

Oil Prices, Environmental Protection, and India's LCT Exports to OECD Markets: A Gravity Model Approach

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Amidst heightened concerns over cross-border transfer of cleaner and greener products, this paper examines how oil import price fluctuations and environmental protection expenditure in OECD countries influence India's low-carbon-technology (LCT) exports, aligned with SDG 7, SDG 13, and SDG 17. Employing a Poisson Pseudo Maximum Likelihood estimator with a structural gravity model for 24 OECD countries between 2002–2021, the analysis uncovers asymmetric dynamics. Rising oil import prices significantly stimulate India's LCT exports through heightened demand for energy substitutes, whereas increased OECDs' environmental protection expenditure suppresses imports by virtue of enhanced domestic green manufacturing capacities. These findings challenge the conventional assumption that greater environmental expenditure universally expands global clean-tech trade. India's export competitiveness in solar PV, wind, and EV components underscores its potential to leverage OECD's China+1 diversification strategies and trade realignments. Policy coherence with Sustainable Development Goals (SDGs) standards, R&D intensity, and multilateral climate cooperation emerges as critical for sustaining LCT export growth.

Keywords: LCT exports, SDG-7, gravity model, OECD countries, environmental protection expenditure, oil imports, PPML estimation

JEL Classifications: C33, F14, F18, Q37, Q56

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Introduction

The global shift toward decarbonization has redefined the strategic significance of low-carbon technologies (LCTs) in international trade, particularly for emerging economies such as India (International Monetary Fund 2022). Energy markets are facing increasing volatility and climate

policy is gaining momentum, so understanding how external energy price shocks and environmental spending commitments influence green trade flows has become essential. As countries strive to meet ambitious climate targets under frameworks such as the Paris Agreement and, more recently, CBAM (Carbon Border Adjustment Mechanisms), demand for green technologies – spanning renewable energy systems, energy-efficient machinery, electric vehicles, and carbon mitigation tools – has surged.

For emerging economies like India, this represents a strategic export opportunity to integrate into high-value global green value chains. India has rapidly expanded its LCT capabilities over the past decade, with firms increasingly exporting solar components, smart grid equipment, and clean energy solutions. Yet, the external determinants of India's LCT export performance remain underexplored in the empirical literature, especially in relation to demand-side variables in destination countries. Among India's key trading partners, the OECD countries stand out for aligning their import demand with and increasing their investments in environmental protection and climate mitigation.

This paper explores the dual impact of rising oil import prices and public environmental protection expenditures by 24 OECD countries (selected as per data availability) on India's exports of low-carbon technologies to them over a period of 20 years, using reduced-form of the structural gravity model estimated via Poisson Pseudo Maximum Likelihood (PPML). The study hypothesizes that higher oil prices may raise the relative competitiveness of LCT products by increasing the cost of fossil-based alternatives, while increased environmental expenditure signals policy-driven demand for clean technologies – both factors potentially spurring LCT imports from technologically capable partners like India. However, the results obtained are counterintuitive and enlightening. This inquiry is situated at the intersection of three strands of literature: energy prices and green innovation, the role of environmental policy in shaping trade, and empirical gravity models applied to environmental goods. The study reinforces the critical role of international trade in low-carbon technologies as a mechanism for advancing access to clean, modern energy systems serving as a trigger for accelerated clean energy adoption – a dynamic that India, as a low-cost green technology supplier, can leverage to support SDG 7. Promoting LCT exports from developing economies contributes to global emissions reductions, aligning with SDG 13 on climate actions. The study's recommendations for enhancing trade

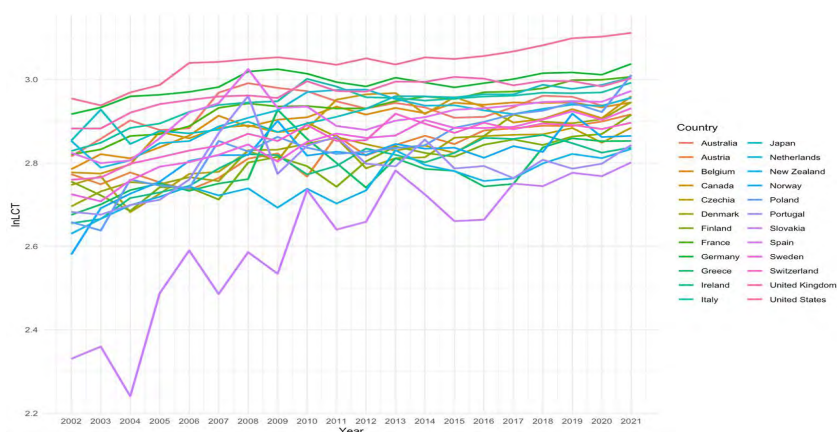


FIGURE 1 Trend Plot of LCT Exports from India to the 24 OECDs Over the Period 2002–21

diplomacy, mutual recognition of environmental standards, and bilateral cooperation align closely with SDG 17, which advocates for equitable trade and export promotion from developing countries.

A longitudinal perspective of Indian LCT exports to the OECD countries in the line chart in figure 1 from 2002 to 2021 confirms an unambiguous increase. During the early 2000s, most nations had comparatively modest levels of Indian imports of LCTs. But from around 2010, the evidence indicates an obvious speeding up. It is a period when there was growing international policy attention to addressing climate change, the dissemination of renewable energy objectives, and Indian investment in significant clean technology production capacity. By 2021, the aggregate magnitude of LCT exports is much larger than at the beginning of the sample period. Not only does the growth persist, but it also appears to be resilient to short-term economic shocks like the global financial crisis and the COVID-19 pandemic, suggesting that Indian LCT exports became more and more integrated into value chains globally.

In the context of a global energy transition, this study's conclusions have significant ramifications for the OECD's import planning as well as India's export strategies. Finding that crude oil prices are a major factor in LCT exports gives India a definite tool for promoting exports. Concurrently, when developed countries like the OECDs increase expenditure on environmental protection, it often coincides with tighter environmental regulations and stricter product standards for energy efficiency and recyclability, implying that if LCT products coming from develop-

ing countries like India fail to meet these heightened environmental or sustainability criteria, they may be barred from the market or subject to *non-tariff barriers* (NTBs), such as compliance certifications, testing, or eco-labelling requirements. The resulting reduced demand for LCT exports acts as a lesson for policy makers in India to aim for upgrading the product quality of such green exports to successfully boost export-led-growth performances. OECD nations are under increasing pressure to separate their industrial and energy systems from the volatility of fossil fuels as oil prices rise. With its existing manufacturing capabilities and policy incentives, India has a window of opportunity to establish itself as a dependable and affordable LCT supplier, particularly in industries like solar photovoltaic (PV) systems, smart grids, and energy-efficient devices.

The rest of the paper is organized as follows. The second section provides the theoretical framework that conceptualizes the constructs, reviews the literature further and proposes the hypotheses to be tested. The third section discusses the methodology, the variables of the study and the data sources. The fourth section presents the PPML estimation results. The fifth section interprets the empirical findings and, finally, the sixth section highlights the policy considerations and concludes the paper.

Theoretical Framework

The relationship between oil prices and green innovation has generated extensive debate. One strand of literature argues that rising fossil fuel prices act as a market-based stimulus for clean technology adoption by improving the relative competitiveness of low-carbon alternatives. Popp (2002) and Aghion et al. (2016) show that energy price shocks significantly spur innovation and deployment of renewable technologies. For oil-importing countries, such shocks often lead to a reorientation of energy portfolios toward renewables, stimulating trade in green technologies (Doda 2014; El-Karimi 2022; Shadab 2025; Adekunle 2025). Conversely, periods of low oil prices weaken incentives to shift towards cleaner alternatives, potentially dampening demand for green exports. Despite substantial evidence from developed economies, the implications of oil price dynamics for low-carbon technology (LCT) exports from emerging economies such as India remain underexplored.

Parallel to energy price dynamics, environmental protection expenditure by OECD governments has emerged as a key proxy for green policy commitment. Such spending – covering pollution abatement, renewa-

ble subsidies, environmental R&D, and green infrastructure – has been shown to stimulate both innovation and trade in environmental goods, particularly when supported by regulatory frameworks and green procurement policies (Johnstone et al. 2010; Costantini and Mazzanti 2012; Bryngemark et al. 2023; Gisselman et al. 2025; Dechezleprêtre and Sato 2017; Binh et al. 2025). These expenditures foster domestic demand for LCT imports and enhance market opportunities for exporters. They capture the fiscal effort and policy intensity of countries in reducing environmental externalities. However, one cannot ignore an exact opposite line of explanation of a possible negative relationship. Rising environmental expenditure reflects strong domestic industrial policy channelled towards building domestic LCT manufacturing capacity, subsidizing local firms, and strengthening innovation ecosystems, thereby reducing dependence on external suppliers such as India.

A growing body of literature highlights international trade as a crucial channel for the diffusion of LCTs, central to sustainable development. Cobbold et al. (2024), using data from 32 countries (1996–2020), find that LCT imports stimulate domestic green innovation, with stronger effects when supported by environmental policies such as green taxes. Trade also enhances foreign direct investment and knowledge spillovers, reinforcing innovation ecosystems. Tran (2022), employing a generalized synthetic control method, demonstrates that ratification of the Kyoto Protocol increased environmental goods exports by 31–32%, indicating that multilateral climate agreements can reshape comparative advantages and boost green trade. Nyasha (2024), motivated by Zimbabwe's commitment to reducing greenhouse gas emissions and expanding renewable energy while assessing whether such energy use can also stimulate economic recovery, uses annual data from 1990–2019 and an ARDL model to show that renewable energy consumption positively influences economic growth in both the short and long run. Together, these studies underline how trade openness, climate regulation, and Intellectual Property Rights (IPR) regimes jointly facilitate cross-border diffusion of green technologies.

Empirical evidence also suggests that greater trade openness accelerates LCT diffusion. Pigato et al. (2020) show that tariff reductions significantly boost LCT imports, while binding climate policies further strengthen this effect. However, despite extensive literature on fossil fuel prices and renewable energy consumption, there is only limited work examining how crude oil import prices influence LCT trade flows. This

gap is significant given the evolving global structure of LCT production. While China dominates global supply – accounting for around 80% of solar PV cells and EV (electric vehicle) battery production – India has emerged as a critical alternative supplier within the ‘China +1’ strategy. High US tariffs on Chinese goods, coupled with relatively lower tariffs on Indian products, have enhanced India’s competitiveness. Indian PV exports increased over 23-fold between FY 2022 and FY 2024, with the US absorbing over 97% of these exports. Government initiatives such as the Production Linked Incentive (PLI) scheme have further strengthened India’s export capacity. OECD countries remain heavily dependent on oil imports, and the post-Ukraine war energy price surge has reinforced the urgency to reduce fossil fuel dependence for both environmental and energy security reasons. Policy measures such as the EU Green Deal aim to subsidize clean energy and penalize carbon-intensive imports, while US tariffs on Chinese goods have created protected demand for non-Chinese LCTs. In this context, India’s role as a low-cost, innovation-driven exporter of solar modules, EV components, and energy-efficient technologies is growing but remains insufficiently examined in empirical trade literature.

Although India’s domestic green industrial policies have received attention, its bilateral green trade dynamics with advanced economies have rarely been investigated using rigorous econometric approaches. This is particularly notable given rising OECD environmental ambition, including mechanisms such as the EU’s Carbon Border Adjustment Mechanism (CBAM) and expanded green procurement policies. Addressing this gap, the present study examines how external macroeconomic forces (specifically oil import prices) and institutional environmental commitment (proxied by environmental protection expenditure) jointly shape India’s LCT exports to OECD countries. In doing so, it contributes to a more nuanced understanding of the evolving geography of the global green technology trade.

Based on the above literature and theoretical rationale, the study proposes the following hypotheses:

- H1 Higher international oil prices are positively associated with India’s LCT exports to OECD countries.
- H2 Increased public expenditure on environmental protection by OECD countries may accelerate or dampen their imports of LCTs from India.

Environmental protection expenditure, however, is not a homogeneous policy instrument. Under the COFOG (Classification of the Functions of Government), it includes heterogeneous components such as waste management, pollution abatement, biodiversity protection, environmental infrastructure, and environmental research and development. These components may have different implications for international trade: while public procurement of environmental infrastructure may stimulate imports of environmental goods, expenditures directed toward domestic R&D or industrial subsidies may strengthen local production capacity and reduce reliance on foreign suppliers. This implies that the ambiguity is not a surprise but an empirical outcome of competing mechanisms.

In order to empirically test these relationships, we employ a structural gravity model with Poisson Pseudo-Maximum Likelihood (PPML) estimation, which effectively manages zero trade flows and heteroskedasticity while maintaining the multiplicative functional form of the gravity equation. We create a panel dataset that spans 20 years, from 2002 to 2021, for 24 selected OECD economies, based on data availability. Our key findings reveal a significant positive association between crude oil import prices and India's LCT exports. This finding supports hypothesis H1 that high oil prices – through both energy security and substitution effects – encourage greater demand for clean technologies, thus improving India's export performance in the sector. However, there exists an inverse relationship between OECD nations' environmental protection spending (EEP) and Indian LCT exports. While one would expect higher environmental spending to simulate higher LCT imports, the evidence suggests otherwise. We lay out the plausible underlying reasoning, including domestic capacity building, shifting regulatory standards, trade policy innovations, and shifts in market preferences, in the later parts of the paper.

Methodology, Variables and Data Sources

THE STRUCTURED GRAVITY MODEL

The pioneering work of Tinbergen (1962) that developed the gravity model of international trade has been the standard econometric specification for trade empiricists to analyse and predict bilateral trade flows. The gravity framework remains the empirical workhorse in international trade analysis, offering a robust structure to model trade flows based

on exporter-importer characteristics and dyadic trade frictions. The structured gravity model extends the traditional multiplicative gravity equation by incorporating internal consistency with economic principles such as firm-level heterogeneity and market structure. Rooted in trade theory and consistent with Anderson and van Wincoop (2003), this model allows for a theory-driven analysis of bilateral trade flows, capturing both economic mass and bilateral resistance terms. In its structural form, it explicitly accounts for multilateral resistance terms and enables incorporation of policy variables (such as environmental expenditure) and macroeconomic shocks (like oil import price changes) within a coherent econometric setup. The general specification of the structured gravity equation is given as (Krisztin and Fischer 2015):

$$X_{ij} = \frac{E_i^\sigma}{P_i^{1-\sigma}} \frac{Y_j}{P_j^{1-\sigma}} \phi_{ij}, \quad (1)$$

where X_{ij} represents the bilateral trade flow from exporter (i) to importer (j), E_i and Y_j are the economic sizes (GDP or output) of the exporter and importer, respectively, P_i and P_j are outward and inward multilateral resistance terms, σ represents the elasticity of substitution between goods, and ϕ_{ij} captures bilateral trade costs, often modelled as a function of geographic distance, trade agreements, tariffs, and other trade barriers.

A log-linear transformation of the gravity equation is often used in estimation. However, the presence of zero trade flows (Santos Silva and Tenreyro 2006; Helpman et al. 2008; Burger et al. 2009) poses a challenge, rendering log-linearization infeasible. Several methods have been suggested to deal with the zero flows problem, such as excluding zero trade flows from the data set and estimating the parameters of interest on the truncated sample of countries. However, this generates biased estimates due to loss of data and should be avoided (Westerlund and Wilhelmsson 2011). The approaches followed by the other empirical studies have tried to modify the dependent variable to accommodate the log transformation but ended up yielding generally inconsistent estimates, where the severity of these inconsistencies will depend on the model and the specific characteristics of the sample used. The safest alternative estimation technique employed by most of the recent studies to address heteroskedasticity and the presence of zero trade flows is the Poisson Pseudo-Maximum Likelihood (PPML) estimator introduced by Santos Silva and Tenreyro (2006). The PPML regression equation is specified as:

$$X_{ij} = \exp(\beta_0 + \beta_1 Z_{ij} + \gamma_i + \delta_j) + \varepsilon_{ij}, \quad (2)$$

where Z_{ij} is a vector of bilateral trade cost variables (distance, common language, shared border, trade agreements, etc.), γ_i and δ_j are exporter and importer fixed effects capturing multilateral resistance terms, and ε_{ij} is the error term.

PPML estimation proceeds by solving the following first-order condition:

$$\sum_{ij} (X_{ij} - \hat{X}_{ij}) Z_{ij} = 0, \quad (3)$$

$$\text{where } \hat{X}_{ij} = \exp(\hat{\beta}_0 + \hat{\beta}_1 Z_{ij} + \hat{\gamma}_i + \hat{\delta}_j) \quad (3.1)$$

Unlike OLS, which assumes additive errors and ignores zero trade flows, PPML models trade flows in levels and provides a robust and consistent estimation framework under multiplicative error forms that is standard in gravity models.

VARIABLES AND DATA SOURCES

Specifically, in our case, to examine the impact of oil import prices and environmental protection expenditure of the OECD countries on the export value of LCT products from India, the following PPML estimation specification is constructed based on the reduced-form gravity model:

$$\begin{aligned} X_{jt} = \exp & (\beta_0 + \beta_1 OIP_{jt} + \beta_2 EPP_{jt} + \beta_3 GDP_{jt} + \beta_4 DIST_{jt} \\ & + \beta_5 POP_{jt} + \beta_6 LANG_{jt} + \beta_7 TER_{jt} + \beta_8 REER_{jt} \\ & + \beta_9 WGI_{jt} + \beta_{10} REC_{jt} + \delta_j + \phi_t) + \varepsilon_{ijt}, \end{aligned} \quad (4)$$

where the dependent variable X_{ijt} is the natural flow of LCT exports from India to the j^{th} destination OECD country in period t (in years), and the two primary explanatory variables are OIP_{jt} , that captures the oil import prices, and EPP_{jt} , which is the expenditure on environmental protection faced by the OECD countries. Control variables typically used in gravity models are also included: the annual growth rate of Gross Domestic Product (GDP_{jt}) reflects the economic size of the importing partner; $DIST_{jt}$ measures the geographical distance of the j^{th} country from India, representing transportation costs; POP_{jt} indicates the annual growth rate of the population, representing the potential market size; and $LANG_{jt}$ is a dummy variable that equals 1 if India and the j^{th} OECD country share

a common official language, and o otherwise, capturing communication-related trade facilitation.¹

In addition to these, the specification in Equation (4) incorporates a few more factors that also influence LCT exports based on the relevant literature: TER_{jt} refers to the enrolment ratio (gross) in tertiary education; $REER_{jt}$ represents the Real Effective Exchange Rate between India and the j^{th} importing country; WGI_{jt} stands for World Governance Indicators, reflecting the institutional quality level of the j^{th} importing country; and REC_{jt} is the renewable energy consumption as a percentage of total final energy consumption. Higher tertiary education enrolment increases technological absorptive capacity and environmental awareness within importing economies. Countries with more skilled labour forces are better positioned to adopt and integrate advanced low-carbon technologies, which can stimulate demand for imported clean technology. Renewable energy consumption captures the intensity of the energy transition within importing countries. Higher renewable penetration reflects investments in clean energy infrastructure that often require complementary imported technologies, components, and equipment, thereby influencing bilateral trade flows in LCT products. β_o is the constant term and β_k (where $k = 1, \dots, 10$) are the corresponding coefficients to be estimated; δ_j captures imported fixed effects, controlling for time-invariant inward multilateral resistance across OECD markets; φ_t are the time fixed effects that proxy export-year shocks² affecting India's overall export supply; and ε_{jt} is the error term. Time fixed effects also absorb common global shocks affecting all trade relationships in a given year, including global supply-chain disruptions, tariff escalations, or broad industrial policy shifts influencing clean-technology markets. By controlling for these time-specific factors, the estimation isolates the variation arising from differences in oil price exposure and environmental expenditure across OECD importing countries. In order to improve the normality, reduce variability, and improve the linearity of the independent variables, the natural logarithmic value of all the variables excepting the dummy has been considered. So, the estimates of the coefficients corresponding to the log-transformed variables can now be interpreted as the semi-elasticities. We proceed to brief on the data sources.

India's exports of LCT products to OECD economies is sourced from the IMF Climate Change Dashboard, which offers annual trade values in USD for each country-year pair. To get real values, all figures are deflated using the US Consumer Price Index (CPI). Carbon capture systems,

wind turbines, solar panels, and biomass equipment are a few examples. The product classification suggested by Howell et al. (2023), which associates 124 5-digit HS codes (2017 revision) with LCT products, is the basis for the reported trade data. According to OECD and Eurostat (1999), these technologies constitute a particular subset of the larger category of 'environmental goods'. Crude oil import prices are obtained from the IEA's Crude Oil Import Register, which is accessed through the OECD Data Explorer. These prices not only mirror global supply and demand patterns but are also influenced by geopolitical events and energy market changes. The total import value, as reported by customs officials for each tariff line, is divided by the corresponding import volume to determine the average import price. The real price was calculated using the deflator for GDP at market prices. The IMF's Climate Change Indicators Dashboard, which uses the Government Finance Statistics (GFS) database, provides data on government spending on environmental protection by the OECD countries. According to the COFOG framework, this variable records public spending on a variety of environmental initiatives such as waste and wastewater management, pollution reduction, biodiversity and landscape preservation, and associated environmental research and development. To ensure temporal comparability, the study's measure is the total amount of money spent by the government on environmental protection, expressed in constant prices. The information offers a uniform and globally comparable indicator of environmental policy commitment across nations.

Among the control variables, the annual GDP growth rate is obtained from the World Bank's World Development Indicators (WDI) database. Expressed in constant 2015 USD for cross-country comparability, it reflects annual percentage growth at market prices. The bilateral distance between India and each destination country, proxied by capital-to-capital distance, is sourced from the CEPII GeoDist database and serves as a standard trade cost proxy in gravity models. The Common Official Language dummy variable is also sourced from CEPII and annual population growth rate data (percent) are obtained from the WDI database.

Tertiary education enrolment (TER – percent of the relevant age group) is sourced from the WDI, as higher enrolment in OECD importers fosters an environmentally conscious, technologically absorptive market (Castellacci and Lie 2017; Cohen and Levinthal 1990), supporting demand for imported greener imports. The Composite World Governance Indicators (WGI), constructed as the arithmetic mean of six governance

dimensions – voice and accountability, political stability, government effectiveness, regulatory quality, rule of law, and control of corruption – are drawn from the World Bank dataset. Stronger governance in OECD countries promotes credible environmental regulation and institutional capacity, enhancing LCT import demand (Fredriksson and Svensson 2003; Porter and van der Linde 1995; Koźluk and Timiliotis 2016). The Real Effective Exchange Rate (REER) from WDI captures India's external price competitiveness, where currency depreciation boosts LCT exports and appreciation suppresses demand. Finally, renewable energy consumption (REC) – measured as the share of renewables in total final energy use from WDI – acts as a demand-side driver for LCTs, indicating investment in clean infrastructure and energy transition.

Empirical Analysis

EXPLORATORY EVALUATION

The empirical analysis begins by examining the general behaviour of our variables. The summary statistics are computed as in table 1 for a preliminary overview.

The shape of the LCT imports distribution is symmetric with a mean and median of 16.61 and 16.62, respectively, which corresponds to a very balanced distribution. The range of the LCT imports is between 8.40 and 21.46, and the inter-quartile range (15.46 to 17.94) indicates that most of the observations are clustered around the mean. The negative skewness (−0.50) reflects the presence of a slight left tail, meaning that while most of the countries import large to medium amounts of LCTs, there are some instances of relatively lower amounts of imports. The kurtosis measure (4.20) is greater than that of the normal distribution, which reflects the presence of the heavier tails and higher probability of extreme observations, though the latter are not dominant. The variable Oil Import Prices (OIP) also follows a symmetric distribution with mean value 4.15 and median value 4.18. The minimum and maximum values of OIP are 3.19 and 4.78, respectively, and most of the values lie between the first (3.92) and third (4.52) quartiles. The negative value of skewness (−0.43) and moderate value of kurtosis (2.52), indicating weak left tail and relatively normal distribution, reflect that extreme oil price volatility is uncommon in the sample. The parallelism of the distributional characteristics of the LCT imports and OIP is striking. Both series are extremely close in their means and medians, and both are only moderately negatively skewed.

TABLE 1 Summary Statistics of the Study Variables

Variable	Min	First_ Quantile	Median	Mean	Third_ Quantile	Max	Skewness	Kurtosis
LCT	8.40	15.46	16.62	16.61	17.94	21.46	-0.50	4.20
OIP	3.19	3.92	4.18	4.15	4.52	4.78	-0.43	2.52
EEP	0.03	0.44	0.55	0.54	0.66	1.01	-0.27	3.30
GDP	-2.48	0.58	1.11	0.81	1.42	3.24	-1.33	4.27
DIST	8.52	8.64	8.72	8.82	8.87	9.44	1.29	3.42
LANG	0.00	0.00	0.00	0.25	0.25	1.00	1.15	2.33
TER	3.52	4.13	4.25	4.27	4.40	5.02	0.15	4.28
REER	4.11	4.56	4.61	4.59	4.64	4.86	-0.99	6.40
WGI	0.12	0.67	0.88	0.82	0.98	1.08	-0.99	3.26
REC	0.64	2.19	2.69	2.70	3.26	4.13	-0.13	2.59

This would suggest that exploration of the connection between oil prices and LCT imports can be done without much concern about biasing outlier-driven effects. With the availability of ample variation between the two series, the empirical approach of tracing the potential influence of oil prices in determining the LCT imports is highly legitimate. Other control variables, including EEP, REC, and TER, possess distributions with low skewness and moderate kurtosis; GDP and POP, however, possess more extreme negative skewness, representing infrequent observations of lower economic output or population sizes, which could represent some country-year pairs undergoing economic contraction or demographic transformation. REER and WGI are also negatively skewed, with REER possessing greater kurtosis, representing some infrequent but extreme low values.

The visualization in figure 1 supports the hypothesis that Indian LCT exports to the 24 OECD nations have grown consistently during the past two decades. The recent acceleration of export volumes from 2010 onwards is of special interest and could be the result of various mutually reinforcing drivers: the global increase in climate policy commitments (e.g. the Paris Agreement); increasing fossil fuel prices and spurring the attractiveness of renewable solutions; and the strategic positioning of India as a cost-effective producer of clean technologies. The scatter plot in figure 2 further assesses the correlation between oil import prices (x-axis) and LCT imports (y-axis) for all country-year observations in the sample.

The scatter plot suggests a positive association between oil import prices and LCT imports across the sample of OECD countries. While the relationship is not perfectly tight, the general upward pattern is consist-

ent with the hypothesis that higher fossil fuel prices may encourage sub-

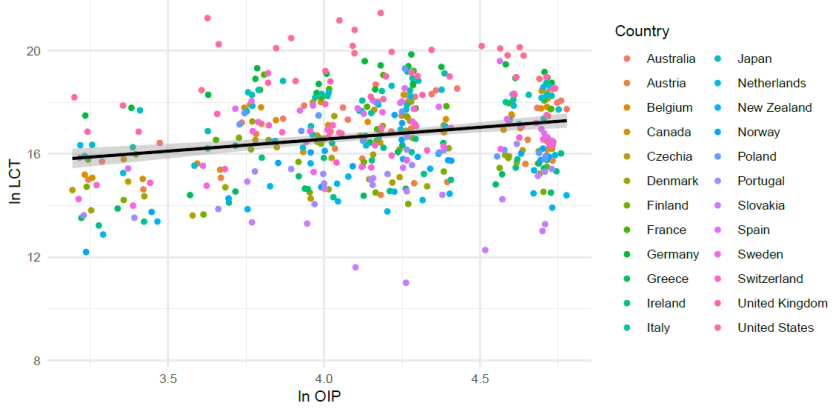


FIGURE 2 Scatter Plot with Trend Line Showing Relationship Between Oil Import Price and LCT Exports

stitution toward cleaner technologies, although causal relationships are formally examined in the econometric analysis. The positive correlation provides preliminary descriptive evidence that oil price dynamics may be associated with LCT trade patterns.

Coming out of the ambiguity in Hypothesis H2, the scatter plot in figure 3 shows a loose negative relationship between environmental protection spending and LCT imports, indicating that greater domestic spending on environmental protection is, on average, linked with lower levels of LCT imports from India. Although there is extensive dispersion in country-specific policy regimes, economic structures, and varying en-

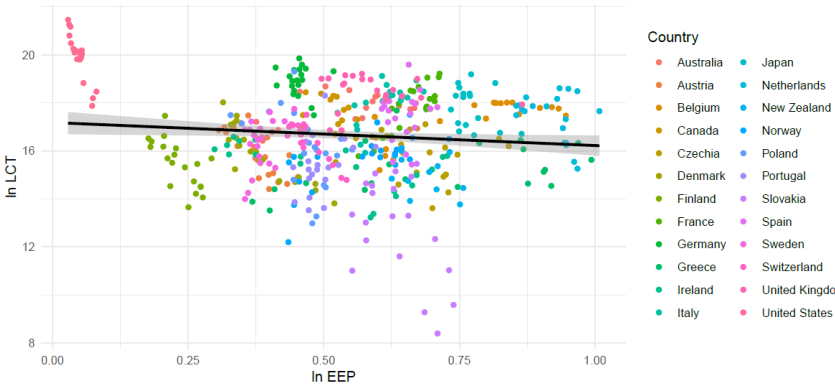


FIGURE 3 Scatter Plot Showcasing Relation Between India's LCT Exports and Environmental Protection Expenditures by OECDs

vironmental management approaches, the general trend is that countries that spend more on environmental protection are not necessarily good markets for Indian LCT products.

PPML ESTIMATION

The results of the PPML estimation employed to study the two hypotheses H1 and H2 obtained using Stata 16 software are presented in table 2.

We begin with the standard fixed effects gravity model with only the two primary explanatory variables ($\ln OIP_{jt}$ and $\ln EEP_{jt}$) in model specification 1, and then progressively add on the control variables in the subsequent specifications. The results show that oil import price shocks faced by the OECDs significantly favour Indian LCT exports to these countries, while increasing expenditure on environmental protection by

TABLE 2 PPML Estimation Results

	(1)	(2)	(3)	(4)
Variables	LCT exports	LCT exports	LCT exports	LCT exports
OIP	0.669*** (0.147)	0.647*** (0.152)	0.782*** (0.148)	0.854*** (0.158)
EEP	-0.562*** (0.343)	-0.440** (0.306)	-1.014*** (0.309)	-1.219*** (0.388)
pcGDP		0.00988 (0.0957)	0.0648 (0.0847)	0.0606 (0.0821)
DIST		-0.382 (0.339)	-0.261 (0.352)	-0.692** (0.338)
POP		-0.344 (0.322)	0.718** (0.360)	0.871** (0.347)
LANG		0.670*** (0.223)	0.652*** (0.224)	1.308*** (0.265)
TER			-0.0430 (0.263)	-0.545* (0.293)
WGI			-3.429*** (0.401)	-4.410*** (0.394)
REER				-2.139*** (0.684)
REC				0.676*** (0.140)
Constant	14.80*** (0.602)	18.13*** (3.056)	19.20*** (3.125)	33.41*** (3.814)
Observations	480	480	480	480

NOTES Robust standard errors in parentheses

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

the OECDs has a significant dampening effect. Interestingly, we note that once we are controlling for the effects of real exchange rate (REER) and share of renewables in total energy consumption (REC) in specification 4, the coefficients for both our explanatory variables ($\hat{\beta}_1$ and $\hat{\beta}_2$) become larger, implying greater and more accurate explanatory power. While in specification 1 a rise in oil import prices by 1 percentage point *raises* LCT exports by 0.669 percentage points, LCT exports *raises* by 0.854 percent points in specification 4. Again, in specification 1, a rise in expenditure on environmental protection by 1 percentage point *decreases* LCT exports by 0.562 percentage points, and in specification 4 by 1.219 percentage points.

If we take a moment to analyse as to why this may be happening, REER exhibits a negative and highly significant coefficient (-2.139), implying that an appreciation of India's currency adversely affects the competitiveness of its low-carbon technology exports. Interesting is the positive and highly significant coefficient of REC (0.676). This suggests that greater renewable energy penetration in OECD economies complements rather than substitutes India's LCT exports. As OECD countries expand the share of renewables in their energy mix, investment in renewable energy infrastructure, grid modernization, energy storage, and complementary clean technologies also increases, generating greater demand for imported LCT products. India's growing competitiveness in sectors such as solar photovoltaic components, energy-efficient equipment, and other low-carbon technologies enables it to benefit from this expanding demand. Consequently, once the positive influence of renewable energy transition and the adverse impact of exchange-rate appreciation are explicitly controlled for, the estimated positive effect of oil import prices and the negative effect of environmental protection expenditure become even more pronounced, indicating that these variables capture distinct structural channels influencing India's LCT exports to OECD markets.

Discussion of Results

The positive and statistically significant correlation between oil import prices and India's LCT exports to OECD countries aligns with existing literature and operates through several reinforcing channels. Rising oil prices increase energy costs in developed economies, encouraging a shift away from fossil fuels in transportation, manufacturing, and electricity generation. This transition raises demand for solar, wind, electric mobility, and other energy-efficient technologies, creating expanded export opportunities for India in green technology segments. OECD govern-

ments often respond to higher oil prices with climate-aligned policies such as renewable energy subsidies, tax incentives for energy-efficient imports, reduced tariffs on LCT products, and public procurement of green technologies. These measures lower regulatory and economic barriers for importing competitively priced LCT products from developing economies, thereby supporting India's LCT export growth. Higher oil prices also increase global freight and logistics costs, encouraging OECD countries to diversify and de-risk supply chains by sourcing from a wider range of suppliers, including LCT manufacturers in developing economies. The consistently strong positive oil-price coefficient across gravity model specifications indicates a stable structural relationship between fossil-fuel market dynamics, energy transition policies, and global clean-technology trade patterns.

Conversely, the negative and statistically significant relationship between OECD environmental protection expenditure (EEP) and India's LCT exports suggests dominance of the export dampening over the export accelerating effect as was proposed in H2. Although higher environmental spending could increase demand for clean technologies, several mechanisms explain the opposite effect. First, rising EEP often reflects strong domestic industrial policy, with OECD countries directing funds toward building local LCT manufacturing capacity, subsidizing domestic firms, and strengthening innovation ecosystems, thereby reducing reliance on external suppliers like India. Second, greater environmental spending is frequently accompanied by stricter regulatory standards and technical requirements, which can function as non-tariff barriers for exporters from developing economies. Finally, environmentally conscious consumers increasingly prioritize traceability, transparency, and verified environmental certifications, creating a reputational disadvantage for exporters lacking internationally recognized standards. This interpretation is consistent with studies showing that environmental policy instruments often operate simultaneously as innovation policies that strengthen domestic green industries and reduce reliance on imports (Dechezleprêtre and Sato 2017; Costantini and Mazzanti 2012).

Conclusion and Policy Implications

This paper examines the determinants of India's low-carbon technology (LCT) exports to OECD countries, focusing on how oil import prices and environmental protection expenditures influence trade flows. Using a Poisson Pseudo Maximum Likelihood (PPML) gravity model that

accommodates heteroskedasticity and zero trade flows, the study provides robust evidence on the macroeconomic and environmental factors shaping India's green technology exports.

The results show that higher oil import prices in 24 selected OECD countries have a positive and significant impact on India's LCT exports, suggesting that fossil fuel cost pressures increase demand for clean alternatives – an opportunity India can leverage. Conversely, environmental protection expenditures in OECD economies have a significant negative effect on imports of Indian LCT products. This may indicate a shift toward strengthening domestic clean-tech ecosystems, increased reliance on non-tariff barriers, or diversion of environmental budgets toward non-tradable services and R&D. The finding highlights India's challenges in meeting the stringent quality, certification, and traceability standards demanded in high-income markets. Despite global opportunities arising from the 'China +1' strategy and energy security concerns, India's LCT export potential remains constrained by credibility issues in its supply chains and limited regulatory alignment with OECD standards.

Policy implications follow directly from these patterns. India should strategically target markets where LCT demand is highly responsive to oil price swings, especially countries experiencing energy transitions or dependence on fossil fuels. Strengthening bilateral trade and technology partnerships during periods of high global oil prices could amplify export gains. The negative link between environmental spending and Indian exports underscores the urgency of regulatory harmonization; India must pursue mutual recognition agreements, improve certification processes, and assist firms in complying with strict environmental and product standards. Measures such as green export clusters, public-private certification platforms, and quality-assurance subsidies can help bridge compliance gaps. To reduce vulnerability to external standards, India should upgrade its position in the LCT value chain through investments in R&D, design, and service integration. Moving from component exports to full-solution offerings can improve competitiveness and resilience.

This study has some limitations that suggest avenues for future research. While the analysis focuses on key macroeconomic and policy variables, future work could explore firm-level dynamics, sectoral variations within LCT, and the influence of global environmental agreements. Additionally, disaggregating the environmental protection expenditure into its functional components (e.g. pollution control, environmental

R&D, biodiversity protection as per COFOG framework) or by introducing an interaction term between environmental expenditure and indicators of governance quality or innovation capacity to better identify which types of environmental spending stimulate or substitute for imports of low-carbon technologies.

The current analysis could be further strengthened by conducting additional robustness checks, such as using bilateral real exchange rates instead of aggregate measures, employing alternative proxies for environmental policy stringency, excluding crisis years like the COVID-19 period, or estimating simplified specifications to test the stability of the key coefficients. Further work could also examine India's share in total LCT imports of each OECD country – rather than export flows alone – to better capture India's export competitiveness relative to other source countries, recognizing that comparative advantage operates in a multi-lateral rather than purely bilateral context.

Overall, the study shows how energy market dynamics and environmental policies in high-income countries shape LCT trade, emphasizing the need for India to strengthen its role in global clean energy value chains and climate-oriented trade networks.

Notes

- 1 The empirical specification includes variables measured in different forms – log levels, shares, and growth rates – reflecting differences in the economic nature of the underlying indicators. Policy variables are log-transformed to allow elasticity interpretation and to reduce heteroskedasticity, while certain macroeconomic controls such as GDP growth and population growth are retained in percentage form because they represent short-run demand conditions rather than scale variables. This mixed specification is common in empirical gravity applications where explanatory variables capture both structural market characteristics and cyclical macroeconomic dynamics. Log linearizing is done as $\text{sign}(x) \cdot \ln(|x|+1)$.
- 2 In structural gravity models, multilateral resistance terms must be controlled for to ensure theoretical consistency (Anderson and van Wincoop 2003). In our empirical setting, India is the sole exporter, while trade flows are observed across multiple OECD importing countries over time. Consequently, exporter-year fixed effects would be perfectly collinear with time effects. To address outward multilateral resistance, the model therefore includes time fixed effects that capture common exporter-specific shocks affecting India's export supply in each year, such as macroeconomic conditions, technological changes, or trade policy shifts. Inward multilateral resistance is controlled for through importer fixed effects, which account for time-invariant trade frictions and structural characteristics of each OECD market.

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Appendix

List of the 24 OECD Countries Used in the PPML Estimation

Australia	Austria	Belgium	Canada	Czechia	Sweden
Denmark	Finland	France	Germany	Greece	Switzerland
Ireland	Italy	Japan	Netherlands	New Zealand	United Kingdom
Norway	Poland	Portugal	Slovakia	Spain	United States