to theorize a real model for the Pollution haven hypothesis, instead, were Copeland and Taylor, who developed a model of general economic equilibrium to formalize the relationship between international trade and pollution (Copeland and Taylor 1994; see also Copeland and Taylor 2004 for a review). Other studies added the existence of relocation costs, concluding that immobile industries would be insensitive to differences in regulation stringency between regions (Ederington et al. 2005) challenging the generality of the PHH. At the empirical level, the results are contrasting. Among the studies in favor of the Pollution haven hypothesis we find Ederington & Minier (2003) and Levinson and Taylor (2008). On the other hand, the study by Cole et al. (2005) does not find convincing evidence on the nature of the PHH. The study by Mulatu et al. (2003) examines data on manufacturing net exports to Germany, the Netherlands, and the United States, but reports mixed results. The results show that the estimated effects of environmental policy rigor on exports differ between countries. For the United States, environmental regulation seems to play an unfavorable role in competitiveness, for Germany the negative relationship exists for industries with high pollution intensity, while for Holland no negative effects are highlighted. Also, for Babool and Reed (2010), the results are mixed, depending on the analyzed sectors. For paper and wood and textile products, they find a positive relationship between net exports and environmental regulation; for most of the other manufacturing sectors, on the other hand, they find a negative relationship.

The Pollution haven hypothesis was challenged by Harvard Business School professor Michael Porter in the early 1990s.

The "revisionist" view states that improving environmental performance is a possible source of competitive advantage. According to this point of view, in fact, environmental improvement can lead to more efficient processes, an improvement in productivity and therefore lower compliance costs but also new market opportunities. Proponents of this vision are Michael Porter and Class van der Linde, who in their 1995 paper “Toward a New Conception of Environment-Competitiveness Relationship” theorized and described the so-called “Porter Hypotheses” (PH) (Porter and van der Linde 1995a). The two authors also argue that traditional theories identify a static relationship between environment and competitiveness where economic elements such as technology, products, and processes are fixed. For this reason, the traditional view identifies regulation as a cause of cost increases, and consequently a loss of competitiveness. The two authors state that: "the new paradigm of international competitiveness is a dynamic model based on innovation."[1]

The success of the firm in environmental and economic terms depends on solutions based on innovation that are able to promote both environmentalism and competitiveness (Porter & van der Linde 1995a; Borghesi et al. 2013). Jaffe and Palmer (1997), intending to empirically test the statements made first by Porter and later also by Class van der Linde, tried to clarify and schematize the PH, suggesting subdividing them into three versions: "weak", "strong" and "narrow". The weak hypothesis (PHW) states that environmental regulation will have a positive effect on environmental innovation, that is, greater innovation aimed at minimizing the costs of environmental input/output subject to regulation.

In the narrow version (PHN), on the other hand, flexible (market-based) environmental policy tools aimed at results rather than at the design of production processes will be more likely to increase innovation and improve the performance of firms than those not market-based. This difference arises from the greater freedom that market-based tools leave to firms to identify innovative solutions to meet compliance costs. Furthermore, once a standard is met, non-market-based tools are unable to provide incentives to develop or adopt cleaner technologies, unlike market tools (Fabrizi et al. 2018).

The strong version (PHS) finally states that environmental regulation, by stimulating both green product and process innovation, will lead to cost savings and increases in productivity that will exceed the costs of regulation. Green-product innovation will in fact raise the value of production, while green-process innovation will reduce production costs. Various studies have subjected these hypotheses to empirical verification with different results.

As for the weak version, most empirical studies find support for the hypothesis (Jaffe and Palmer 1997); (Brunnermeier and Cohen 2003); (Rubashkina et al. 2015); (Fabrizi et al. 2018); (Martínez-Zarzoso et al. 2019); (De Santis et al. 2021). Regarding the narrow version, some empirical studies support it (Jaffe and Stavins 1995); (Johnstone et al. 2008) (Costantini and Mazzanti 2012); (Costantini and Crespi 2013); (Fabrizi et al. 2018); (De Santis et al. 2021), while others do not find empirical support (Popp 2003); (Taylor 2012).

Finally, in the case of the strong version, there are studies that do not support the hypothesis, such as (Rubashkina et al. 2015) (Nie et al. 2021), and studies that report positive results, such as (Costantini and Mazzanti 2012); (Martínez-Zarzoso et al. 2019); (Wang et al. 2019a, b); (Yang et al. 2020); (De Santis et al. 2021).

In the case of the strong version, there are many competitiveness indicators used in the literature (labor productivity, total factor productivity, competitiveness in

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[1] Porter & van der Linde, Toward a New Conception of Environment-Competitiveness Relationship, 1995a p. 97.

international markets, etc.), as well as units of analysis (companies, sectors, countries). Since we aim to contribute to testing the strong hypothesis by referring to exports at the country level, in the remaining part of the section we focus on studies that have analyzed the effects of regulation on international competitiveness. The study by Jaffe et al. (1995), which examines most of the studies up to those years, argues that there is little evidence to support the hypothesis that environmental regulation has effects on trade flows.

Among the recent studies that empirically analyze Porter's version of the relationship between ER and international trade is that of Costantini and Mazzanti (2012). This work explores how the competitiveness of EU exports has been affected by environmental regulation and innovation. Unlike other studies, the two authors divide the strong version of the PH into strong and strictly strong. This second version mainly investigates the environmental assets sector. The results of the strong version suggest that the overall effect of environmental policies does not appear to be detrimental to the competitiveness of manufacturing sector exports, while specific energy tax policies and innovation efforts positively influence the dynamics of export flows, revealing a mechanism similar to Porter (Costantini and Mazzanti 2012). For the strictly strong version, on the other hand, environmental policies, but more incisively environmental innovation efforts, promote green exports (Costantini and Mazzanti 2012). In the study of Lodi and Bertarelli (2023), based on cross-sectional data at the firm level in Germany and Eastern Europe, results show that regulation inducing eco-innovation can generate either a positive or negative effect on export propensity. The results also show that productivity, size, and geographical heterogeneity of firms are extremely relevant.

Petroni et al. (2019) affirm that the validity of the Porter hypothesis cannot be proved in any condition, given the fact that the profitability construct may be significantly affected by environmental regulation (both in a positive and in a negative way), but at the same time, there are numerous additional factors that have a relevant influence on that construct, which can lead to a validation or rejection of the hypothesis. They believe that the real message of the hypothesis is that under certain circumstances (e.g., a given industry, a well-defined regulation, a capable firm), environmental regulation can lead to a profitable situation and/or to an increase in a firm's (or industry) competitiveness. Few studies have investigated the conditions under which the strong hypothesis holds. In the work of Wang et al. (2019a, 2019b) the main result shows that environmental policies have a positive impact on green productivity growth within a certain level of stringency, beyond which the impact becomes unfavorable, because the compliance cost effect is higher than the innovation compensation effect. He et al. (2020) find three main results: first the Porter hypothesis itself is not supported in China's manufacturing sector, and environmental regulation tends to reduce the financial performance of manufacturing companies; second, property rights protection has a positive impact on corporate financial performance, and a good property rights environment can induce corporate innovations and mitigate the negative impact of environmental regulation on corporate financial performance; third, the moderating effect of property rights protection on the relationship between environmental regulation and enterprise performance shows different degrees of the moderating effect in different types of enterprises in terms of their ownership natures and the regional economic development level in the area where it is located.

Among the factors affecting the impact of regulation on competitiveness, pollution intensity may play an important role with contrasting predictions. On the one hand, Lanoie et al. (2008) argue that the positive effect of regulation on performance should be more important for firms that are initially more polluting since they have more opportunities to identify and eliminate inefficiencies. On the other hand, Petroni et al. (2019) highlight that environmental regulation will be more favorable for less polluting firms/sectors since they will face lower compliance costs while reaping the same strategic advantages from ecologically friendly initiatives. Lanoie et al. (2008), differently from their expectations, find that in the Quebec manufacturing sector Porter's strong hypothesis is supported only for less polluting industries, while more polluting industries see long-run declines in productivity after an increase in the stringency of environmental regulation.

The great majority of studies looking at the relationship between environmental regulation and exports refer to the Heckscher Ohlin framework. This paper, in line with the PH, adopts a different approach, allowing us to test directly and indirectly (through innovation) the impact of the stringency of environmental regulation on international competitiveness (export dynamics). In particular, we use the technology gap approach to trade (Soete 1981; Laursen and Meliciani 2002, 2010; Dosi et al. 2015) to estimate the impact of innovation on export dynamics while relating environmental regulation to innovation. The instrumental variables (IV) estimation allows us to capture both the impact of regulation on innovation (weak Porter hypothesis) and the indirect impact of regulation on international competitiveness through innovation (strong Porter hypothesis). Finally, we also test the direct impact of regulation on exports. This impact could be negative if regulation increases production costs (as in the Pollution Haven hypothesis) but it could also be positive if it fosters structural change towards sectors/products with a higher income elasticity of demand (Galindo et al. 2020; Guarini and Porcile 2016; Althouse et al. 2020). In this setting, we also allow the direct and indirect impact of regulation on international competitiveness to depend on the country's pollution intensity. We have no a priori expectation of the sign of the moderating factor, in fact, on the one hand, we expect that countries with a higher level of pollution intensity will be pushed to look for more innovative solutions, but on the other, they will also incur higher compliance costs (see Fig. 1). By estimating the net effect, we can shed light on the overall costs and benefits of introducing stringent environmental regulations for countries with different levels of pollution intensity, leading to important policy implications.

3 Empirical specification and econometric methodology

In order to empirically analyze the direct and indirect impact of environmental regulation on international competitiveness through the innovation channel, we estimate a simultaneous-equation system model. The basic structure of the system is a two-equation model with an interaction term:

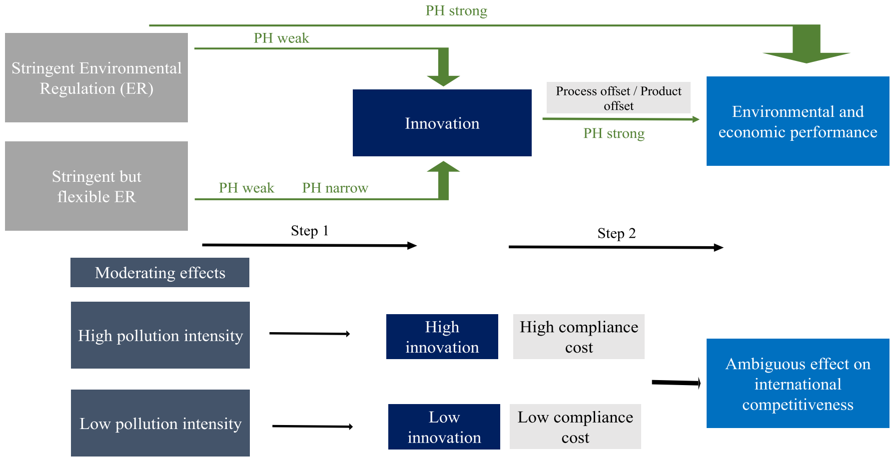

Fig. 1 The causal relations of the Porter hypothesis. Source: authors' elaborations based on a contribution by (Ambec and Barla 2005)

$$\begin{aligned} EXPSH_{it} = {} & \beta_0 + \beta_1 ULC_{it-1} + \beta_2 INV\_EMP_{it-1} \\ & + \beta_3 PAT\_POP_{it-1} + \beta_4 POP_{it-1} + \beta_5 EXC_{it-1} + \beta_6 EPS_{it-1} \\ & + \beta_7 GHG\_GDP_{it-1} + \beta_8 EPS_{it-1} xGHG\_GDP_{it-1} + \alpha_i + \gamma_t \end{aligned} \tag{a}$$

$$\begin{aligned} PAT\_POP_{it-1} = {} & \beta_0 + \beta_1 RD\_GDP_{it-1} + \beta_2 POP\_D_{it-1} + \beta_3 EPS_{it-1} \\ & + \beta_4 GHG\_GDP_{it-1} + \beta_5 EPS_{it-1} xGHG\_GDP_{it-1} \alpha_i + \gamma_t \end{aligned} \tag{b}$$

where, respectively, $i = 1, \ldots., 34$ stands for OECD countries, $t = 1991\ldots, 2020$ refers to years. The time interval of the analysis depends on the availability of the Environmental Stringency Policy Index.

The outlined simultaneous-equation system model allows us to link a technology gap approach to the trade model (Eq. a) and a knowledge production function (equation b) through innovation (Griliches 1998; Nagaoka et al. 2010; Di Cagno et al. 2014; Fabrizi et al. 2018). In fact, the output of the simplified knowledge production function, the patent intensity, is also considered among the dependent variables of the country's international competitiveness model (Laursen and Meliciani 2010).

Starting from Eq. (a), *EXPSH* is export of goods market shares in constant prices and purchasing power parity; the purpose of the empirical analysis is to explain export market shares (absolute advantages) for each country and time period. These are defined as: $EXP_{it}/\sum_{n=1}^{i} EXP_{it}$ but we calculate exports by all countries' average $EXP_{it}/\sum_{n=1}^{i}(EXP_{it})/n$, rather than all the countries' sum to obtain symmetry with the cost variable (where the sum would make no sense). For the same reason, we calculate the other variables in a similar fashion. This is common in the literature (Magnier and Toujas-Bernate 1994; Amable and Verspagen 1995; Laursen and Meliciani 2000, 2010). *ULC* is unit labor costs expressed as the ratio of total labor compensation per hour worked to output per hour worked (labor productivity) and measured in indices (2015 = 100);

PAT_POP is triadic patent families[2] over population; *POP* is population of a given country; *INV_EMP* is investment per employee; *EXCH* is national currency per US dollar; *EPS* is Environmental Policy Stringency Index, *GHG_GDP* is the total greenhouse gases and emissions including land use, land-use change and forestry per unit of *GDP*, a proxy of pollution intensity of the country, and β_0, α_i, γ_t and v_it are, respectively, a constant, time dummies, country dummies and a white noise residual. When we test the narrow Porter hypothesis (Table 2), we distinguish between three different components of the EPS index: EPS_MKT (market-based policies), EPS_NMKT (non- market-based policies) and EPS_TECHSUP (technology support policies). For equation b) the dependent variable *PAT_POP* is the ratio between the total number of triadic patent families and the population (patent intensity). The regressors, besides *EPS* and *GHG_GDP*, are variables $RD\_GDP_{i,t-1}$ and $POPD_{i,t-1}$, the ratio of R&D total expenditure and GDP (R&D intensity) and population over area (population density), respectively, and β_0, α_i , γ_t and v_it are, respectively, a constant, time dummies, country dummies, and a white noise residual. All variables are expressed in logarithms.

Since our dependent variable is total export market share, we focus on total patents rather than only on green patents.[3] Barbieri et al. (2023) find that the development of green technologies strongly relies on non-green technological domains whose importance for the green transition is often neglected.

In Appendix 1, we report the control variables included in the export and patent equations, their expected sign, and the reference literature (Table 3), the detailed description of all variables with the sources and period covered (Table 4) and summary statistics (Table 5) of the variables and their correlations (Table 6).

Regarding the econometric methodology, we estimate the simultaneous-equation system model with CMP routine (Roodman 2011). This routine fits a large family of multi-equation (as Seemingly Unrelated (SUR) and instrumental variables (IV) systems), multi-level, conditional mixed-process estimators, where a dependent variable in one equation can appear on the right-hand side of another equation and the model can vary by observation. CMP fits essential seemingly unrelated regression models (SUR) that consider potential correlated errors among equations. The SUR system is a special case of simultaneous-equation systems in which the dependent variables are generated by independent processes with exception of correlated errors. However, the CMP routine can be used also in a larger class, as in our case, where endogenous variables can figure in one another's equation, obtaining consistent estimates of parameters when the systems are recursive with clearly defined stages and are fully observed, meaning

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[2] Triadic patent families are a set of patents filed at three of the major patent offices to protect the same invention: the European patent Office (EPO), the Japan Patent Office (JPO), and the United States Patent and Trademark Office (USPTO). These patents are attributed to the country of residence of the inventor or applicant and, with respect to time, to the date on which the patent was first registered worldwide (source: OECD Data). Triadic patents constitute a category of high economic and technological value patents (Criscuolo 2006) with a high potential from an innovative point of view, which improve the quality and the international comparability of patent indicators (van Pottelsberghe et al. 2001), without the potential "home bias" effect for patents registered only in one country or region.

[3] Results are robust to using green patents rather than total patents in the patent equation.

that the endogenous variables appear in the right-hand side only as observed and not in the form of a latent variable (Roodman 2011).[4]

3.1 Data on environmental regulation

We proxy green policies with the OECD Environmental Stringency Policy (EPS) Index. The EPS is extracted from the OECD database (Botta and Koźluk 2014 and Kruse et al. 2022). These indexes were developed in 2014 by the OECD both for individual policy instruments as well as for overall environmental policy, and are defined "*as a higher, explicit or implicit, cost of polluting or environmentally harmful behavior*" (Botta and Koźluk 2014) and have been recently updated (Kruse et al. 2022).[5] The proposed definition is clearly relevant for instruments such as taxes or emission limit values, but harder to interpret for subsidizing instruments such as feed-in tariffs. In this case, a higher subsidy can be interpreted as a more stringent environmental policy. Such subsidies increase the opportunity costs of polluting and it can be assumed are paid by the bulk of taxpayers or consumers, hence providing an advantage to "cleaner" activity.

The index proposed by the OECD seeks to compensate for the lack of reliable, comparable measures of the stringency of environmental policies, which limited the possibility of the cross-country analysis of the economic effects of these environmental policies (for a review, Kruse et al. 2022). In the 2022 version,[6] the index is based on a selection of 13 environmental policy instruments,[7] mainly related to climate and air pollution, aggregated into a composite stringency index for 40 countries (34 OECD countries[8] and six non-OECD countries[9]) from 1990 to 2020. The index ranges from 0 (not stringent) to 6 (highest degree of stringency).

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[4] Our recursive (triangular) framework is a limited information maximum likelihood (LIML) estimator, which replicates standard IV intuitions but considers both the trade model (1) and the knowledge production function (2) models as a joint system of equations. This method may potentially generate a gain in efficiency because it considers potential linkages between the error processes of two equations (Bettarelli et al. 2021). Moreover, our framework allows us to analyze the direct effects of EPS (controlling for the pollution intensity) and the indirect ones (mediation effect) through the innovation variable (PAT_POP).

[5] The new version of the index (2022), if compared to the previous one (2014), covers a greater number of OECD countries (from 26 to 34) and years (until 2020)

[6] Compared to the previous version, two instruments have been excluded because of limited data availability and concerns about the data quality: Deposit & Refund Schemes and White Certificates (also known as energy efficiency certificates).

[7] The list is as follows: CO_2 Trading Schemes, Renewable Energy Trading Scheme, CO_2 Taxes, Nitrogen Oxides (NOx) Tax, Sulphur Oxides (Sox) Tax, Fuel Tax (Diesel), Emission Limit Value (ELV) for nitrogen oxides (Nox), ELV for sulphur oxides (Sox), ELV for Particulate Matter (PM), Sulphur content limit for diesel, Public research and development expenditure (R&D), Renewable energy support for Solar and Wind (for data sources and coverage see Kruse et al. 2022).

[8] Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Korea, Rep., Mexico, Netherlands, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom, and United States.

[9] Brazil, China, India, Indonesia, Russia, and South Africa.

Two EPS indexes are proposed – one for the energy sector, and an extended one to proxy for the broader economy ("economy-wide"). We use the latter in the empirical analysis (our EPS). The aggregation procedure, which is the same for both the energy and broader indicator, follows a two-step approach. First, the instrument-specific indicators (e.g., taxes on SOx, NOx and CO_2) are aggregated into mid-level indicators according to their type (e.g., environmental taxes). Second, the obtained mid-level indicators are grouped into the three broad categories of market-based (our EPS_MKT), non-market-based instruments (our EPS_NMKT) and technology support policy (our EPS_TECHSUP).[10] Subcomponents can be used and aggregated in various ways; for example, to obtain "stick" and "carrot" versions of the indicators, where the former represents policies punishing environmentally harmful activity (e.g., taxes on pollutants), while the latter policies reward "environmentally friendlier" activities (e.g., subsidies). At each level of aggregation, equal weights are applied, which reflects the lack of priors in this respect.

In Appendix 2, in Fig. 5 we represent the trend of the EPS index and of the three sub-indexes MKT, NMKT, and TECHSUP over time and in Table 7 the average values of the same indices for the 34 OECD countries. From 1990 (first year of the series) onwards, on average for the 34 OECD countries, the absolute value of the EPS index has grown steadily (going from a value around 1 to a value around 3). Looking at the sub-indexes, the stringency of non-market-based policy instruments has increased the most in absolute terms, followed by technology support policies and market-based policies. Over the past 10 years, as pointed out by Kruse et al. (2022), the level of technology support policies has weakened, raising concerns that incentives to innovate in clean technologies may be declining. At the country level, the Nordic European countries, together with Switzerland and Japan, on average, register the highest values of the indices.

4 Main results

This section reports the results of the impact of green regulation on innovation and international competitiveness with reference to the PH, as shown in Tables 1 and 2. With reference to the econometric model presented in paragraph 3, Table 1 refers to the two-equation model (equations a and b) in the short (lag of 1 year, column (1), (2), (3)) and in the medium term (lag of 2 years, column (4)) and lag of 3 years, column (5)), respectively, and Table 2 refers to the two-equation model in which the EPS index is disaggregated into the three sub-indexes EPS_MKT, EPS_NMKT and EPS_TECHSUP for the short term (column (1), (2), (3) and (4)) and for the medium term (column 5). The empirical analysis allows us to have a general and complete view of PH. It tests both the direct and indirect impact of green policies on exports:

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[10] The third sub-index (EPS_TECHSUP) was introduced with the latest revision of 2022. Technological support policies are the aggregation of technological support measures upstream (such as public expenditure in R&D) and downstream (such as policies to support renewable energy).

Table 1 Direct and indirect effects of Environmental Policy Stringency (EPS) on export market shares

	(1) BASE (LAG1)	(2) EPS_TOT (LAG1)	(3) EPS_TOT&GHG (LAG1)	(4) (LAG2)	(5) LAG3
Equation 1.a					
EXP market share					
ULC	0.0970	– 0.0250	– 0.0682	– 0.119	– 0.112
	(1.12)	(– 0.27)	(– 0.74)	(– 1.23)	(– 1.17)
INV_EMP	0.311***	0.272***	0.198***	0.139**	0.104
	(6.95)	(5.78)	(3.78)	(2.26)	(1.58)
TPAT_POP	0.227***	0.226***	0.243***	0.266***	0.254***
	(9.47)	(9.72)	(9.70)	(10.84)	(10.49)
POP	– 1.315***	– 1.483***	– 1.604***	– 1.642***	– 1.685***
	(– 8.34)	(– 8.81)	(– 8.96)	(– 9.70)	(– 10.75)
EXC	0.261**	0.166	0.206**	0.143	0.124
	(2.56)	(1.64)	(2.08)	(1.54)	(1.39)
EPS		0.115***	0.0897***	0.107***	0.105***
		(5.21)	(3.77)	(4.64)	(4.79)
GHG_GDP			– 0.192***	– 0.215***	– 0.214***
			(– 3.48)	(– 4.06)	(– 4.06)
EPS x GHG_GDP			0.0609***	0.0612***	0.0781***
			(2.77)	(2.96)	(4.09)
Country dummies	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Time dummies	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Constant	– 1.491***	– 1.957***	– 2.314***	– 3.057***	– 3.256***
	(– 4.59)	(– 5.80)	(– 6.25)	(– 8.97)	(– 9.91)

Table 1 (continued)

	(1) BASE (LAG1)	(2) EPS_TOT (LAG1)	(3) EPS_TOT&GHG (LAG1)	(4) (LAG2)	(5) LAG3
Equation 1.b					
Patent intensity					
RD_GDP	0.950***	0.880***	0.930***	0.907***	0.852***
	(6.11)	(5.62)	(5.95)	(5.87)	(5.43)
POPD	– 0.702	– 0.878	– 0.785	– 0.434	– 0.354
	(– 1.48)	(– 1.64)	(– 1.19)	(– 0.68)	(– 0.53)
EPS		0.173***	0.116*	0.112*	0.100*
		(3.07)	(1.81)	(1.83)	(1.65)
GHG_GDP			– 0.0391	– 0.0510	– 0.0165
			(– 0.31)	(– 0.42)	(– 0.14)
EPS x GHG_GDP			0.318***	0.313***	0.300***
			(3.73)	(3.92)	(3.79)
Country dummies	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Time dummies	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Constant	– 3.035***	– 3.346***	– 3.149***		0.322
	(– 3.87)	(– 3.89)	(– 3.00)		(0.32)
atanhrho_12					
Constant	– 0.191**	– 0.228***	– 0.330***	– 0.322***	– 0.319***
	(– 2.18)	(– 2.67)	(– 3.33)	(– 3.61)	(– 3.69)
Full model					
Observations	902.000	881.000	873.000	846.000	815.000
Log pseudo-likelihood	– 126.6912	– 72.26051	– 42.50756	33.37484	67.46052

Table 1 (continued)

	(1) BASE (LAG1)	(2) EPS_TOT (LAG1)	(3) EPS_TOT&GHG (LAG1)	(4) (LAG2)	(5) LAG3
Wald test model (*p value*)	0.0000	0.0000	0.0000	0.0000	0.0000
Wald test of interaction terms (1) (2) (3) *(p value*)			0.0000	0.0000	0.0000
Wald test of interaction terms (4) (5) (6) (*p value*)			0.0001	0.0005	0.0011

Note: z statistics in parentheses. all variables in logarithms. Conditional mixed-process estimator with robust standard errors. *Atanhrho* is the (unbounded) correlation coefficient between equation and * , ** , *** indicate 10%, 5%, 1% significance levels

Table 2 Direct and indirect effects of market, non-market and technology support environmental policy stringency (EPS) on export market shares

		(1) EPS_MKT (LAG1)	(2) EPS_NMKT (LAG1)	(3) EPS_TECH-SUP (LAG1)	(4) All Sub-Indices (LAG1)	(5) (LAG2)	(6) LAG3
Equation 2.a							
EXP market share							
ULC		0.0534	– 0.105	– 0.0603	– 0.145*	– 0.213**	– 0.230***
		(0.60)	(– 1.22)	(– 0.61)	(– 1.76)	(– 2.51)	(– 2.62)
INV_EMP		0.238***	0.241***	0.281***	0.333***	0.288***	0.240***
		(4.73)	(4.63)	(6.18)	(7.96)	(5.67)	(4.19)
TPAT_POP		0.204***	0.267***	0.149***	0.195***	0.218***	0.208***
		(8.75)	(9.67)	(7.04)	(7.77)	(8.79)	(8.82)
POP		– 1.734***	– 1.260***	– 1.529***	– 1.405***	– 1.347***	– 1.228***
		(– 9.50)	(– 6.70)	(– 7.70)	(– 7.25)	(– 7.17)	(– 6.58)
EXC		0.00717	0.228**	0.211**	0.200*	0.180*	0.151*
		(0.07)	(2.26)	(2.06)	(1.95)	(1.95)	(1.78)
EPS_MKT	(1)	0.00172			– 0.0365	– 0.0298	– 0.0365
		(0.08)			(– 1.38)	(– 1.12)	(– 1.37)
EPS_NMKT	(2)		0.0691***		0.0521**	0.0569**	0.0558***
			(3.14)		(2.16)	(2.57)	(2.75)
EPS_TECHSUP	(3)			0.0492***	0.0403**	0.0407***	0.0468***
				(3.21)	(2.48)	(2.69)	(3.23)
GHG_GDP	(4)	– 0.301***	– 0.178***	– 0.0839*	– 0.162***	– 0.152***	– 0.107*
		(– 5.08)	(– 2.83)	(– 1.95)	(– 2.89)	(– 2.72)	(– 1.91)
EPS_MKT x GHG_GDP	(5)	0.134***			0.0917***	0.0701**	0.0490
		(4.98)			(2.77)	(2.25)	(1.61)
EPS_NMKT x GHG_GDP	(6)		0.0795***		0.0202	0.0228	0.0191
			(4.29)		(0.95)	(1.13)	(1.03)

Table 2 (continued)

		(1) EPS_MKT (LAG1)	(2) EPS_NMKT (LAG1)	(3) EPS_TECH-SUP (LAG1)	(4) All Sub-Indices (LAG1)	(5) (LAG2)	(6) LAG3
EPS_TECHSUP x GHG_GDP	(7)			0.134***	0.0774***	0.0865***	0.105***
				(6.56)	(3.26)	(3.90)	(4.88)
Country dummies		*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Time dummies		*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Constant		– 2.894***	– 1.759***	– 2.163***	– 1.858***	– 2.266***	– 2.219***
		(– 8.12)	(– 4.36)	(– 6.16)	(– 5.13)	(– 6.66)	(– 6.85)
Equation 2.b							
Patent intensity							
RD_GDP		0.671***	0.794***	1.510***	0.970***	0.993***	1.009***
		(4.44)	(5.55)	(9.40)	(6.39)	(7.22)	(7.27)
POPD		– 0.296	– 0.932	1.249*	0.255	0.803	0.905
		(– 0.51)	(– 1.49)	(1.73)	(0.39)	(1.35)	(1.48)
EPS_MKT	(8)	0.0415			0.00971	– 0.0338	– 0.0678
		(0.55)			(0.10)	(– 0.35)	(– 0.72)
EPS_NMKT	(9)		0.0980*		0.163***	0.142***	0.140***
			(1.84)		(3.40)	(3.16)	(3.21)
EPS_TECHSUP	(10)			– 0.0466	– 0.0562	– 0.0188	– 0.00856
				(– 0.81)	(– 0.87)	(– 0.30)	(– 0.14)
GHG_GDP	(11)	– 0.255	– 0.167	0.404***	0.109	0.123	0.0955
		(– 1.64)	(– 1.27)	(2.92)	(0.61)	(0.76)	(0.59)
EPS_MKT x GHG_GDP	(12)	0.672***			0.508***	0.409***	0.402***
		(7.64)			(3.44)	(3.17)	(3.13)
EPS_NMKT x GHG_GDP	(13)		0.304***		– 0.0539	0.142***	– 0.0227
			(6.98)		(– 0.93)	(3.16)	(– 0.47)

Table 2 (continued)

		(1) EPS_MKT (LAG1)	(2) EPS_NMKT (LAG1)	(3) EPS_TECH-SUP (LAG1)	(4) All Sub-Indices (LAG1)	(5) (LAG2)	(6) LAG3
EPS_TECHSUP x GHG_GDP	(14)			0.186^{**}	0.113	0.0967	0.0591
				(1.97)	(0.99)	(0.91)	(0.56)
Country dummies		*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Time dummies		*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Constant		-2.149^{**}	-3.255^{***}	– 0.857	-1.853^{*}	1.048	1.729^{*}
		(– 2.32)	(– 3.24)	(– 0.77)	(– 1.86)	(1.19)	(1.88)
atanhrho_12							
Constant		-0.480^{***}	-0.399^{***}	-0.297^{***}	-0.560^{***}	(– 5.77)	-0.581^{***}
		(– 5.19)	(– 3.81)	(– 3.11)	(– 5.55)	(– 5.77)	(– 6.43)
Full model							
Observations		849.000	839.000	768.000	734.000	707.000	677.000
Log pseudolikelihood		42.84087	– 19.54739	224.8626	295.8385	374.8787	408.0863
Wald test		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Wald test of interaction terms (1) (4) (5) (*p* value)					0.0001	0.0008	0.0078
Wald test of interaction terms (2) (4) (6) (*p value*)					0.0001	0.0008	0.0046
Wald test of interaction terms (3) (4) (7) (*p value*)					0.0001	0.0000	0.0046
Wald test of interaction terms (8) (11) (12) (*p value*)					0.0000	0.0000	0.0000
Wald test of interaction terms (9) (11) (13) (*p value*)					0.0041	0.0087	0.0102
Wald test of interaction terms (10) (11) (14) (*p value*)					0.4020	0.6545	0.8474

Note: z statistics in parentheses. All variables in logarithms. Conditional mixed-process estimator with robust standard errors. *Atanhrho* is the (unbounded) correlation coefficient between equation and * , ** , *** indicate 10%, 5%, 1% significance levels namely, the weak and narrow versions of PH are tested in equation (b), while the strong version is tested both directly in Eq. (a) and indirectly in Eqs. (a) and (b).

The technology gap export model is generally supported both in the original form and in all other integrations. To better understand the results, we underline that in the model all variables are expressed in relative terms with respect to the average across countries. Specifically, technological factors have a positive impact on export market share: investment per employee (INV_EMP) and patent intensity (PAT_POP) have significant and positive coefficients. Furthermore, price factors are determinants for international competitiveness. On the one hand, the exchange rate (EXCH) has a positive coefficient and is not always significant because depreciation facilitates the international price-competitiveness, but obviously with a decreasing impact over time. Finally, unit labor cost (ULC) has generally insignificant coefficients, while countries with a larger population tend to have lower market shares (largest domestic market).

According to the literature (Ambec et al. 2013; Lanoie et al. 2008; Martínez-Zarzoso et al. 2019), the use of lags corroborates the significance of estimations both in conceptual and methodological terms: consistently with the PH framework, green policies need time to produce effects and be effective; different lags permit us to consider different temporal perspectives of policy strategies (short and medium term); the introduction of lags can attenuate potential cases of simultaneity between the dependent and independent variables (as in the case of Kaldor's paradox).

Let us analyze in depth the empirical findings related to the PH framework. The general framework of PH is supported in the short and medium term and the moderating factor, pollution intensity, is positive and significant.

The weak version is strongly verified with a significance level of 1% for all correspondent coefficients in the short and medium term. Indeed in columns (2), (3), (4), and (5) of Equation 1.b the coefficients of EPS are equal to 0.173, 0.116, 0.112, 0.100, respectively, with significance at 1% for the first coefficient and at 10% for the other ones; moreover, in columns (3), (4), and (5) the coefficient of EPS x GHG_GDP is significant at 1% and it is equal to 0.318, 0.313, 0.300, respectively. Estimates also support the strong version of PH; the stringency of green policies has both a direct and indirect positive impact on international competitiveness. The two-equation model captures the indirect impact of EPS on exports represented by the positive and significant coefficient of PAT_POP, which in turn takes into account also the positive and significant impact of EPS on PAT_POP. This result is valid both with and without the moderating effect regarding pollution intensity. Specifically, in Table 1, equation 1.a and columns (2), (3), (4), (5), the coefficient of EPS is always positive and significant at 1% with values equal to 0.115, 0.0897, 0.107, 0.105, respectively, and the coefficient of PAT_POP is positive and significant at 1% with values equal to 0.226, 0.243, 0.266, 0.254, respectively.

Results also show a negative direct impact of pollution intensity on exports: the coefficient of GHG_GDP is always negative and significant at 1%; namely, in Table 1, equation 1.a, its values in columns (3), (4), and (5) are equal to – 0.192, – 0.215, – 0.214, respectively.

In order to better understand the moderating impact of pollution intensity on the relationship between green policies and patents and green policies and export

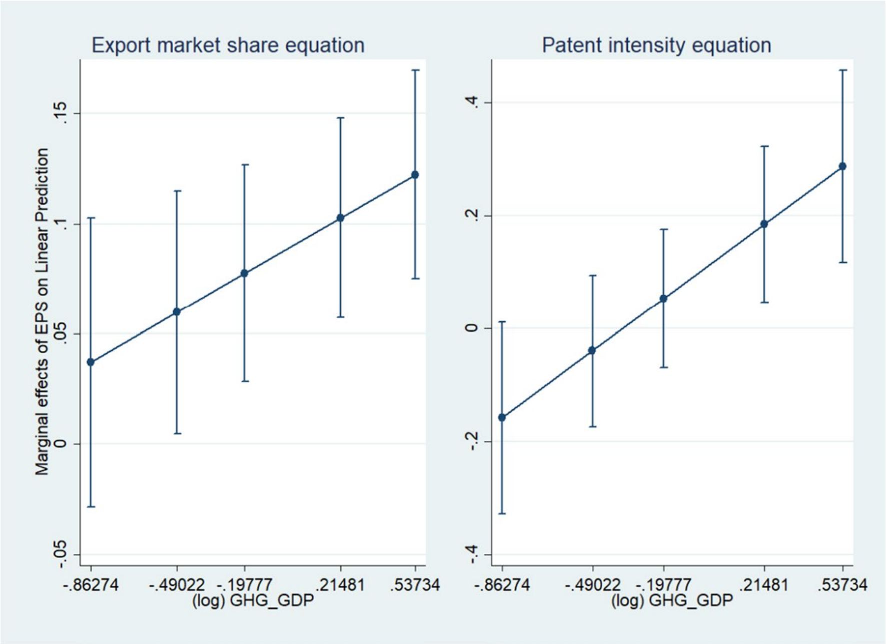

Fig. 2 Marginal effects of Environmental Policy Stringency index (EPS). Note: Marginal effects of EPS sub-indices (MKT and NMKT) estimates, from Table 1 (column 3) and equation (1) and (2), at percentile values (p10, p25, p50, p75, p90) of (log) GHG_GDP variable, using the following formulas: dEPSSH/dEPS = $\beta_6 + \beta_8$ GHG_GDP and dPAT_POP/dEPS = $\beta_3 + \beta_5$ GHG_GDP . Level of confidence interval: 95%. * and ** indicate 10% and 5%, significance levels

shares, we have also graphically represented the positive average marginal effects of EPS on PAT_POP and on EXPSH, as GHG_GDP (percentiles) varies, in our system of two equations (column 3), in Fig. 2. For Eq. (a), these effects are always positive, while for Eq. (b), they become positive for values of GHG_GDP above the median. Overall, it appears that the incentive to innovate as a result of green policies increases with the level of pollution intensity.

When looking at different policy instruments (market-based and non-market-based policies in Table 2 and Figs. 3 and 4) and concentrating on equation (4), which takes into account their joint effect, we find support for the narrow Porter hypothesis only for high levels of pollution intensity (see Fig. 4). When looking at the impact of market-based and non-market-based instruments on international competitiveness (Fig. 3), we find that non-market-based instruments have a larger positive impact on exports with respect to market-based instruments at all levels of pollution intensity. Finally, we find that technology support measures stimulate competitiveness: in Table 2 equation 2.a in columns (4), (5), and (6) the coefficient of EPS_TECHSUP is significant at 5, 1, and 1%, respectively, and it is equal to 0.0403, 0.0407, 0.0468, respectively, also the coefficient of EPS_TECHSUP x GHG_GDP is significant at 1% and equal to 0.0774, 0.0865, 0.105, respectively.

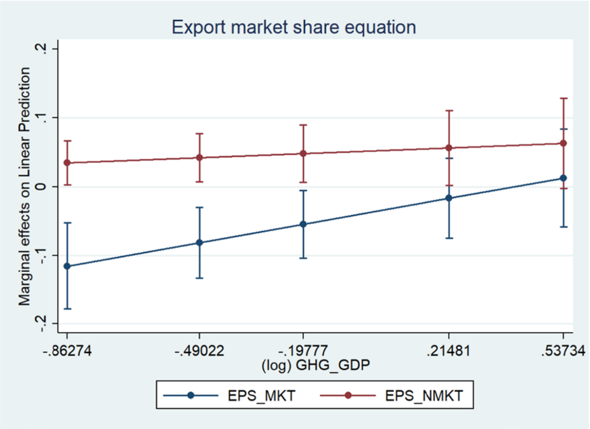

Fig. 3 Marginal effects of market (MKT) and non-market (NMKT) Environmental Policy Stringency (EPS) indexes – export market share equation. Note: Average marginal effects of EPS sub-indices (MKT and NMKT) estimates, from Table 2 (column 4) and equation (1) and (2), at percentile values (p10, p25, p50, p75, p90) of GHG_GDP variable, using the following formulas: dEPSSH/dEPS_MKT = $\beta_{6\_EPS\_MKT}$ + β_8 GHG_GDP and dEPSSH/dEPS_NMKT = $\beta_{6\_EPS\_NMKT}$ + β_8 GHG_GDP. Level of confidence interval: 95%. * and ** indicate 10% and 5%, significance levels

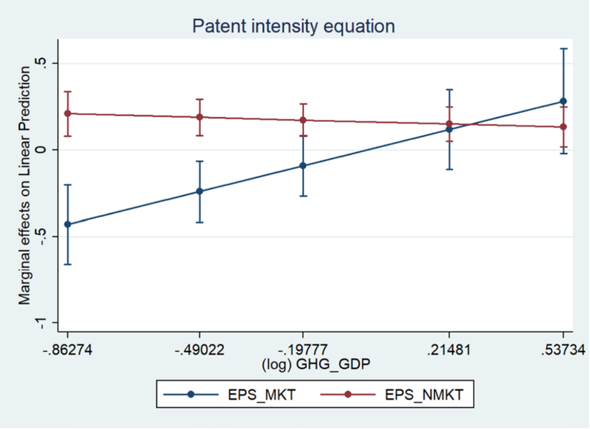

Fig. 4 Average marginal effects of market (MKT) and non-market (NMKT) Environmental Policy Stringency (EPS) indexes - patent intensity equation. Note: Average marginal effects of sub-indices (MKT and NMKT) of EPS estimates, from Table 2 (column 4) and equation (1) and (2), at percentile values (p10, p25, p50, p75, p80, and p90) of GHG_GDP variable, using the following formulas: dPAT_POP/dEPS_MKT = $\beta_{3\_EPS\_MKT}$ + β_5 GHG_GDP and dPAT_POP/dEPS_NMKT = $\beta_{3\_EPS\_NMKT}$ + β_5 GHG_GDP. Level of confidence interval: 95%. * and ** indicate 10% and 5%, significance levels

However, these measures do not appear very effective for innovation: the only significant coefficient is the one of EPS_TECHSUP x GHG_GDP in column (3) with value equal to 0.186 (significant at 5%).

5 Discussion

The results of this paper support the weak and strong versions of PH at international macroeconomic level: green regulation positively impacts innovation in line with previous studies (Jaffe and Palmer 1997; Brunnermeier and Cohen 2003; Rubashkina et al. 2015; Fabrizi et al. 2018; Martínez-Zarzoso et al. 2019; De Santis et al. 2021) and can improve countries' international competitiveness both directly and indirectly through its positive impact on innovation. The general empirical confirmation of the strong version of the Porter hypothesis for international competitiveness is in line with the results of other empirical studies (Costantini and Mazzanti 2012; Lodi and Bertarelli 2023), but with important different elements. First of all, we have considered all export sectors at the macroeconomic level. Moreover, we have originally implemented the two-equation model in order to capture the green policies' impact on international competitiveness both directly (by the policy variables in the export equation) and indirectly (by the patent variable in the export equation that takes into account also the effect of green policies on innovation as estimated in the patents equation). Differently from Lanoie et al. (2008), using a similar model but looking at business performance, we have found a positive indirect impact of green regulation on exports at the macroeconomic level, supporting the strong version of the Porter hypothesis. We have also found a positive direct impact of green regulation on exports, which is coherent with the theoretical and empirical contributions arguing that the ecological transition can improve the non-price competitiveness of exports and consequently our results could capture the positive impact of green standards on the income elasticity of demand (Galindo et al. 2020; Guarini and Porcile 2016; Althouse et al. 2020); specifically, similarly to the national context, in the global markets green standards contribute to increasing consumers' preferences towards green products by making them more aware of climate change (Peattie 2001) and available to pay a premium on price for green goods (Codron et al. 2006); moreover, green standards induce firms to demand more green technologies and equipment (Costantini and Crespi 2008).

The empirical analysis sheds new light on the role of pollution intensity, which is negative for international competitiveness but at the same time is a positive moderating factor of the impact of regulation on innovation and exports. The fact that the effectiveness of green policies increases with pollution intensity supports the idea that high levels of pollution intensity make the ecological conversion more "profitable" in the global market: the high revenues of this change overcome the compliance costs. On the supply side, this finding is consistent with the PH framework (Porter and Linde 1995b) where pollution, as waste, reflects various forms of inefficiency, thus the most polluting countries have the highest potential margins of improvement in terms of production efficiency, and consequently, in terms of value added. On the demand side, a change in the "green image" of a country could be really appreciated by international consumers as happens at microlevel, where the green reputation of a firm increases thanks to its green efforts (Majumdar and Marcus 2001; Dangelico and Pujari 2010; Kunapatarawong and Martínez-Ros 2016).

The results of this paper have several theoretical implications. From a theoretical perspective, they suggest the importance of integrating the Porter hypotheses within the technology gap approach to trade. To the extent that innovation is the main driver of international competitiveness in the medium term, environmental regulation can indirectly and positively affect international market shares if it contributes to product and process innovation. The paper's second important theoretical contribution is the moderating role of pollution intensity. This suggests the importance of integrating the Porter hypotheses with the literature pointing to the heterogeneity of the impact of regulation across sectors/activities/countries with different levels of pollution intensity (Lanoie et al. 2008). It also paves the way to regarding the strong Porter hypothesis as a conditional hypothesis which can find or not find support depending on the conditions that might affect the balance between the costs and benefits of a more stringent environmental regulation (Petroni et al. 2019).

6 Concluding remarks and policy implications

Some significant policy implications derive from the findings of this paper. National institutions should incorporate green policies with industrial and trade policies (Anzolin and Lebdioui 2021) by promoting a holistic vision and implementing a multi-tool strategy for the sustainable competitiveness defined as "the set of institutions, policies and factors that make a nation productive over the longer term, while ensuring social and environmental sustainability" (Corrigan et al. 2014). For instance, the European Union is working to address the trade policy according to the European Green Deal framework (European Union 2021). Green regulation can turn out to be instrumental for international competitiveness thanks to innovation processes by transforming the ecological issues from a burden to a business opportunity. This path can represent a win–win perspective for all trade partners only with international cooperation on technological transfer and institutional capacity building, given the complex international market characterized by intensive global relationships across very different national economic contexts with various technological specializations (Poletti et al. 2021; Meliciani 2001). The introduction of green instances in the trade agreements entails important innovations in terms of rules, tools, the methods of international cooperation and the processes of civil society participation (Velut et al. 2022); therefore, in order to be effective, institutions should consider the multidimensional nature of green innovations (such as their technological, legal, economic, social, and political dimensions) (Zefeng et al. 2018). Green innovation policies can sustain a general framework of competitiveness not based on low-cost strategies, but rather on technological and human capabilities, allowing for the pursuit of the social sustainability of international trade. This policy perspective becomes necessary for establishing international trade agreements conforming to social and environmental sustainability. The implementation of green standards generates international economic advantages in the medium and long term; therefore, governments should set green policy strategies according to the first mover advantage approach (Porter and van der Linde 1995b).

This paper also has some limitations that will lead to future research. First, as for the majority of studies on the Porter hypotheses, the analysis is based on advanced countries for which we have found some support for a positive effect of environmental regulation on exports; further studies could enlarge the sample to include also emerging and developing countries to test whether these results can be generalized. Broadening the knowledge to countries with different levels of development is important since green regulations have large externalities and effective policies should be designed and coordinated at the international level. Moreover, the finding that the impact of regulation differs according to the level of pollution intensity suggests the importance of broadening our understanding of the conditions under which the strong Porter hypothesis is supported. For example, Petroni et al. (2019) suggest the possible role of value appropriation through, for example, firms' green reputation and brand effects, while Fabrizi et al. (2018) identify the importance of the policy mix between green regulation and green networks. Future studies, at both country and firm level, could focus on the moderating factors affecting the relationship between green regulation and competitiveness. This would allow for the conception of more tailored policies for reconciling competitiveness with sustainability.

Appendix 1

Table 3 The determinants of export market share and technology intensity: Control variables and expected impact

Variable name	Definition	Expected effect on export shares	Literature
ULC	Unit labor cost, (total economy, index, 2015 = 100)	Negative. Higher unit labor costs lead to higher prices with a negative impact on exports	Soete (1981); Laursen and Meliciani (2002; 2010); Evangelista et al. (2015); (Dosi et al. 2015)
INV_EMP	Gross fixed capital formation (US dollar, constant prices, PPPs, millions) over employment (persons, millions)	Positive. Investment contributes to expand the capacity and economies of scale and is a proxy of embodied technology, favoring exports as well as the survival in export markets	Soete (1981); Laursen & Meliciani (2010); Dosi, Grazzi & Moschella (2015)
POP	Total population (thousands)	Ambiguous. Population is a proxy for size: larger countries may export more in absolute value, but small countries are more open to trade	Soete (1981); Laursen & Meliciani (2010); Costantini and Mazzanti (2012); Dosi, Grazzi & Moschella (2015)
EXCH	Exchange rates (monthly averages, national currency per US dollar)	Positive. A depreciation of the exchange rate makes domestic goods more competitive thus increasing export market shares	Laursen & Meliciani (2002, 2010); Bolatto et al. (2022)
TPAT_POP	Total triadic patents over population	Positive. Patents are a proxy of innovation which positively affects export market shares	Soete (1981); Laursen & Meliciani (2002); Dosi, Grazzi & Moschella (2015); Costantini and Mazzanti (2012)
Variable name	Definition	Effect on innovation (patent intensity)	Literature
POP_D	Total population over area (sq. km)	Positive. Population density is a proxy of agglomeration economies that favor innovation	Marrocu et al. (2013); Di Cagno et al. (2016, 2021)
RD_GDP	Total R&D expenditure over GDP	Positive. Patents have been treated as an output of the knowledge production function with R&D as an input. Patents can be generated by R&D	Griliches (1998); Di Cagno et al. (2014); Nagaoka et al. (2010); Fabrizi et al. (2018)

Table 4 Description of variables

Variable name	Definition	Source	Year coverage
EXPSH	Export of goods (US dollar, Constant prices, PPPs) market share	Own elaborations on OECD data	1990–2020
ULC	Unit labor cost, (total economy, index, 2015 = 100)	OECD data	1990–2020
INV_EMP	Gross fixed capital formation (US dollar, Constant prices, PPPs, millions) over employment (persons, millions)	Own elaborations on OECD data	1990–2020
POP	Total population (thousands)	OECD data	1990–2020
POP_D	Total population over area (sq. km)	Own elaborations on OECD data	1990–2020
EXCH	Exchange rates (monthly averages, national currency per US dollar)	OECD data	1990–2020
TPAT_POP	Total triadic patents over population	Own elaborations on OECD data	1990–2020
RD_GDP	Total R&D expenditure (2015 Dollars - Constant prices and PPPs, millions) over GDP ((2015 Dollars - Constant prices and PPPs, millions)	Own elaborations on OECD data	1990–2020
GHG_GDP	Total greenhouse gases and emissions incl. land use, land-use change, and forestry per unit of GDP	Own elaborations on OECD data	1990–2020
EPS	Environmental policy stringency index: all components	OECD data	1990–2020
EPS_MKT	Environmental policy stringency index: Market-based policies	OECD data	1990–2020
EPS_NMKT	Environmental policy stringency index: Non-market-based policies		
EPS_TECHSUP	Environmental policy stringency index: Technology support policies	OECD data	1990–2020

Table 5 Summary statistics

Variable	Obs.	Mean	Std. Dev.	Min	Max
EXPSH	967	1	1.140728	0.010246	5.663581
ULC	846	1	0.198315	0.332747	1.997714
INV_EMP	1010	1	0.418754	0.171566	5.018024
POP	1054	1	1.57661	0.007263	9.391316
POP_D	1044	1	0.963041	0.01629	3.8938
EXCH	1011	1	3.227751	4.09E-05	21.99378
RD_GDP	670	1	0.574545	0.10282	2.801784
PAT_POP	1014	1	1.317736	0	7.672852
GHG_GDP	1037	1	0.681046	– 0.27547	4.765108
EPS	1054	1	0.60034	0	2.50093
EPS_MKT	1054	1	0.745095	0	3.813314
EPS_NMKT	1054	1	0.624259	0	1.876419
EPS_TECHSUP	1054	1	0.846744	0	3.811361

Table 6 Correlations

Nr.	Variable	1	2	3	4	5	6	7	8	9	10	11	12	13
1	EXPSH	1												
2	ULC	0.0839	1											
3	INV_EMP	0.0252	0.2436	1										
4	POP	0.8274	0.1086	– 0.0016	1									
5	POP_D	0.2455	0.2016	0.1517	0.0512	1								
6	EXCH	0.0888	0.046	– 0.1033	0.0966	0.3578	1							
7	RD_GDP	0.2548	0.2289	0.3126	0.1599	0.469	0.1988	1						
8	PAT_POP	0.1989	0.1582	0.5029	0.1151	0.3644	– 0.0459	0.5925	1					
9	GHG_GDP	– 0.0807	– 0.4249	– 0.2496	– 0.0333	– 0.168	– 0.019	– 0.0978	– 0.2715	1				
10	EPS	0.0883	0.5952	0.4497	0.0439	0.1905	– 0.0605	0.2244	0.3592	– 0.4872	1			
11	EPS_MKT	– 0.0539	0.2757	0.2578	– 0.0675	0.0127	– 0.0865	0.1866	0.2074	– 0.3919	0.6926	1		
12	EPS_NMKT	0.0751	0.6256	0.4125	0.0438	0.1795	– 0.0017	0.1395	0.2321	– 0.4469	0.9284	0.5399	1	
13	EPS_TECHSUP	0.1528	0.4293	0.4066	0.0914	0.2266	– 0.1029	0.2621	0.4743	– 0.3754	0.8278	0.4102	0.625	1

Appendix 2

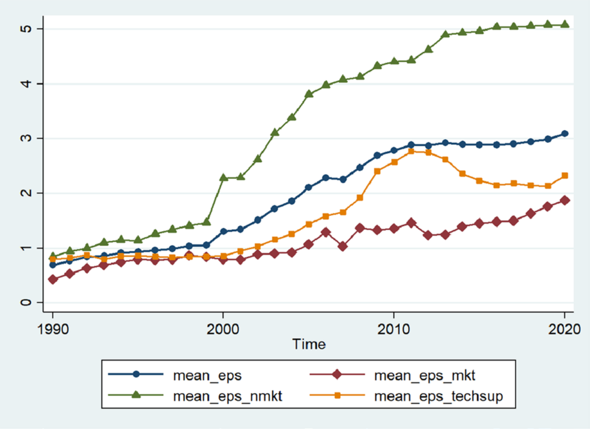

Fig. 5 Total Environmental Policy Stringency index (EPS) and sub-indices (annual average of OECD countries) over time. Note: MKT index policy instruments: CO_2 Trading Schemes, Renewable Energy Trading Scheme, CO_2 Taxes, Nitrogen Oxides (NOx) Tax, Sulphur Oxides (Sox) Tax, Fuel Tax (Diesel); NMKT index policy instruments: Emission Limit Value (ELV) for nitrogen oxides (Nox), ELV for sulfur oxides (Sox), ELV for Particulate Matter (PM), Sulphur content limit for diesel; TECHSUP policies: Public research and development expenditure (R&D), Renewable energy support for Solar and Wind

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Table 7 Total Environmental Policy Stringency index (EPS) and sub-indices by OECD countries (mean 1990-2020)

Nr.	Countries	EPS_TOT	Countries	MKT	Countries	NMKT	Countries	TECHSUP
1	Switzerland	2.8638	Sweden	3.1129	Germany	4.3468	Japan	3.6048
2	Japan	2.8530	Denmark	2.3387	Luxembourg	4.3468	Switzerland	3.2984
3	Finland	2.8109	Norway	2.2688	Finland	4.1129	France	3.1613
4	France	2.8002	Poland	1.7151	Austria	4.0968	Finland	2.8790
5	Denmark	2.6747	Italy	1.6828	Switzerland	4.0565	Luxembourg	2.6613
6	Sweden	2.6559	United Kingdom	1.6290	Czech Republic	3.9758	Italy	2.4839
7	Luxembourg	2.5977	France	1.5699	Netherlands	3.9355	Netherlands	2.4435
8	Italy	2.5905	Finland	1.4409	Belgium	3.7823	Estonia	2.1855
9	Norway	2.5439	Japan	1.2688	United Kingdom	3.7097	Germany	2.1290
10	Germany	2.4758	Switzerland	1.2366	Japan	3.6855	Denmark	2.0161
11	Netherlands	2.4167	Czech Republic	1.1935	Korea, Rep.	3.6855	Canada	2.0081
12	Austria	2.3091	Hungary	1.1720	Denmark	3.6694	Austria	1.9274
13	United Kingdom	2.2124	Belgium	1.1075	France	3.6694	Norway	1.7097
14	Estonia	2.1326	Slovak Republic	1.0538	Norway	3.6532	Greece	1.5726
15	Czech Republic	2.1263	Ireland	1.0430	Portugal	3.6290	United States	1.5726
16	Belgium	2.0923	Estonia	0.9785	Spain	3.6210	Hungary	1.5161
17	Korea, Rep.	2.0143	Portugal	0.9731	Italy	3.6048	Sweden	1.4597
18	Hungary	1.9982	Australia	0.9624	Poland	3.4758	Korea, Rep.	1.3952
19	Portugal	1.9695	Korea, Rep.	0.9624	Ireland	3.4677	Belgium	1.3871
20	Canada	1.9283	Germany	0.9516	Sweden	3.3952	Turkey	1.3387
21	Spain	1.8943	Austria	0.9032	Canada	3.3790	Australia	1.3145
22	Poland	1.8808	Spain	0.8925	Hungary	3.3065	Portugal	1.3065
23	Greece	1.8522	Netherlands	0.8710	Estonia	3.2339	United Kingdom	1.2984
24	Ireland	1.8047	Turkey	0.8441	Greece	3.1935	Czech Republic	1.2097

Table 7 (continued)

Nr.	Countries	EPS_TOT	Countries	MKT	Countries	NMKT	Countries	TECHSUP
25	United States	1.7428	Greece	0.7903	United States	2.9355	Spain	1.1694
26	Australia	1.6514	Luxembourg	0.7849	Slovenia	2.8790	Slovak Republic	1.1048
27	Slovak Republic	1.6147	Slovenia	0.7742	Slovak Republic	2.6855	Ireland	0.9032
28	Slovenia	1.5108	United States	0.7204	Australia	2.6774	Slovenia	0.8790
29	Turkey	1.4615	Canada	0.3978	Mexico	2.3065	New Zealand	0.5323
30	Mexico	0.8978	Iceland	0.3656	Turkey	2.2016	Israel	0.4758
31	Chile	0.7195	Chile	0.3441	Chile	1.8145	Poland	0.4516
32	Israel	0.5242	Israel	0.2742	Israel	0.8226	Mexico	0.1290
33	New Zealand	0.5116	New Zealand	0.2688	New Zealand	0.7339	Chile	0.0000
34	Iceland	0.3315	Mexico	0.2581	Iceland	0.6290	Iceland	0.0000
	Total	1.9548	Total	1.0927	Total	3.1976	Total	1.5742

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- The research does not involve humans or animals
- The data that support the findings of this study are available from the corresponding author upon request.
- The opinions expressed in this publication are those of the authors.

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