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Renewable energy consumption and international trade: Does climate policy stringency matter?☆

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ABSTRACT

This study explores the connection between renewable energy consumption and international trade, with a particular focus on the influence of climate policy. We argue that this relationship is nonlinear and subject to threshold effects. Using a dynamic threshold model developed by Seo and Shin (2016), we analyze data from 1990 to 2023 for a panel of 29 developed and developing countries. Our findings reveal that climate policy plays a crucial role in shaping the renewable energy–trade nexus, with effects varying according to policy stringency and a country's development level. In developing countries, renewable energy consumption consistently enhances exports, regardless of policy stringency. In contrast, in developed countries, strict policies reduce import dependence, indicating a move toward energy independence, but they may also dampen the positive trade effects of renewable energy due to higher compliance costs and regulatory barriers. These results underscore the need for tailored policy strategies: developed countries should balance ambitious environmental goals with trade efficiency by streamlining regulations and fostering international policy harmonization, while developing countries can leverage renewable energy adoption as a tool to enhance exports, attract investment, and strengthen technological capabilities.

1. Introduction

Energy is a fundamental driver of societal well-being and economic development. However, the heavy reliance on fossil fuels has led to significant environmental degradation and a sharp rise in carbon dioxide emissions, thereby exacerbating global warming. In response, the energy sector is undergoing a transformative shift towards renewable energy sources, aiming to improve efficiency and minimize environmental harm (Gyamfi et al., 2018; Panwar et al., 2011).

The transition to renewable energy is increasingly reshaping international trade dynamics, particularly in the areas of energy imports and exports. As nations reduce their dependence on fossil fuels and address the challenges of climate change, renewable energy technologies—such as wind and solar—have become central to national energy strategies (Lewis, 2014; Khan et al., 2020; Ilechukwu and Lahiri, 2022). This shift is transforming global trade patterns and has sparked growing academic interest in the interplay between trade and renewable energy—two key pillars of sustainable economic development (Zeren and Akkuş, 2020). Technological transfer, closely intertwined with international trade, has played a crucial role in accelerating the global diffusion of renewable energy solutions. As the global energy landscape evolves, trade in renewable energy is expected to have a significant impact on global trade patterns, while fostering job creation, economic growth, and technological innovation (Medvedkina and Khodochenko, 2020).

Governments worldwide have concurrently implemented various policy measures—including subsidies, tax incentives, and environmental regulations—to promote renewable energy adoption and reduce greenhouse gas emissions (Alagoz and Alghawi, 2023; Lewis, 2014; Valentine, 2011). While these policies aim to lower carbon leakage and enhance energy security, they also create trade pressures as countries

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seek to protect their domestic renewable energy industries while capitalizing on the economic benefits of the green transition. This dynamic has intensified global competition for leadership in renewable energy technologies, thereby reshaping international economic relations (Alagoz and Alghawi, 2023).

Despite a growing body of research on the relationship between renewable energy use and trade, the findings remain inconclusive. Some studies report a positive impact of renewable energy on trade performance (Brini et al., 2017; Khan et al., 2020), while others suggest that it may undermine trade competitiveness (Zeren and Akkuş, 2020; Ilechukwu and Lahiri, 2022). Several factors may help explain these divergent findings. First, much of the existing literature treats trade as a monolithic concept, without differentiating between its key components—such as net exports and net imports—which may respond differently to renewable energy adoption (Aïssa et al., 2014; Tiba and Frikha, 2018; Ilechukwu and Lahiri, 2022). Second, only a limited number of studies have utilized nonlinear dynamic threshold models to explore the effect of renewable energy on trade across different countries, with the majority assuming a linear relationship despite growing empirical evidence of nonlinear dynamics (Zhang et al., 2021). Third, there is a lack of research exploring the moderating and mediating factors that influence the renewable energy-trade nexus. While understanding the direct relationship between renewable energy and trade is essential, identifying the underlying mechanisms—such as mediators and moderators—that influence this relationship is equally important. Among the few studies that consider moderation effects, Opeyemi et al. (2019) analyzed the dynamic relationship between renewable energy usage and trade performance in sub-Saharan Africa (SSA), accounting for institutional factors such as corruption control, regulatory quality, and private sector access to finance. The study found that, in the absence of effective institutions and regulatory support, renewable energy adoption can negatively affect trade performance. However, when supported by strong corruption control, an improved regulatory framework, and enhanced financial access, renewable energy usage contributed positively to manufacturing exports.

This study addresses these gaps by examining whether the stringency of climate policy influences the relationship between trade and renewable energy consumption. While previous research has explored the individual impacts of environmental policy stringency on renewable energy (see Marra and Colantonio, 2021; Bashir et al., 2022; Alsagr, 2023; Hassan et al., 2024) or trade (see Brandi et al., 2020; Usman et al., 2024), the conditional influence of climate policies remains largely underexplored. In this context, this paper addresses a crucial question: How do climate change policies shape the interplay between renewable energy deployment and global trade dynamics? Climate policies can enhance this relationship by creating regulatory incentives, stimulating technological innovation, and fostering international markets (Popp, 2019; IRENA, 2021; Hale, 2020; Zhang et al., 2021). However, they can also hinder it through trade barriers, domestic subsidies, or technical standards that distort global trade flows (Dorsch and Flachsland, 2017).

Against this backdrop, this study contributes to the literature in several ways. First, it is the first to examine the conditional role of climate policies in the renewable energy-trade nexus. Second, it employs the nonlinear dynamic threshold model developed by Seo and Shin (2016), which allows for the identification of threshold levels at which climate policies become either effective or counterproductive. This model offers several advantages over traditional approaches: it captures nonlinear relationships without imposing a specific functional form, addresses potential endogeneity due to reverse causality, and enables a more accurate interpretation of policy impacts. Third, to account for heterogeneity that might exist among developed and developing countries, we perform the analysis separately for each group of countries. Given their distinct economic characteristics and environmental challenges, developing countries' trade flows may respond differently to the adoption of renewable energy compared to those of developed nations (Brandi et al., 2020). Fourth, the paper provides valuable empirical evidence to guide the formulation of more effective climate and trade policies. By examining the impact of varying policy stringencies on the relationship between renewable energy and trade, this study provides nuanced insights into balancing environmental sustainability and economic growth within the context of global trade and energy transition.

The rest of the paper is structured as follows: Section 2 offers a brief review of the existing empirical literature. Section 3 details the data and presents the empirical methodology proposed by Seo and Shin (2016). Section 4 discusses empirical findings. The conclusion is provided in Section 5, along with the policy implications.

2. Background

This section synthesizes the economic literature that motivated the question regarding the conditional impact of climate change policies on the renewable energy-trade nexus. Our study intersects four key areas: (i) the effect of renewable energy on international trade, (ii) the effect of climate change policies on international trade, (iii) the effect of climate change policies on renewable energy, and (iv) the effect of climate change policies on the link between renewable energy and trade. Each area is discussed in detail below.

2.1. The effect of renewable energy on international trade

The relationship between renewable energy and trade has been a topic of interest in the recent decade. Many studies have attempted to empirically evaluate the effect of using renewable energy on trade. For instance, Ben Jebli and Ben Youssef (2015) investigated the relationship between renewable energy use, non-renewable energy consumption, and trade openness in 69 countries. Using cointegration and panel Granger causality tests over the period from 1980 to 2010, their study revealed a significant bidirectional causality between non-renewable energy consumption and trade. They also found a unidirectional short-run causality from renewable energy use to trade. In another study, Ben Jebli and Ben Youssef (2017) verified the cointegration between trade and renewable energy from 1980 to 2011 using the Johansen-Juselius test.

Ben Jebli et al. (2016) examined 25 OECD countries from 1980 to 2010, using Granger causality tests, and found a positive bidirectional causal relationship between imports and renewable energy consumption. Brini et al. (2017) analyzed the connection between trade, oil prices, economic growth, and renewable energy in Tunisia from 1980 to 2011, discovering a short-term positive relationship. Similarly, Amri (2017) identified a one-way causal relationship between trade and renewable energy use in both developed and developing nations from 1990 to 2012, indicating that trade increases with higher renewable energy consumption. However, Opeyemi et al. (2019) used a System GMM approach to analyze the relationship between trade performance and renewable energy in sub-Saharan Africa from 2004 to 2016, finding a negative correlation.

Khan et al. (2020) examined the interaction between renewable energy consumption, international trade, and environmental quality in Nordic countries from 2001 to 2018. Using a dynamic common correlated effect (DCCE) model, the study found that renewable energy is strongly and positively associated with international trade in Nordic countries**.** Ilechukwu and Lahiri (2022) used a gravity model to analyze panel data from 1990 to 2014. They found that higher renewable energy consumption increases imports and decreases exports. Specifically, a 1 % rise in renewable energy usage results in a 1.026 % decrease in exports and a 0.39 % increase in imports, suggesting that renewable energy reduces trade competitiveness due to higher costs.

Das and Mahalik (2023) used firm-level panel data to investigate the effect of renewable energy intensity on the export performance of six manufacturing industries in India. Utilizing a dynamic panel data model, fixed effect estimators, and Driscoll and Kraay standard errors, they found that renewable energy usage positively impacts export intensity in most of the industries studied.

2.2. The effect of climate change policies on international trade

Climate change policies significantly impact international trade through various mechanisms. The implementation of carbon pricing mechanisms, such as carbon taxes or cap-and-trade systems, increases the cost of carbon-intensive goods, potentially leading to higher prices for imports and prompting countries to adjust trade policies to protect domestic industries or promote cleaner technologies (Timilsina, 2022). Additionally, such policies may result in trade barriers or tariffs on high-emission goods while encouraging trade agreements that focus on the exchange of green technologies and sustainable practices, thus affecting global trade dynamics (Copeland and Taylor, 2004). As countries invest in green technologies, their comparative advantage may shift, altering their trade balance and competitive position (Ward et al., 2019; Jakob, 2021). Climate policies can also lead to shifts in global supply chains as companies seek suppliers with lower carbon footprints or relocate production to regions with favorable environmental regulations, impacting trade patterns. Furthermore, these policies drive innovation in clean technologies, creating new export opportunities for leading nations and potentially boosting their trade sectors (Hepburn et al., 2021). However, regulatory uncertainty from varying standards across countries can pose challenges for businesses, influencing investment decisions and trade flows (Olasehinde-Williams et al., 2023).

Various studies have empirically explored the impact of climate change policies on international trade. For example, Levinson and Taylor (2008) confirmed a relationship between U.S. environmental regulations and trade flows among the U.S, Mexico, and Canada during the period 1977–1986. Their findings indicate that companies facing the highest increases in pollution abatement costs exhibited the highest rises in net imports. Brandi et al. (2020) investigated the effect of environmental regulations and provisions on trade for a panel of developed and developing countries from 1984 to 2016 using a gravity equation model. They found that those stringent environmental regulations led to a decrease in dirty exports and an increase in green exports from developing countries. Usman et al. (2024) focused on the nonlinear effects of stringency environmental policies on trade in the world's most polluted economies over the period 1991–2021. Their results reveal that a positive shock of environmental policy stringency leads to a long-term decrease in conventional tradable energy.

2.3. The effect of climate change policies on renewable energy

Climate change policies profoundly influence the development and deployment of renewable energy technologies. By setting ambitious targets for reducing greenhouse gas emissions, governments create a favorable environment for renewable energy investments. Policies such as feed-in tariffs, renewable portfolio standards, and tax incentives drive demand for renewable energy sources by ensuring stable revenue streams and reducing financial risks for investors. These policies also stimulate innovation in renewable technologies by providing research and development funding, thereby accelerating technological advancements and cost reductions (IEA, 2022). Ad ditionally, international climate agreements and national regulations can promote the adoption of renewable energy by setting clear policy frameworks and creating markets for renewable energy certificates (REN21, 2023). However, the effectiveness of these policies can be inconsistent due to factors such as policy uncertainty and regulatory challenges, which may affect the growth of the renewable energy sector.

Several scholars have provided empirical evidence on the relationship between climate change policies and renewable energy. For instance, Marra and Colantonio (2021) examined the intricate and dynamic interactions between policy stringency and renewable energy use for 12 net energy-importing European Union nations over the period 1990–2015 using a panel vector autoregressive model. Their findings indicate that climate policy stringency has a positive direct and indirect impact on renewable energy consumption. Bashir et al. (2022) employed a panel Westerlund co-integration test and quantile regression approaches to investigate the impact of environmental policies on renewable energy consumption in 29 OECD nations from 1996 to 2018. Their findings indicate that renewable energy consumption in OECD economies is hindered by environmental regulations. Godawska and Wyrobek (2021) studied the impact of strict environmental policy stringency on the development of renewable energy in Poland, the Czech Republic, Slovakia, and Hungary between 1993 and 2012 using a Panel Pooled Mean Group Autoregressive Distributive Lag model. Their results reveal that stricter environmental regulations exert a long-term positive effect on renewable energy production.

Alsagr (2023) employed a QARDL model to examine the impact of stringent environmental policies on renewable energy investment in the BRICS nations. The results show that increases in renewable energy investment are triggered by positive shocks in environmental policy stringency in both the short and long term.

A more recent study by Hassan et al. (2024), based on the CS-ARDL model over the period 1990 to 2019 in 32 OECD countries, shows that a stricter policy stringency index increases renewable energy consumption. Using the same technique, Husain et al. (2024) confirm the effectiveness of environmental policy stringency in promoting renewable energy development in the major OECD nations.

2.4. The effect of climate change policies on the link between renewable energy and trade

Climate change policies may play a crucial role in conditioning the relationship between renewable energy adoption and trade. By setting regulatory frameworks, incentivizing technological innovation, and altering cost structures, these policies can either enhance or hinder trade flows in renewable energy products and related industries.

Beyond their direct effects on renewable energy and trade, climate change policies can positively impact the relationship between them by establishing regulatory frameworks, incentivizing technological innovation, and influencing global economic dynamics (Popp, 2019; Zou and Wang, 2024). International agreements like the Paris Agreement mandate countries to reduce greenhouse gas emissions, compelling investments in renewable energy sources. This creates a global market for renewable technologies and components, thereby fostering international trade (Hale, 2020). National policies, including renewable energy targets, tax incentives, and subsidies, stimulate domestic production and consumption, enhancing trade in renewable energy technologies (Zhang et al., 2021). Additionally, carbon pricing mechanisms and economic incentives make renewable energy more cost-competitive, increasing its attractiveness both domestically and globally (Meckling et al., 2017). Trade policies that reduce tariffs on renewable technologies further promote their adoption and international exchange. These policies also bolster energy security by reducing dependence on fossil fuel imports, thereby affecting trade balances (Cherp et al., 2017). Furthermore, climate policies encourage international cooperation and technology transfer, fostering a global market for renewable energy products and driving geopolitical competition in the green economy. For instance, China's leadership in solar panel manufacturing has significantly impacted global trade dynamics, pushing other countries to enhance their renewable energy sectors to remain competitive (Nahm, 2017). Additionally, investments in resilient infrastructure to cope with climate change are crucial for maintaining trade flows, including those related to renewable energy components (Moser et al., 2019).

However, climate policies can also negatively affect the relationship between renewable energy and trade. Trade barriers, such as tariffs on imported renewable energy technologies or raw materials, can increase costs and slow the adoption of renewable systems. Domestic subsidies for renewable energy might create trade imbalances, potentially leading to disputes with other countries (Dorsch and Flachsland, 2017). Stricter environmental and technical standards can act as trade barriers by limiting the entry of foreign products. Furthermore, climate policies that favor certain types of renewable energy over others can distort global trade flows. Policies that create investment uncertainty or impose local content requirements can also deter foreign investment and complicate international trade in renewable energy equipment.

Given these opposing effects, understanding how climate policies condition the renewable energy-trade relationship is essential for designing effective policies that balance environmental goals with trade competitiveness. This study contributes to the literature by empirically examining these conditional effects, identifying the thresholds at which policy measures become either beneficial or restrictive for trade.

3. Empirical strategy

3.1. Framework

The purpose of this paper is to analyze how climate change policies may lead to non-linearity in the effect of renewable energy on trade, specifically on exports and imports. In other words, we investigate whether different levels of climate change policies impact the effect of renewable energy on trade. To this end, we employ the panel threshold model proposed by Seo and Shin (2016). This approach uses a GMM estimator within a dynamic panel threshold model, accommodating a potentially endogenous threshold variable.

Formally, the model examines if the relationship between variables x and y changes depending on whether a variable z is below or above a threshold $\bar{z}$. Unlike existing literature, our approach does not exogenously set the threshold level; instead, it allows the data to determine $\bar{z}$ and its standard deviation endogenously. Additionally, the method permits more than one coefficient in the investigated relationship to change with the threshold.

Our contribution to the existing literature lies in employing a threshold regression approach to investigate the conditions under which renewable energy enhances trade. To our knowledge, this is the first study to use the threshold approach to examine the contingency effects in the renewable energy–trade relationship. We argue that this approach provides valuable insights into the conditional relationship between renewable energy and trade.

To illustrate the Seo and Shin (2016) method, consider the following basic regression:

$$y_{it} = \mu_i + \beta'(\bar{z})\, x_{it} + e_{it} \tag{1}$$

, where β is the estimated coefficient and x_{it} is vector of explanatory variables. If the relationship between y_{it} and x_{it} is linear, estimating (1) gives the best fit of the data. However, if the true model is non-linear, there exists at least one threshold ($\bar{z}$), and the estimation should adopt a method that allows determining the threshold and testing whether it is significant. If the threshold is not significant, it is not binding and (1) can be estimated using traditional techniques. Let's consider a significant threshold ($\bar{z}$). The Seo and Shin (2016) regression is based on the following relationship:

$$y_{it} = X_{it}'\beta + \left(1, X_{it}'\right)\delta\, l\{q_{it} > \gamma\} + \mu_i + \varepsilon_{it} \quad \mathrm{i} = 1, \ldots.\mathrm{N}\ ;\ \mathrm{t} = 1, \ldots\mathrm{T} \tag{2}$$

where X_{it} may include lagged dependent variables, q_{it} is the threshold variable (climate change policies in our case). γ is the threshold level/parameter that divides the equation into two regimes, l (.) is an indicator function, and δ is the slope parameter.

In this paper, we adopt the first-differenced generalized method of moments (GMM) estimators. The key distinguishing feature of the proposed FD-GMM and FD-2SLS approaches, compared to Hansen (1999), is their ability to accommodate both the threshold variable and the regressors as endogenous.

The null hypothesis of this test is:

$$H_0 : \delta_0 = 0 \text{ For any } \gamma \in \Gamma \tag{3}$$

where Γ denotes the parameter space for γ.

Against the alternative:

$$H_1 : \delta_0 \neq 0 \text{ For some } \gamma \in \Gamma \tag{4}$$

Testing whether the model is non-linear is accomplished using the statistic for the null hypothesis, H_0:

$$supW = \underset{\gamma \in \Gamma}{Sup} W_n(\gamma), \tag{5}$$

where $W_n(\gamma)$ is the standard Wald statistic for each fixed γ. According to Seo and Shin (2016), the limiting distribution of this statistic is not asymptotically pivotal, and critical values cannot be tabulated. We bootstrap critical values or p-values.

3.2. Model and data

Our purpose here is to analyze how the level of climate change policies may lead to a non-linearity in the effect of renewable energy on exports and imports. Specifically, we explore whether a threshold level of climate change policy exists that determines the direction—positive or negative—of the impact of renewable energy on trade. To this end, drawing on the work of Doojav et al. (2024), Nguyen et al. (2021), Zhu et al. (2022), and Shakeel (2021), we adopt the following specification:

$$\begin{aligned} Log\ (X_{it}) = c + \beta_1\ Log(RE_{it}) + \beta_2\ Log(Fossil_{it}) + \beta_3\ Log(GDP_{it}) + \beta_4 Climat_{it} \\ + \beta_5 \mathrm{Techpol}_{it} + \beta_6\ Log(REER_{it}) + u_{it} \end{aligned} \tag{6}$$

$$\begin{aligned} Log(M_{it}) = e + \delta_1\ Log(RE_{it}) + \delta_2\ Log(Fossil_{it}) + \delta_3\ Log(GDP_{it}) + \delta_4 Climat_{it} \\ + \delta_5 \mathrm{Techpol}_{it} + \delta_6\ Log(REER_{it}) + \eta_{it} \end{aligned} \tag{7}$$

where i represents the country index and t denotes time. X_{it} and M_{it} represent the volume of a country's exports and imports, respectively. *RE* denotes renewable energy consumption, defined as the percentage of renewable energy in total energy consumption. *Fossil* refers to fossil energy consumption, defined as the percentage of fossil energy in total energy consumption. *GDP* stands for gross domestic product. Climate policy (*Climat*) is measured using the Environmental Policy Stringency Index (EPSI). The EPSI is a quantitative measure assessing the rigor and effectiveness of a country's environmental policies. This index evaluates the stringency of regulations and standards aimed at reducing environmental pollution and promoting sustainable practices. It ranges from 0 (not stringent) to 6 (highest stringency) and is based on the degree of stringency of 14 environmental policy instruments, divided into three equally weighted subindices: market-based (e.g., carbon taxes or trading schemes), non-market-based (e.g., emission limit values), and technology support policies (e.g., public R&D). The latter one plays a crucial role in fostering the transition towards a sustainable energy future, and renewable energy technologies, particularly biomass and biofuels, are increasingly recognized for their potential to contribute to this shift. *Techpol* denotes technology support policies defined as an instrument and an environmental measure, ranged from 0 to 6. Following Bryngemark and Söderholm (2022), Mohammadi and Saddler (2025), Levidow and Papaioannou (2014), we assume that *Techpol* is a proxy for public policies designed to support the utilization of renewable energy sources especially those based on the production of biofuels. *REER* is the real effective exchange rate, while u_{it} and η_{it} represent white noise error terms. The appendix provides a detailed overview of the variables and their respective sources.

To examine whether there is a threshold effect of climate change policies on the impact of renewable energy on trade, Equations (6) and (7) can be rewritten according to the method proposed by Seo and Shin

(2016) as follows:

$$\begin{aligned} Log\ (X_{it}) &= c + \beta_{1L}\ Log(RE_{it}) l\{Climat \leq \gamma\} + \beta_{1U}\ Log(RE_{it}) l\{Climat > \gamma\} \\ &\quad + \beta_2\ Log(Fossil_{it}) + \beta_3\ Log(GDP_{it}) + \beta_4 Climat_{it} + \beta_5 \mathrm{Techpol}_{it} \\ &\quad + \beta_6\ Log(REER_{it}) + u_{it} \end{aligned} \tag{8}$$

$$\begin{aligned} Log\ (M_{it}) &= e + \gamma_{1L}\ Log(RE_{it}) l\{Climat \leq \gamma\} + \gamma_{1U}\ Log(RE_{it}) l\{Climat > \gamma\} \\ &\quad + \gamma_2\ Log(Fossil_{it}) + \gamma_3\ Log(GDP_{it}) + \gamma_4 Climat_{it}\ + \gamma_5 \mathrm{Techpol}_{it} \\ &\quad + \gamma_6\ Log(REER_{it}) + \eta_{it} \end{aligned} \tag{9}$$

where β_{1L} and β_{1U} $(\gamma_{1L}\ and\ \gamma_{1U})$ are, respectively, the coefficients of the lower and upper regime.

We now turn to the expected sign of the different coefficients based on the literature review. We expect the *Fossil* variable to affect positively both components of trade. Fossil energy is currently the most used energy, crucial for manufacturing and transporting items for exports and imports. These items particularly require fossil energy for fuel transportation (Shakeel, 2021; Sadorsky, 2011, 2012). For the *GDP* variable, we expect that an increase in GDP will have a positive effect on both the export and import equations. Increases in GDP facilitate exports by boosting productivity and transferring skills and technology. Similarly, imported intermediate goods represent a key input in production, explaining the positive relationship between GDP and imports (Pawlos, 2004; Halicioglu, 2011; Weil, 2014).

Regarding the *Climat* variable, we expect a negative effect on the export equation. Higher stringent environmental regulations can lead to a decrease in conventional exports. However, in the long run, an efficient energy structure and improved environmental quality that help mitigate climate change are predicted to increase the volume of green exports (Brandi et al., 2020; Usman et al., 2024). We expect an increase in *Climat* to positively affect imports. Improved environmental quality is linked with increased demand for renewable energy consumption, which results in higher import volumes (Ilechukwu and Lahiri, 2022). We expect the *Techpol* variable to have a positive effect on the components of trade. Public R&D can lead to knowledge spillovers that benefit both domestic and international firms, potentially facilitating technology transfer from developed countries to developing nations and fostering trade (Kim and Kim, 2015; Das and Chatterjee, 2021). The effective real exchange rate (*REER*) is expected to negatively affect the export equation and positively affect the import equation. An appreciation of exchange rates results in increased imports and reduced exports, making imports cheaper and exports less competitive.

To investigate the relationship between renewable energy consumption, international trade, and climate change policies, we use a balanced panel data covering 29 nations from 1990 to 2023.[2] Our panel covers a variety of developed and developing countries selected according to their specific characteristics regarding renewable energy production, economic status, policy frameworks, and technological capabilities. Developed countries typically exhibit advanced renewable energy technologies and strong environmental policies promoting renewable energy use and creating comparative advantages in technology transfer, while developing nations are advancing in the export of raw materials used in the production of renewable energy (e.g., abundant solar or wind resources) but exhibit modest policies and regulatory frameworks (Gasser et al., 2022; Hunt et al., 2024).

Due to the lack of data availability for the climate policy stringency index before 1990, we selected the period of 1990–2023. The sample includes 19 developed countries (USA, France, UK, Sweden, Spain, Italy, South Korea, Japan, Ireland, Greece, Germany, Netherlands, Norway, Switzerland, Czechia, Denmark, Canada, Finland, and Belgium) and 10 developing countries (China, India, Indonesia, Mexico, Brazil, Russia, Turkey, South Africa, Hungary, and Poland). The selection of these countries is based on three main considerations. First, the availability and completeness of the Climate Policy Stringency Index, which is only reported for 30 OECD and partner countries, limits the scope of potential observations. As this index plays a central role in our empirical strategy—as the threshold variable used to assess regime-dependent effects—its availability directly determines our sample structure. Second, the sample was constructed to ensure a meaningful level of heterogeneity in terms of economic development, trade openness, and renewable energy profiles. This diversity allows us to capture variations in the way countries respond to climate policy stringency, which is essential for testing our core hypothesis. By including both developed and developing economies—within the constraints of data availability—we ensure comparability while retaining the empirical power necessary to identify the moderating effect of climate policies. Third, institutional quality constitutes an additional dimension guiding the selection process. It plays a key role in shaping the formulation and enforcement of climate and energy policies, directly influencing the effectiveness of renewable energy deployment and trade performance. A significant portion of the sample—particularly OECD countries—is characterized by relatively strong institutional frameworks, including stable governance, high regulatory quality, and effective public sector management. These attributes are essential for sustaining stringent climate regulations and facilitating the allocation of public support for clean energy innovation. To ensure institutional heterogeneity, the sample also includes countries with weaker institutional capacities, where administrative challenges or political constraints may hinder policy implementation. This institutional diversity enhances the external validity of our findings and justifies the use of threshold analysis, given the well-documented moderating role of institutional quality in the relationship between policy stringency, renewable energy adoption, and trade performance (Opeyemi et al., 2019; Brandi et al., 2020).

4. Empirical results and discussion

This section is divided into three sub-sections. In the first sub-section, we present and discuss the descriptive statistics results. In the second sub-section, we conduct a preliminary investigation into how the impact of renewable energy on trade varies depending on climate change policies. We estimate Equations (6) and (7) by adding an interaction term ($Interaction = Climate$*Log(RE)). The introduction of this term provides a preliminary indication of whether the effect of renewable energy on trade is influenced by climate change policies. In the final sub-section, we perform more rigorous econometric tests to determine the role of climate policies in the relationship between renewable energy and trade. Specifically, we employ the nonlinear panel threshold model of Seo and Shin (2016) to examine the nonlinear connection between renewable energy and trade, with a particular focus on the role of climate change policies as a moderating factor.

4.1. Descriptive analysis

We begin the presentation of the empirical results with the descriptive statistics, as summarized in Table 1. This Table provides key indicators for the variables covering the period from 1990 to 2023, including the mean, minimum, maximum, and standard deviation. On average, developed countries exhibit a slightly higher growth rate in renewable energy (RE) deployment (2.51 %) compared to developing countries (2.16 %), despite the latter displaying similar or even slightly higher GDP levels. A notable difference lies in the strength of technology support policies: developing countries lag significantly behind, with a mean index of 0.67 versus 2.10 in developed countries. These policies—designed to support the production and adoption of renewable energy across sectors—are more firmly established in advanced economies, likely contributing to their superior performance in renewable

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[2] The data can be obtained from the corresponding author.

Table 1
Descriptive statistics for key variables.

Full sample	Log(X)	Log(I)	Log(RE)	Log(REER)	Log(GDP)	Log(Fossil)	Climat	Techpol
Mean	3.42	3.4	2.28	4.55	27.59	4.32	2.11	3.42
Min	1.9	1.69	−1.66	3.67	24.83	3.22	0.05	0
Max	5.43	5.33	4.16	5.1	30.92	4.59	4.97	6
Standard dev	0.67	0.6	1.22	0.18	1.25	0.25	1.18	0.67
Observations	986	986	986	986	986	986	986	986
Number of Countries	29	29	29	29	29	29	29	29
Developing countries								
Mean	3.27	3.23	2.16	4.46	27.96	4.37	1.62	0.67
Min	1.9	1.69	−0.51	3.67	25.59	3.93	0.05	0
Max	4.79	4.61	4.08	4.89	30.92	4.59	4.22	3.5
Standard dev	0.58	0.55	1.08	0.2	1.09	1.09	1.62	0.91
Observations	340	340	340	340	340	340	340	340
Number of Countries	10	10	10	10	10	10	10	10
Developed countries								
Mean	3.5	3.49	2.51	4.59	27.40	4.3	2.37	2.1
Min	2.1	1.91	−1.66	3.76	24.83	3.22	0.08	0
Max	5.43	5.33	4.16	5.1	30.7	4.59	4.97	6
Standard dev	0.7	0.6	1.27	0.14	1.28	0.27	1.09	1.27
Observations	646	646	646	646	646	646	646	646
Number of Countries	19	19	19	19	19	19	19	19

energy expansion. Furthermore, developed countries demonstrate more stringent climate policy frameworks (Climat mean = 2.37) relative to developing ones (1.62), reflecting a stronger institutional commitment to environmental governance.

In terms of trade, developed nations report higher average levels of both imports and exports, alongside a slightly more stable real effective exchange rate (REER). Despite these differences, fossil fuel consumption remains relatively high across both groups. Overall, the statistics highlight a clear policy and technological gap that favors developed economies, offering insight into their relative advantage in renewable energy development.

4.2. Linear analysis

In this section, we conduct a linear analysis to examine if the impact of renewable energy on trade varies depending on the climate change policies. To achieve this, we estimate the following equations:

$$Log\ (X_{it}) = c + \beta_1\ Log(RE_{it}) + \beta_2\ Log(Fossil_{it}) + \beta_3\ Log(GDP_{it}) + \beta_4 Climat_{it} + \beta_5 \text{Techpol}_{it} + \beta_6\ Log(REER_{it}) + \beta_7 (Log(RE_{it})^{*}Climat_{it}) + u_{it} \tag{10}$$

$$Log(M_{it}) = e + \delta_1\ Log(RE_{it}) + \delta_2\ Log(Fossil_{it}) + \delta_3\ Log(GDP_{it}) + \delta_4 Climat_{it} + \delta_5 \text{Techpol}_{it} + \delta_6\ Log(REER_{it}) + \delta_7 (Log(RE_{it})^{*}Climat_{it}) + \eta_{it} \tag{11}$$

The interaction term $(Log(RE_{it})^{*}Climat_{it})$ captures the combined effect of renewable energy and climate on trade flows. Statistically significant coefficients for this term (β_7 *and* δ_7) indicate that the impact of renewable energy on exports and imports depends on the strength of climate policies. Table 2 presents empirical results, emphasizing the joint and individual effects of renewable energy deployment and climate policy on trade performance.

For the full sample, renewable energy deployment (Log (RE)) has a

Table 2
Linear estimation.

Export Equation	Full sample		Developed Countries		Developing countries	
	Fixed-effects	Random-effects	Fixed-effects	Random-effects	Fixed-effects	Random-effects
Log(RE)	0.08***(4.18)	0.04**(2.4)	0.16***(8.32)	0.15***(7.84)	0.03(0.66)	0.02(0.47)
Log(REER)	−0.16***(-3.7)	−0.19***(-4.38)	−0.34***(-5.4)	−0.36***(-5.55)	−0.3***(-3.7)	−0.32***(-3.93)
Log(GDP)	0.11***(3.52)	0.02(0.67)	−0.05*(-1.68)	−0.09***(-2.79)	−0.09(-1.21)	−0.13***(-2.92)
Log(Fossil)	0.01(0.77)	0.01(0.74)	−0.43***(-3.8)	−0.38***(-3.44)	2.07***(5.7)	2.03***(7.13)
Climat	0.01(0.63)	0.06***(2.85)	0.08***(4.03)	0.11***(5.02)	0.2***(3.2)	0.23***(4.63)
Techpol	−0.014(-1.18)	−0.019(-1.58)	−0.01(-1.31)	−0.01(-1.58)	−0.05*(-1.87)	−0.04(-1.48)
$(Log(RE_{it})^{*}Climat_{it})$	0.01***(2.69)	0.01**(2.02)	−0.01(-1.31)	−0.01(-1.58)	−0.05*(-1.87)	−0.04(-1.48)
Constant	0.68(0.75)	3.39***(4.03)	−0.004(-0.74)	−0.006(-1.05)	−0.02(-1.28)	−0.03*(-1.85)
Import Equation	**Full sample**		**Developed Countries**		**Developing countries**	
	Fixed-effects	Random-effects	Fixed-effects	Random-effects	Fixed-effects	Random-effects
Log(RE)	0.06***(3.7)	0.02*(1.65)	0.12***(7.17)	0.11***(6.64)	0.07*(1.66)	0.05(1.35)
Log(REER)	−0.19***(-5.1)	−0.22***(-5.81)	−0.39***(-7.1)	−0.41***(-7.23)	−0.3***(-4.7)	−0.37***(-5.01)
Log(GDP)	0.12***(4.38)	0.02(1.11)	0.005(0.18)	−0.03(-1.41)	−0.07(-1.02)	−0.13***(-3.06)
Log(Fossil)	0.007(0.66)	0.007(0.63)	−0.16*(-1.73)	−0.12(-1.27)	2.08***(6.33)	2.15***(7.92)
Climat	0.03(1.52)	0.07***(4.04)	0.09***(4.86)	0.11***(6.2)	0.14***(2.6)	0.18***(3.98)
Techpol	−0.004(-0.42)	−0.008(-0.83)	0.005(0.54)	0.001(0.11)	−0.05*(-1.9)	−0.04(-1.6)
$(Log(RE_{it})^{*}Climat_{it})$	0.01***(2.75)	0.01**(2.02)	0.005(0.54)	0.001(0.11)	−0.04*(-1.9)	−0.04*(-1.65)
Constant	0.57(0.72)	3.3***(4.51)	−0.007(-1.45)	−0.009*(-1.83)	−0.002(-0.17)	−0.009(-0.6)

Note: *, **, and *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively. Unless otherwise indicated, the values in parentheses are t-statistics.

positive and significant impact on both exports and imports, indicating that green energy supports trade performance. The real effective exchange rate (log (REER)) negatively affects trade, suggesting that currency appreciation reduces competitiveness. GDP has a positive influence under fixed effects, while climate policy stringency (Climat) significantly boosts both exports and imports, particularly under random effects. The interaction term $(Log(RE_{it})*Climat_{it})$ is also positive and significant, suggesting that stronger climate policies enhance the trade benefits of renewable energy.

When the sample is split between developed and developing countries, important differences emerge. In developed countries, the effect of renewable energy deployment is consistently positive and highly significant for both exports and imports. This indicates that advanced economies are able to leverage renewable energy technologies to strengthen their trade performance. These countries likely benefit from mature energy infrastructure, stronger institutional frameworks, and greater integration into global green value chains. Moreover, in these countries, the real effective exchange rate exerts an even stronger negative effect on trade, underlining their greater sensitivity to currency fluctuations due to higher trade exposure. Interestingly, GDP has a negative effect on exports in developed countries, which may reflect economic maturity and a structural shift toward service-oriented or domestic consumption-driven growth. Additionally, fossil fuel use is negatively associated with exports, implying that continued reliance on fossil energy undermines trade competitiveness, particularly in the context of increasingly green global markets. Climate policy stringency also plays a strong and positive role in both exports and imports, confirming the strategic importance of environmental governance in shaping trade flows.

However, fossil fuel consumption has a strong and positive association with both exports and imports in developing countries. This highlights the ongoing reliance on fossil-based industries for trade and growth, pointing to a slower transition toward renewable alternatives. At the same time, climate policy stringency shows a strong and positive effect, particularly on imports, suggesting that environmental reforms in these countries may lead to increased demand for green technologies and cleaner inputs.

In contrast, the results for developing countries present a more complex picture. The effect of renewable energy deployment is statistically insignificant for exports and only marginally significant for imports, suggesting that these countries have not yet reached the stage where renewable energy investments translate into tangible trade gains. This may reflect infrastructural challenges, limited technological capabilities, or weaker policy enforcement.

Notably, the interaction between renewable energy and climate policy is negative and weakly significant for developing countries. This result may imply that, without adequate institutional support, the simultaneous implementation of renewable energy strategies and stringent climate policies could create policy conflicts or inefficiencies that hinder trade expansion.

Finally, the impact of technological policy (*Techpol*)—used in this study as a proxy for public policies supporting the deployment of renewable energy technologies, particularly those targeting biofuel production—appears limited across both developed and developing countries. In advanced economies, the estimated coefficients are generally negative and statistically insignificant, suggesting that existing technology-related policies may not exert a direct or immediate influence on trade flows. One plausible explanation is that many of these countries have already reached a level of technological maturity in key renewable sectors, such as biofuels and wind energy, where additional public R&D spending yields diminishing marginal returns in terms of export growth or competitiveness (Popp, 2019). In such contexts, marginal increases in innovation investment may contribute more to incremental efficiency gains or cost reductions in domestic energy systems than to significant expansions in renewable energy exports.

Complementing this perspective, Ye et al. (2022) argue that policies aimed at supporting renewable energy can sometimes unintentionally increase technical risk. This arises when firms fear that their current technologies may become obsolete more rapidly, thereby discouraging further innovation and reducing the effectiveness of the policy. In such cases, rather than stimulating new technological development, policy measures may inadvertently generate uncertainty, weakening firms' incentives to invest in and adopt novel technologies.

Furthermore, many of these policies tend to prioritize upstream innovation, early-stage R&D, or domestic energy resilience, rather than explicitly promoting export-oriented industrial development. For example, biofuel policies in OECD countries have often been driven by climate objectives and rural development goals rather than trade competitiveness, which may account for their limited impact on international trade performance (Kim and Kim, 2015). Additionally, renewable energy industries in developed economies are often dominated by large incumbent firms, potentially reducing the sector's dynamism and responsiveness to public R&D incentives—a pattern consistent with the theory of path dependency (Acemoglu et al., 2012). These structural and institutional factors constrain the short-term trade effects of *Techpol*, as its influence may materialize through longer-term channels such as productivity gains, sectoral restructuring, or innovation spillovers (Dechezleprêtre and Glachant, 2014). Moreover, the time lag between policy implementation and observable export outcomes—particularly in sectors characterized by lengthy development cycles and regulatory complexity—suggests that some effects may not be fully captured in an empirical specification focused on short-term trade outcomes.

In developing countries, the coefficients on *Techpol* are weakly negative and only marginally significant in some specifications, suggesting a distinct set of structural constraints. Many emerging economies operate within underdeveloped technology policy frameworks that often lack strategic coherence, sufficient funding, and effective coordination between trade, energy, and research ministries (Aghion et al., 2016). These limitations are further exacerbated by institutional weaknesses—such as low absorptive capacity, regulatory uncertainty, and enforcement deficits—that undermine the impact of R&D-driven policy interventions (Hall and Helmers, 2013). Moreover, technology support in these contexts tends to emphasize the adaptation and deployment of foreign innovations over the development of indigenous R&D ecosystems, thereby limiting contributions to export competitiveness. The effectiveness of technological policy is also shaped by the choice and design of policy instruments. For example, feed-in tariffs and renewable portfolio standards have produced mixed results across countries, depending on their alignment with local institutional and market conditions (Hille and Oelker, 2023). Additionally, the diffusion of renewable energy technologies is often facilitated by international knowledge spillovers and sectoral relatedness, meaning that countries with stronger capabilities in related industries are better positioned to leverage such policies to enhance renewable energy trade.

Another plausible explanation is that the effects of *Techpol* are nonlinear, potentially exhibiting threshold behavior—where positive impacts only emerge once policy intensity or institutional support exceeds a certain level. For example, Bryngemark and Söderholm (2022) find that public support for biofuel-related R&D in OECD countries led to tangible market outcomes only after surpassing specific policy intensity thresholds. Similarly, Kim and Kim (2015) highlight the importance of aligning R&D incentives with export-oriented industrial strategies to realize trade gains. Therefore, while the linear results may appear limited, the impact of *Techpol* could become more pronounced under specific institutional or policy regimes—particularly when strong environmental or trade institutions enhance the effectiveness of technological investment. The nonlinear threshold analysis presented in the next subsection further explores this hypothesis.

4.3. Nonlinear analysis

The findings from the previous subsection were based on the assumption of a linear relationship between renewable energy and international trade. However, this assumption may be overly simplistic and could lead to erroneous findings, contradictory conclusions, and misguided policy implications, as noted by Huang et al. (2022). In other words, the connection between renewable energy and trade might not be linear and could instead exhibit a threshold effect. It is anticipated that a threshold effect exists, as the relationship may depend on the extent of climate change policies. Simply put, a threshold may need to be reached before climate change policies have a significant impact on the link between renewable energy and trade.

Table 3 displays empirical results showing how different levels of climate change policies influence the relationship between renewable energy and trade. These results confirm the existence of significant thresholds in both equations, which are different from zero and lie within the specified interval. Specifically, the Sup-Wald statistics indicate that the null hypothesis of no threshold effect is rejected at the 1 % level. This finding suggests that climate change policies exert threshold effects on the relationship between renewable energy consumption and trade.

For the export equation, the threshold value of climate change policies is estimated at 2.22, delineating two differentiated regimes. In the lower regime (below the threshold), the coefficient for renewable energy is positive but statistically insignificant. However, once climate policy stringency surpasses the threshold (Regime 2), the renewable energy coefficient turns negative and statistically significant. This indicates that at higher levels of climate change policies, renewable energy usage adversely affects exports. Specifically, when climate change policies exceed the 2.22 threshold, a one-unit increase in renewable energy consumption is associated with a 0.85-unit decline in exports.

Table 3
Climate's impact on the link between renewable energy and trade.

Independent Variable	Export Eq		Import Eq	
	Regime 1 (below threshold)	Regime 2 (above threshold)	Regime 1 (below threshold)	Regime 2 (above threshold)
Export $_{t-1}$	−0.37(-1.21)	0.7(1.46)	–	–
Import $_{t-1}$	–	–	−0.01(-0.09)	0.31(0.7)
Log(RE)	0.41(0.79)	−0.85*** (-3.15)	−0.68** (-1.97)	−0.21(-0.63)
Log(REER)	1.01(1.13)	−0.56(-0.4)	0.15(0.35)	−1.17(-0.83)
Log(GDP)	0.95*** (2.61)	0.42*** (2.19)	1.11***(3.3)	0.38(0.85)
Log(Fossil)	4.36*** (2.38)	−4.5*** (-3.32)	−2.01(-1.13)	−0.42(-0.48)
Climat	0.058(0.26)	0.27(0.78)	−0.31*** (-3.41)	1.51(1.09)
Techpol	−0.45*** (-2.62)	0.38*** (2.38)	0.13(1.38)	−0.68*** (-3.11)
Constant	8.05(1.01)		−7.2(-0.54)	
Threshold Levels (P-value)	2.22***(0.00)		3.42***(0.00)	
95 % Confidence Interval	[1.04; 3.4]		[1.5; 5.35]	
Number of Countries	29		29	
Number of Observations	986		986	
Period	1990–2023		1990–2023	
Sup-Wald Statistics (P-Value)	2.38***		3.5***	

Note: *, **, and *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively. Unless otherwise indicated, the values in parentheses are t-statistics.

The estimated threshold value of 2.22 on the Environmental Policy Stringency Index (EPSI) corresponds to a moderate level of regulatory commitment. On the EPSI scale—ranging from 0 (no stringency) to 6 (maximum stringency)—this level typically reflects the presence of basic carbon pricing mechanisms, moderate emissions standards, and early-stage support for renewable energy technologies. Policy environments operating below this threshold tend to emphasize foundational regulatory frameworks aimed at facilitating market entry and gradual technological adoption. In contrast, exceeding this threshold often signals a transition toward more comprehensive and stringent regulatory regimes, marked by higher carbon taxation, tighter emissions controls, and stricter compliance requirements. While such measures are crucial for advancing long-term decarbonization goals, they may also impose higher marginal costs on firms, particularly in trade-exposed or energy-intensive sectors. Without complementary measures—such as targeted innovation incentives, export promotion instruments, or regulatory streamlining—increased policy stringency can undermine export competitiveness and reshape trade patterns. This highlights the need for coordinated policy design that balances environmental ambitions with economic and industrial objectives.

Table 4 shows that out of the 29 countries considered, 4—Canada, Mexico, South Africa, and Spain—fall under the lower climate policy regime. This implies that their current climate policy stringency remains below the peak of the inverted U-shaped curve. Therefore, strengthening renewable energy use in these countries is likely to boost their exports.

In contrast, the remaining 25 countries — including Belgium, Brazil, China, Czech, Denmark, Finland, France, Germany, Greece, Hungary, India, Indonesia, Ireland, Italy, Japan, Netherlands, Norway, Poland, Russia, South Korea, Sweden, Switzerland, Turkey, UK and USA—are situated in the upper regime. For these countries, further expansion of renewable energy may lead to a decrease in their exports. Notably, the upper regime includes 17 countries out of 19 developed countries and 8 out of 10 developing countries.

These findings, presented in Tables 3 and 4, are not unexpected. Excessive environmental regulations, particularly in developed countries, can undermine the positive trade effects of renewable energy by raising compliance costs, introducing bureaucratic hurdles, and erecting

Table 4
Classification of countries by climate policy stringency based on estimations from Equation (8).

Lower regime	Upper regime
	Belgium
Canada	Brazil
Mexico	China
South Africa	Czech
Spain	Denmark
	Finland
	France
	Germany
	Greece
	Hungary
	India
	Indonesia
	Ireland
	Italy
	Japan
	Netherlands
	Norway
	Poland
	Russia
	South Korea
	Sweden
	Switzerland
	Turkey
	UK
	USA

trade barriers. Such regulations often need substantial investments in compliance infrastructures, ultimately reducing the competitiveness of companies engaged in renewable energy production and export (Arouri et al., 2012; Wüstenhagen and Menichetti, 2012).

Our findings corroborate those of Qiang et al. (2021), who investigated the impact of environmental regulations on export trade at the provincial level in China from 2008 to 2017 using panel quantile regressions. They identified an inverted U-shaped relationship between environmental regulations and exports. According to their study, moderate levels of ecological regulations incentivize companies to innovate technologically, enhance production efficiency, and replace polluting products with more sustainable alternatives, thereby expanding their export scale. However, excessively stringent regulations can reduce expected output, eroding competitive advantage and diminishing export trade.

This also aligns with previous research by Zhang et al. (2020), Yang et al. (2022) and Cai et al. (2023), who posit that excessive environmental regulations can increase production costs for enterprises and industries, reduce their R&D investment and innovation, and consequently decrease their competitiveness and efficiency, leading to diminished exports.

Additionally, our results are consistent with Li et al. (2024), who provide evidence of an inverted U-shaped relationship between environmental regulations and the overall Global Value Chain (GVC) position of the Chinese manufacturing sector. Specifically, when environmental regulations are below a certain threshold, strengthening them shifts the GVC position upstream. However, once regulations exceed this threshold, further tightening leads to a downstream shift in the GVC position.

For the import equation, the threshold value of climate change policies is estimated at 3.42. Below this threshold, renewable energy consumption has a negative effect on imports, indicating a potential substitution of imported energy technologies by domestic alternatives. However, when climate policy index exceeds the threshold (regime 2), the effect becomes significantly positive. This shift suggests that more stringent climate policies drive increased imports of renewable energy technologies, likely due to greater demand for advanced equipment and expertise not yet available domestically. These findings align partially with those of Nesta et al. (2014), who argued that the absence of subsidies for green energy in many countries reduces its competitiveness, potentially worsening the trade balance. In this context, renewable energy subsidies play a critical role: by lowering production costs and encouraging new market entrants, they stimulate innovation and scale. Without such incentives, established energy monopolies may resist adopting renewable technologies that could undermine their existing investments, thereby limiting the potential for transformative innovation.

On the EPSI scale, a threshold value of 3.42 indicates a relatively high level of regulatory stringency. This level is typically observed in countries that have adopted advanced climate policy frameworks, including robust carbon pricing mechanisms (such as high-rate carbon taxes or fully operational emissions trading systems), strict emissions standards, targeted technology mandates, and substantial public investment in renewable energy infrastructure and innovation. At this stage of policy development, the accelerated deployment of renewable energy often exceeds domestic manufacturing capacity, driving increased demand for specialized technologies—such as high-efficiency solar panels, offshore wind turbines, and grid integration systems. Consequently, stringent climate policies can lead to higher imports of renewable energy-related equipment, as countries pursue ambitious decarbonization goals by sourcing advanced technologies from abroad.

It is also noteworthy that 13 countries in the sample fall under the lower climate policy regime (see Table 5). These include Brazil, Canada, Germany, Hungary, India, Indonesia, Japan, Poland, Russia, South Korea, Spain, the UK, and the USA. In this group, greater renewable energy consumption is associated with a decline in imports. In contrast, the remaining 16 countries fall within the higher climate policy regime, where stricter environmental regulations are likely to encourage further imports of renewable energy technologies. This indicates that while stronger climate policies foster clean energy adoption, they may initially increase reliance on foreign technology, especially in the absence of sufficient domestic innovation capacity.

Table 5

Classification of countries by climate policy stringency based on estimations from Equation (9).

Lower regime	Upper regime
Brazil	Belgium
Canada	China
Germany	Czech
Hungary	Denmark
India	Finland
Indonesia	France
Japan	Greece
Poland	Ireland
Russia	Italy
South Korea	Mexico
Spain	Netherlands
UK	Norway
USA	South Africa
	Sweden
	Switzerland
	Turkey

As pointed out in the introduction, trade flows in developing countries may respond differently to renewable energy use compared to developed countries, owing to distinct economic characteristics and environmental priorities. In this context, it is essential to examine the nonlinear relationship between renewable energy and trade separately for each group of countries. Focusing first on developed countries, Table 6 presents empirical evidence of the nonlinear impact of climate

Table 6

Climate's Impact on the Link Between Renewable Energy and Trade for developed countries.

Independent Variable	Export Eq		Import Eq	
	Regime 1 (below threshold)	Regime 2 (above threshold)	Regime 1 (below threshold)	Regime 2 (above threshold)
Export $_{t-1}$	−1.37(-0.18)	1.26(0.18)	–	–
Import $_{t-1}$	–	–	−0.42(-0.09)	−6.5(-1.34)
Log(RE)	1.28*(1.71)	2.55(0.53)	0.1(0.02)	−5.39** (-2.04)
Log(REER)	−6.36(-0.44)	8.59(0.52)	0.27(0.04)	1.54(-0.08)
Log(GDP)	0.15**(1.98)	1.39(0.33)	0.816** (2.13)	−5.44* (-1.67)
Log(Fossil)	−31.3(-1.26)	31.9(1.15)	7.85(0.82)	−4.23(-0.61)
Climat	−16.15*** (-2.54)	15.93** (2.42)	0.04(0.02)	−2.01(-0.77)
Techpol	0.65(0.12)	−0.47(-0.08)	−0.07(-0.05)	1.45(0.57)
Constant	−24.1(-1.23)		21.4(1.6)	
Threshold Levels (P-value)	1.09***(0.00)		3.25***(0.00)	
95 % Confidence Interval	[0.36; 1.82]		[1.32; 5.17]	
Number of Countries	19		19	
Number of Observations	646		646	
Period	1990–2023		1990–2023	
Sup-Wald Statistics (P-Value)	2.93***		3.31***	

*Note: *, **, and *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively. Unless otherwise indicated, the values in parentheses are t-statistics.*

change policies on the relationship between renewable energy and trade within this group.

The results presented in Table 6 confirm the presence of significant threshold effects in both the export and import equations. The Sup-Wald statistics strongly reject the null hypothesis of no threshold effect at the 1 % level, indicating that climate change policies indeed exert threshold effects on the relationship between renewable energy consumption and trade in developed countries.

For the export equation, the threshold value of climate change policies is found to be 1.09. Below this threshold level, the coefficient for renewable energy is significantly positive, suggesting that renewable energy deployment boosts exports in less stringent regulatory environments. However, this effect becomes non-significant once the threshold is exceeded, implying that the relationship between renewable energy and exports is weaker in regimes with more stringent climate policies.

In the import equation, the threshold value for climate change policies is found to be 3.25. Below this threshold, renewable energy consumption has a positive but non-significant effect on imports. However, when the climate policy index exceeds the threshold (regime 2), the effect turns significantly negative. This indicates that in developed countries, stricter climate regulations foster greater self-reliance in renewable energy technology in response to global demand, leading to a reduction in imports and greater energy independence. As noted by Herman and Xiang (2022), stringent environmental policies can drive such self-sufficiency.

Shifting focus to developing countries, the results in Table 7 similarly confirm the existence of significant thresholds in both export and import equations, with thresholds that are different from zero and lie within the specified interval. The Sup-Wald statistics once again reject the null hypothesis of no threshold effect at the 1 % level, confirming the relevance of climate policies thresholds effects in shaping the renewable energy-trade nexus in these countries.

Table 7
Climate's Impact on the Link Between Renewable Energy and Trade for developing countries.

Independent Variable	Export Eq		Import Eq	
	Regime 1 (below threshold)	Regime 2 (above threshold)	Regime 1 (below threshold)	Regime 2 (above threshold)
Export $_{t-1}$	−1.17(-0.36)	1.02(0.35)	–	–
Import $_{t-1}$	–	–	−0.3(-0.1)	2.32*(1.89)
Log(RE)	0.37*(1.79)	0.55*(1.73)	−1.95* (-1.72)	1.06**(2.17)
Log(REER)	−3.18(-1.41)	3.09(0.59)	0.78(0.2)	−1.05(-0.31)
Log(GDP)	0.1*(1.83)	1.79(0.63)	0.52**(2.01)	−2.12* (-1.74)
Log(Fossil)	−21.1(-1.6)	18.3(0.75)	3.12(0.34)	−1.84(-0.79)
Climat	−10.05** (-1.99)	8.71*** (2.71)	0.01(0.02)	−1.91(-0.98)
Techpol	0.6(0.92)	−0.14(-0.86)	0.11(0.13)	1.4(1.07)
Constant	−4.6(-1.51)		10.08(0.86)	
Threshold Levels (P-value)	1.29*(0.09)		1.23*(0.08)	
95 % Confidence Interval	[-7.56; 10.15]		[-9.25; 11.72]	
Number of Countries	10		10	
Number of Observations	340		340	
Period	1990–2023		1990–2023	
Sup-Wald Statistics (P-Value)	1.69*		1.83*	

Note:*, **, and *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively. Unless otherwise indicated, the values in parentheses are t-statistics.

For the export equation, the threshold value of climate change policies is 1.29. In both regimes (regime 1 and regime 2), the renewable energy coefficient remains positive and significant, demonstrating that at every level of climate change policies, renewable energy is favorable to export for developing countries. This group of nations is characterized by specific natural resource advantages (e.g., abundant solar or wind resources) or unique technological innovations adapted to their local context, thereby boosting the growth of export markets, even with less stringent overall environmental policies. These findings are in line with those of Qiang et al. (2021), who found that in China, even under relatively lax environmental regulations, industries tend to innovate, enhance production efficiency, and replace polluting products with sustainable alternatives, thereby boosting exports. Moreover, as emphasized by Falcone (2023), strategic public R&D investments in developing countries play a crucial role in building local technological capabilities and fostering export-oriented renewable energy industries tailored to regional needs.

For the import equation, climate change policies present a threshold value of 1.23. Below the threshold level (Regime 1), the renewable energy coefficient is significantly negative; however, it becomes significantly positive above the threshold. In other words, if the level of climate change policies exceeds the threshold of 1.23, a one-unit increase in renewable energy leads to a 1.06-unit increase in imports for developing countries. This confirms the argument that environmental concerns and the need for cleaner energy sources can drive developing countries to import renewable energy technologies and expertise from developed countries (Hunt et al., 2024). Stringent environmental policies, by promoting the adoption of renewable energy, can foster the expansion of import markets for clean energy technologies and equipment. In this context, public R&D efforts in developing countries often concentrate on adapting and deploying imported renewable technologies to suit local conditions and infrastructure constraints. This can initially help developing nations to increase their imports of technologies and knowledge from developed countries.

4.4. *Robustness checks*

In this sub-section, we first check the robustness of our empirical analysis to the measure of climate policy stringency. We use the Climate Actions and Policies Measurement Framework (CAPMF) climate policy database,[3] developed by Nachtigall et al. (2024), which encompasses 156 policy variables grouped into 56 distinct policies. The CAPMF climate policy index is derived by averaging the stringency values across all 56 policies, and this index is standardized to have a mean of zero (Nachtigall et al., 2024). The results of the estimation are presented in Table 8. Notably, the evidence supporting the idea that the effect of renewable energy consumption on trade exhibits two regimes based on the stringency of climate policies remains consistent.

Nonetheless, some discrepancies between the baseline results and the robustness checks using the alternative CAPMF index warrant further consideration. In the baseline model, renewable energy consumption has a positive but statistically insignificant effect on trade in the lower regime, and a significant negative effect in the upper regime. In contrast, the robustness checks reveal a negative and still insignificant coefficient in the lower regime, while the negative effect in the upper regime becomes more pronounced and statistically significant. These differences likely stem from how the two indices capture climate policy stringency. The EPSI includes only 12 market-based instruments, whereas the CAPMF encompasses a broader set of 56 regulatory and fiscal policies, including non-market mechanisms that may impose compliance costs even in relatively low-stringency settings. This broader policy scope is especially relevant in the lower regime, where such

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[3] The CAPMF data was obtained from the OECD database.

Table 8
Robustness check using an alternative measure of climate policy.

Independent variable	Export Eq		Import Eq	
	Regime 1 (below threshold)	Regime 2 (above threshold)	Regime 1 (below threshold)	Regime 2 (above threshold)
Export $_{t-1}$	−0.41(-0.36)	0.61*** (1.04)	–	–
Import $_{t-1}$	–	–	−0.2(0.78)	0.38(1.08)
Log(RE)	−0.47(-0.66)	−1.17*** (-2.64)	−0.7*(-1.68)	−1.79(-1.23)
Log(REER)	0.88(0.81)	−2.81(-1.01)	0.41(0.45)	−18.58* (-1.75)
Log(GDP)	1.11***(2.9)	0.56(1.42)	2.08*** (3.32)	−0.63(-0.4)
Log(Fossil)	−6.08*** (-2.85)	−5.09*** (-2.8)	−4.54* (-1.67)	−3.82(-0.76)
Climat	−0.19(-0.57)	0.7(1.22)	−0.56*** (-2.83)	2.05*(1.79)
Techpol	−0.03(-0.18)	0.14(0.91)	0.15*(1.71)	−0.05(-0.2)
Constant	18.21(0.88)		11.7*(1.79)	
Threshold Levels (P-value)	2.35***(0.007)		3.46***(0.00)	
95 % Confidence Interval	[0.64; 4.05]		[2.09; 4.83]	
Number of Countries	27		27	
Number of Observations	891		891	
Period	1990–2022		1990–2022	
Sup-Wald Statistics (P-Value)	2.7***		4.96	

Note: *, **, and *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively. Unless otherwise indicated, the values in parentheses are t-statistics.

effects may be overlooked by the narrower EPSI framework. Additionally, the indices differ in their scaling methodologies: EPSI employs an absolute 0–6 scale, while CAPMF uses relative standardization, resulting in differences in threshold calibration. Despite these distinctions, both approaches identify statistically significant regime shifts, reinforcing the robustness of the nonlinear specification.

We further assess the robustness of our findings by incorporating dummy variables to control for period-specific events, including the 2008 Financial Crisis, the 2014 Ukrainian-Russian conflict, and the 2021–2023 energy crisis. Table 9 presents the results: the left panel includes only the 2008 crisis, while the right panel accounts for all three events. The estimates are broadly consistent with those reported in Table 3, reaffirming that the effect of renewable energy consumption on trade remains conditional on the level of climate policy stringency. Specifically, the regime-dependent pattern holds across both export and import equations, even after controlling for these disruptions. While some coefficients vary in magnitude and statistical significance—reflecting the differing economic impacts of each crisis—the structural breakpoints and regime thresholds remain statistically significant. These results confirm the resilience of our core findings to temporal shocks and underscore the importance of accounting for geopolitical and macroeconomic disruptions when analyzing the relationship between renewable energy use, climate policy, and international trade.

A particularly noteworthy and novel result emerges in the export equation of the extended specification: the coefficient on technology policy (*Techpol*) becomes positive and statistically significant in the high-stringency climate policy regime when crisis periods are explicitly controlled for. This effect, absent in the baseline model, suggests that domestic R&D efforts gain traction in promoting renewable energy technology exports when climate policy is ambitious and the external environment is marked by instability. Specifically, under conditions of heightened regulatory stringency and during or following crisis episodes—such as financial disruptions, geopolitical tensions, or energy shocks—public R&D investments appear more effective in enhancing industrial competitiveness and stimulating export growth in renewable sectors. This finding highlights the potential for targeted technological policy to function as a countercyclical tool, strengthening green trade performance during periods of economic or geopolitical volatility (Acemoglu et al., 2012).

5. Conclusion and policy implications

In this paper, we analyzed the relationship between renewable energy consumption and international trade, with a particular focus on the moderating role of climate policy. We argued that this relationship is nonlinear and subject to threshold effects that conventional linear regression models may fail to capture, potentially leading to biased or misleading conclusions. To address this, we employed a dynamic threshold model proposed by Seo and Shin (2016), using data from 1990 to 2023 across a panel of 29 developed and developing countries.

Our findings indicate that climate policy plays a significant role in shaping the renewable energy-trade relationship, with varying impacts depending on the level of climate policy stringency and the development stage of the country. For the full sample, we observe that stringent environmental policies can decrease exports and reduce trade competitiveness. However, in developing countries, renewable energy consumption positively affects exports regardless of policy stringency. In developed countries, severe climate policies reduce import reliance, supporting energy independence. Notably, while stringent policies negatively affect the renewable energy-import relationship in developed countries, the effect is positive in developing nations.

These findings align with existing literature, which suggests that in developed countries, excessive environmental regulations can weaken the positive effect of renewable energy on trade by increasing compliance costs, creating bureaucratic hurdles, and acting as non-tariff trade barriers. These regulations often require significant investments in compliance measures, thereby reducing the competitiveness of companies involved in renewable energy production and trade (Arouri et al., 2012; Wüstenhagen and Menichetti, 2012). In contrast, developing countries may leverage strong environmental regulations to attract investments, stabilize their technology markets, and build local R&D capacity, ultimately boosting long-term export growth. However, inconsistent regulations and frequent changes across countries can hinder international trade and slow sector development (Jaffe and Palmer, 1997; Johnstone et al., 2017; Popp, 2010; Zheng et al., 2020).

The implications of these findings are significant for policymakers in both developed and developing economies. In developed countries, policymakers must strike a careful balance between environmental goals and trade competitiveness. While stringent policies can stimulate domestic innovation and reduce dependency on imported technologies, they may also impose excessive costs that act as barriers to international trade. Harmonizing environmental regulations across borders and streamlining administrative processes can help reduce these barriers and support the global expansion of the renewable energy sector.

For developing countries, more targeted and integrated policy measures are essential to translate renewable energy deployment into sustained trade benefits. Governments should align climate policy with industrial and trade strategies by embedding renewable energy objectives into national export development plans. This requires fostering domestic manufacturing capacities for renewable energy technologies—such as solar panels, wind turbine components, and biofuel processing equipment. For instance, India's Production Linked Incentive (PLI) scheme for solar photovoltaic manufacturing has successfully incentivized domestic production, reduced import dependence, and positioned the country among the world's leading solar manufacturers

Table 9

Robustness check accounting for crises.

	Results Considering the Russia–Ukraine War				Results Considering the Global Energy Crisis			
	Export Eq		Import Eq		Export Eq		Import Eq	
	Regime 1 (below threshold)	Regime 2 (above threshold)	Regime 1 (below threshold)	Regime 2 (above threshold)	Regime 1 (below threshold)	Regime 2 (above threshold)	Regime 1 (below threshold)	Regime 2 (above threshold)
Export $_{t-1}$	−0.41(-1.1)	0.73(1.29)	–	–	−0.54(-1.11)	1.02**(2.1)	–	–
Import $_{t-1}$	–	–	0.3(0.77)	−0.11(-0.08)	–	–	−0.005(-0.02)	0.12(0.17)
Log(RE)	0.38(0.68)	−0.82***(-2.6)	−0.67*(-1.72)	1.47(1.23)	0.47(0.69)	−0.99*(-1.81)	0.08(0.2)	−0.16(-0.29)
Log(REER)	0.96(1.06)	−0.22(-0.08)	0.98(0.29)	−8.53**(-2.21)	1.22(1.49)	−1.05(-0.27)	1.72**(2.1)	−2.8(-1.54)
Log(GDP)	0.91**(2.27)	0.43*(1.73)	0.87(1.42)	−1.05*(-1.7)	1.05**(2.07)	0.57(1.03)	0.98(1.38)	−0.42(-1.11)
Log(Fossil)	4.33**(2.01)	−4.41***(-3.2)	−3.03(-0.71)	7.27***(2.68)	5.95(1.52)	−5.4*(-1.64)	−1.23(-0.16)	−0.38(-0.2)
Climat	0.1(0.47)	0.19(0.46)	−0.29(-0.64)	−1.46(-0.87)	0.1(0.32)	0.17(0.34)	−0.19(-0.59)	0.15(0.39)
Techpol	−0.46**(-2.5)	0.42***(2.25)	−0.03(-0.12)	0.47(0.9)	−0.47*** (-3.05)	0.47**(2.15)	−0.2(-0.67)	0.28(0.65)
2014 Ukrainian-Russian War	−0.01(-0.01)		0.21(0.01)		–		–	
2021–2023 Energy Crisis	–		–		−5.03(-1.38)	5.8*(1.72)	48.01***(2.46)	−50.05***(-2.53)
Constant	5.87(0.46)		38.78**(2.23)		9.7(0.42)		25.24(1.46)	
Threshold Levels (P-Value)	2.22***(0.00)		3.13***(0.00)		2.22**(0.00)			1.95***(0.00)
95 % Confidence Interval	[0.001; 0.88]		[0.002; 1.12]		[0.73; 3.71]			[1.84; 2.07]
Number of Countries	29				29			
Number of Observations	986				986			
Period	1990–2023				1990–2023			
Sup-Wald Statistics (P-Value)	3.25***		3.02***		2.93***		33.02***	

Note: **, **, and *** indicate significance at the 10 %, 5 %, and 1 % levels, respectively. Unless otherwise indicated, values in parentheses are t-statistics.*

(Shiradkar et al., 2022). Similarly, Brazil's development of a domestic ethanol industry demonstrates how aligning biofuel policy with agro-industrial strengths can generate export opportunities, particularly in markets with blending mandates (Goldemberg, 2008).

Developing nations also have an opportunity to enhance economic competitiveness, advance sustainable development, and strengthen their position in a rapidly evolving global trade landscape by upgrading existing infrastructure and building domestic and regional value chains for green goods and renewable energy components. Strategic investments in innovative smart grid technologies are particularly critical for managing the intermittency of renewable energy sources and ensuring a stable, reliable power supply for industrial activity.

International cooperation further reinforces these efforts by facilitating access to advanced renewable technologies and strengthening local absorptive capacity. Strategic technology transfer initiatives—such as South Africa's Renewable Energy Independent Power Producer Procurement Programme (REIPPPP)—have been instrumental in promoting local content development, workforce training, and joint ventures with global firms (Eberhard and Naude, 2016). Similarly, Morocco's partnership with the European Union on the Noor Ouarzazate Solar Complex—the world's largest concentrated solar power (CSP) plant—illustrates how cross-border collaboration can accelerate clean energy infrastructure deployment while progressively building domestic technical expertise and expanding export potential (Leonard et al., 2024).

Clear regulatory frameworks and institutional stability are equally vital for attracting long-term private investment and ensuring the bankability of clean energy projects. Transparent procurement processes, predictable tariff regimes, and consistent support mechanisms reduce policy uncertainty and foster investor confidence. Vietnam's well-defined feed-in tariff scheme, for example, has significantly expanded the country's solar energy capacity (Qureshi et al., 2023). In contrast, countries plagued by frequent policy reversals—such as retroactive tariff cuts or inconsistent licensing—have struggled to sustain investor trust, thereby hindering the development of their renewable energy sectors (Pueyo, 2018).

Moreover, recognizing the existence of nonlinear and threshold effects in the renewable energy–trade relationship is crucial for the design of effective and targeted policy interventions. Accounting for these dynamics enables governments to better align their climate, energy, and trade strategies. By addressing these complex interdependencies, policymakers can foster sustainable development, promote international trade in renewable technologies, and advance global environmental objectives.

Despite its contributions, this study has several limitations. First, the analysis period was constrained by the availability of data on the Climate Policy Stringency Index, which limits the temporal scope and may omit important earlier developments. Second, the relatively small sample size restricts the generalizability of the findings across diverse national contexts. Third, the reliance on aggregated data may obscure important heterogeneities at regional, sectoral, or firm levels, potentially overlooking localized dynamics and specific policy effects. Future research could address these limitations by leveraging more disaggregated and comprehensive datasets, extending both the temporal and geographic coverage, and applying alternative analytical frameworks to validate and enrich the insights presented here.

CRediT authorship contribution statement

Ridha Nouira: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Formal analysis. **Leila Ben Salem:** Writing – review & editing, Writing – original draft, Software, Investigation, Formal analysis, Data curation. **Sami Saafi:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation, Conceptualization. **Christophe Rault:** Writing – review & editing, Writing – original draft, Supervision, Resources, Formal analysis, Conceptualization.

Declaration of competing interest

We attest that in submitting our paper for your journal for publication, there is no potential conflict of Interest including financial, personal or other relationships with other people or organizations within three years of beginning the submitted work that could inappropriately influence, or be perceived to influence, their work.

Appendix: Data Presentation

Variables	Description	Definition	Source	Unit of measure
RE	Renewable energy consumption	is defined as the percentage of renewable energy contribution to total energy consumption. It includes hydro (excluding pumped storage), geothermal, solar, wind, tidal, and wave.	ourworldindata.org (World Bank)	percentage
fossil	Fossil energy consumption	is defined as the percentage of fossil energy contribution to total energy consumption	ourworldindata.org (World Bank)	percentage
IMP	Imports	Volume of imports	IMF (International Monetary Fund)	Million (dollars)
EXP	Exports	Volume of exports	IMF (International Monetary Fund)	Million (dollars)
climat	EPS	Environmental policy stringency index	OCDE.org	index
Techpol	Technology support policy	environmental measure designed to support the production and utilization of renewable energy	OCDE.org	index
GDP	GDP	Gross domestic production	ourworldindata.org (World Bank)	Million (dollars)
REER	Exchange rate	The real effective exchange rate	IMF (International Monetary Fund)	percentage

Countries: India, China, Brazil, USA, France, UK, Sweden, Mexico, Spain, Italy, Russia, South Korea, Japan, Ireland, Greece, Germany, Netherlands, Norway, South Africa, Switzerland, Turkey, Czech Republic, Indonesia, Hungary, Denmark, Canada, Finland, Poland, Belgium.

Data availability

Data will be made available on request.

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