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Powering the Energy Transition in Enterprises: Empirical Insights into the Global Value Chain–Energy Innovation Nexus

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Abstract

Global value chain (GVC) embedding can induce businesses' energy efficiency and decarbonisation transition. Yet, this is the end effect; the granular process-level energy upgrades and enhancements that lay the groundwork for the broader transition remain unexplored. This is the first firm-level examination of the linkage between GVC participation and energy efficiency innovation. Using WBES-BEEPS database in 41 global countries, we find that GVC participation significantly increases enterprises' propensity to take up energy innovation. The mechanism analysis uncovers the mediating role of market scale and induced research and learning spillovers in explaining the studied nexus. We conduct a nuanced heterogeneity analysis to account for variations across firm-level characteristics, sectoral attributes, global regions and country income groups. The positive effect is more evident among SMEs, less financially restrained firms, liable enterprises to environmental regulations, and firms operating in manufacturing, medium-high and high-tech and relatively energy-efficient industries. The income-based cross-country analysis pinpoints the effect of GVCs on intensifying global energy inequality. GVC firms from low-income countries can disproportionately innovate in their energy efficiency, yet only if they function within energy-efficient sectors. Regional heterogeneous results are stronger among MENA firms, and more specifically SMEs, financially unconstrained, medium and low-technologically intensive, and energy-regulated enterprises. A set of robustness checks validates the reliability of baseline results to endogeneity and selection biases. This research encompasses a suite of policy recommendations for leveraging the association between GVC embeddedness and firm-level green energy performance to accelerate macro-level environmental protection.

Keywords: Global value chains, Energy Efficiency Innovation, Environmental Regulation, Developing countries

JEL classification : F1 ; F14 ; O3 ; Q4 ; Q5

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Introduction

Over recent decades, the world has entered a new era of international division that has given rise to global value chains (GVCs), a hallmark of the modern global economy. Around 70% of international trade has increasingly been involved in GVCs. In essence, GVCs is a complex web of interactions among firms from different countries, reshaping global trade patterns by infusing value-added at each stage of the production chain of a final product or service. If a firm produces within at least one stage, it can actively participate in the global realm of high production fragmentation. In such an interconnected trading setting, businesses tap into a wider global market scale where they outsource/offshore parts of their production to/from other countries and interchange modern expertise and technology (Antràs & de Gortari, 2020; Antràs, 2020; Rigo, 2021; OECD, 2024). Participants accordingly unlock multifaceted productivity and efficiency spillovers, endowing them the capacity to take up upgrading approaches to generate higher value (Humphrey & Schmitz, 2002; Meng et al., 2020; Gentile et al., 2021; Krishnan et al., 2022).

Prior related literature substantially delves into identifying firm-level gains from GVC embedding while specifying four fundamental upgrading principles. First, the economic and functional upgrading through the refinement of original products and the introduction of new goods (Humphrey, 2004; De Vries, 2016). Second, the social upgrading in terms of better working conditions, enforced labour rights, and enhanced gender equity (Marslev et al., 2022; Kallini & Zaki, 2024). Third, the technological upgrade relates to increasing resource efficiency and innovating in new organisational mechanisms, products and processes. Given the complementary competencies across the chain and the pressure to align with international quality standards, the complex inter- and intra-firm linkages undoubtedly trigger the exchange of international best-practice knowledge and technologies (Pietrobelli & Rabellotti, 2010; Eissa & Zaki, 2023b). Fourth, the environmental upgrading by minimizing the environmental footprint of business operations along the value chains. Firms tend to optimize their production system in a way that avoids and/or reduces their pollution and resource use (soil, energy, etc.) (Krishnan et al., 2022). This is related to the intricacy of GVCs' interlinkages and transactions that induce expanded production scope, raising concerns about intensifying massive greenhouse gas (GHG) emissions (Cevik & Miryugin, 2022; Meng et al., 2023a, 2023b). Such prompting scrutiny is specifically pressing at energy-intensive production stages owing to the fact that energy is commonly identified as the principal production and consumption source of heating and lighting, making up for more than 75% of global GHG emissions (International Energy Agency, 2024).

A solidified stream of work tackles the area of green value chains while specifying the advantageous impact of businesses' GVC participation on reducing their ecological footprint (De Marchi et al., 2019; Chen et al., 2022; Hua et al., 2022; Gentile et al., 2023; Li et al., 2023; Gao et al., 2024) and prompting their green innovative practices (Hu et al., 2021; Meng et al., 2022). Within the same strand, some scholars direct their attention to energy sustainability, suggesting that decoupling energy consumption from environmental pollution requires firms to adopt sustainable energy practices to refine their energy mix. Most importantly, minimizing unsustainable energy consumption is expedited by reducing used materials and increasing resource savings, confirming the significance of energy-efficient innovation for the transition to a green economy. In principle, energy-efficient innovation refers to installing eco-innovative and clean technologies within the production processes that help reduce firm-level energy-intensity (Rennings, 2000; Capozza et al., 2021; Wu, 2023). Yet, energy efficient transition should be consolidated with virtuous internal energy management, continued policy support, extensive research and development (R&D) investment and massive capital mobilization. Accessibility to such drivers is quite problematic, specifically for enterprises operating in developing countries with obsolete technologies, limited infrastructure, and less regulatory conformity (Koirala, 2019; Tian & Lin, 2019). As a counterforce, a range of researchers stresses on the imperative influence of integration in international markets on absorptive expertise and capabilities for restructuring energy-intensive consumption patterns. Exposure to international environmental protection standards and carbon neutrality targets accelerate their energy efficiency through technological and know-how transferability (Song & Wang, 2016; Hu et al., 2021; Agostino et al., 2023; Siweres et al., 2024). However, others indicate that it can draw adverse effects due to the environmental and technological lock-in effects of relocating the most polluting (energy-intensive) and low-technological industries to developing countries (Chen et al., 2022; Lee & Wen, 2025). To our knowledge, none of the established findings unveil the relationship between embedding in GVC and energy-specific innovation. Since eco-energy innovation relies heavily on internationalisation, technological capacities, internal green awareness, environmental market demand, and regulatory quality (Garrone et al., 2014; Costa-Campi et al., 2015; Song & Oh, 2015; Clementi & Garofalo, 2023), GVC participation can serve as a catalyst by activating these enablers.

Accordingly, this paper examines the extent to which firm-level integration in GVCs can trigger the propensity to innovate in energy efficiency. As far as known, this is the first paper to explore the linkage between firms' participation in GVC and energy innovation related to energy efficiency. This research intends to fill in the gaps of four relevant bodies of literature by referring to areas on: (1) GVC embedding and firms' general environmental performance (Siewers et al., 2024). (2) The nexus between GVC involvement and firm-level innovation (Avenyo et al., 2022; Eissa & Zaki, 2023a; 2023b), and more specifically green innovation (Hu et al., 2021; Meng et al., 2022). (3) GVC embedding and enterprise-level energy efficiency (Agostino et al., 2023; Lee & Wen, 2025). And finally (4) the literature on the GVC positioning and lock-in effects (Huang et al., 2022, Yang et al., 2022; Bai & Wu, 2024). The main research question is scrutinized using the latest firm-level WB-EBRD BEEPS in 41 global countries. Our empirical results suggest that GVC participation significantly increases the propensity for firm-level energy efficiency innovation. The mechanism analysis attributes the positive effect to market scale and the learning effect, particularly with reference to enhanced technological knowledge development and innovation experience. The baseline findings are found to be heterogeneous, where the positive effect is more evident for SMEs, manufacturing businesses, and financially flexible enterprises and liable firms to energy regulations. One of the most compelling results of this paper is consolidating the pollution haven hypothesis. Our country-level heterogeneous results verify that offshoring dirty production stages to enterprises operating in low-income countries locks them in biased technological progress, and so they are confided in a more energy-intensive comparative advantage production. GVCs exacerbate energy insecurity and inequality by blocking the flow of green technological and knowledge flows that could stimulate firm-level innovation in energy-saving production processes in less-developed economies. Another salient finding is the particularly strong effect observed in the MENA region compared to other regions. We move beyond the assumption of a uniform effect by further disaggregating the analysis within MENA to align GVC exposure with firm and sector-specific readiness. SMEs, non-credit-constrained businesses and enterprises classified as part of energy efficient and technology-lean industries are the ones reaping energy innovative benefits from their participation in GVCs. The study is divided as follows. Section one presents the literature review. Section two discusses the data and methodology. Section three presents main results and its robustness checks. Section four is dedicated to mechanism and heterogeneity analyses.

1. Literature Review

1.1. GVCs and transfer of knowledge, productivity and technology

Embedding in global value chains alters a firm's operational environment by expanding its access to foreign markets and intensifying its exposure to competition from foreign entrants in the domestic market (Shu & Steinwender, 2019). Accordingly, productivity-growth opportunities extend to lead firms, local suppliers, and other partner members within the same supply chain. When developed-economies' lead firms outsource components or intermediate input production to developing-countries suppliers, operational synergies are unfolded through effective coordination, intensive interaction, labour movements, and fluid transfer of tacit knowledge, and technologies (Hovhannisyan & Keller 2015; Santacreu-Vasut & Teshima, 2016). Such a cooperative functional structure ensures reciprocal gains for both parties. Foreign lead firms are incentivized to transfer their know-how, advanced technologies, and informational assets, including product specifications and quality standards, to secure efficiency gains through cost reductions and improved output quality (Gentile et al., 2021; Rigo, 2021; Avenyo et al., 2022). As for local suppliers, the inter-firm linkages and seamless diffusion of- foreign-licensed technology and knowledge foster their productivity and innovation capabilities (Gentile et al., 2021; Avenyo et al., 2022). For instance, Ayadi et al. (2020) document that the total factor productivity gains of GVC integration among MENA firms is further agglomerated when they consider the country-sectoral influence of higher connectivity and central positioning within the intermediate trade network.

1.2. GVCs and firm-level innovation

Anchored in economic upgrading from low to high-value added specialisation view, existing contributions validate that GVC involvement induces firm-level product and process innovation. Despite sparse empirical evidence on this stream, the positive association emerges across diverse settings, globally (Elshaarawy & Ezzat, 2022), regionally like Africa and MENA (Eissa & Zaki, 2023a), and nationally (Dang & Dang, 2020). Three main mechanisms are elucidated to explain the innovative gains: product market competition, knowledge spillovers, market scale. First, GVC embedding intensifies competitive pressures in product markets, compelling technologically advanced firms with higher absorptive capacity to innovate for survival, while discouraging laggard firms with weaker innovative capabilities and retard productive capacities (Aghion et al., 2021; Lee & Wen, 2025). Second, cross-border knowledge spillovers arise as firms harness the technological value and learning potential of imported intermediate goods to catch up with the technology frontier, activating their learning-by-exporting and catalyzing their production system upgrading (Eissa & Zaki, 2025). This is where scholars propose that GVC embedding can bias the reallocation of technological and know-how spillovers away from developing countries that have comparative disadvantage in technology production (Aghion et al., 2021; Eissa & Zaki, 2023b; Lee & Wen, 2025). For instance, Eissa and Zaki (2023a) show that innovative firms in developing countries possess higher absorptive capacity and operate in skilled-labour and medium-low technology intensive activities. Third, the integration in a broader market scale allows domestic firms to garner higher sale revenues and profits, and so more feasibility to undertake R&D investments, fostering their competitiveness stance in the new markets (Aghion et al., 2021; Geng & Kali, 2021). Another related stream of empirical evidence identifies the foreign networks across chains as a chief input to boosting the innovation capacities of SMEs by inducing large-scale production and promoting lower cost of oversea information sharing (Lee & Wen, 2025). Thus, GVCs help reverse the negative association between SME's and innovation by substituting for the costly internal R&D investment, improving their market presence (Eissa & Zaki, 2025), and easing their systematic constraints, such as economies of scale and financial accessibility (Elshaarawy & Ezzat, 2022; Cowling & Dvouletý, 2023).

To optimally capitalize on GVC-induced learning gains for reinforcing a firm's readiness for innovation, a group of scholars emphasize key mediating factors of influence, including the acquisition of quality certifications (Avenyo et al., 2022); domestic competition, trade and intellectual property rights policies, and the enforcement of the rule of law (Eissa & Zaki, 2023b). Conversely, certain firm- or context-specific factors could outweigh the positive impact of GVC embedding on firms' innovation, such as firm size, where larger and more productive firms are able to handle the hefty upfront costs and participate in forward GVC linkages, (Antràs, 2020; Gentile et al., 2021); the limited local absorptive capacity and low learning effects (Pietrobelli & Rabellotti, 2010; Piermartin & Rubínová, 2014; De Marchi et al., 2018); and financing constraints, especially in case of firms' locating in middle-income countries[3] (Elshaarawy & Ezzat, 2023).

1.3. GVCs and firm-level environmental performance and eco-efficiency strategies

Although GVC embeddedness provides domestic firms with expanded market access and growth prospects, it simultaneously raises environmental concerns due to increased production scale, requiring an intensive use of non-renewable energy sources (i.e. coal and crude oil, etc.) (Bai & Wu, 2025; Lee & Wen, 2025). Given that energy-related CO_2 emissions pose a major challenge to sustainable development, recent studies increasingly examine how

[3] Authors refer to the main reason of the negative outweighing effects by the high level of risks related to the volatility of exchange rate and high trade costs.

GVC embedding affects firms ‘environmental performance, particularly energy efficiency. Evidence from Chinese firms shows that deeper GVC integration reduces SO_2 emission intensity, particularly among privately owned domestic businesses, firms facing environmental regulations, and those operating in pollution-intensive sectors. This emission-reducing effect is largely driven by access to advanced technology embedded in imported intermediate inputs and improved carbon-use efficiency (Hua et al, 2022; Li et al., 2023; Gao et al., 2024). In this regard, scholars believe that the opportunities brought by GVC participation can outweigh its associated environmental challenges, making GVC-integrated firms environmentally outperform non-GVC ones (Yang & Liu, 2021; Hua et al., 2022; Bai & Wu, 2024). Indeed, GVCs encourage firms to adopt eco-efficiency strategies that translate environmental investments into competitive gains by lowering costs, enhancing resource productivity (i.e. material savings), improving process yields and ensuring effective by-product management (Orsato, 2006). Two dimensions of eco-efficiency are particularly salient: green innovation and energy efficiency. First, green innovation offsets are commonly cited for addressing the environmental problems by improving resource productivity (Porter & Van Der Linde, 1995). In turn, GVC integration triggers eco-friendly technology innovation efficiency, a pre-requisite for allocative resource efficiency, especially for firms subject to regulatory pressures, facing financing constraints, publicly owned enterprises, and those operating in pollution- and capital-intensive sectors as well as firms in developing countries (Meng et al., 2022; Wu et al., 2025). Second, GVC participation promotes sustainable energy practices for the deployment of clean energy technologies and adoption of energy-specific management. GVCs heterogeneously encourage greener aptitude among SMEs and less endowed firms in terms of human capital or financial resources (Agostino et al., 2023; Lee & Wen, 2025).

Scholars also identify three recurring factors mediating the GVC-environment nexus. First, learning and knowledge spillovers from multinational firms facilitate access to advanced knowledge, energy-saving technologies, and environmental management experience (Sun et al., 2019; Ji et al., 2022; Meng et al., 2022; Agostino et al., 2023; Bai & Wu, 2024; Siewers et al., 2024; Wu et al., 2024; Lee & Wen, 2025). Second, increased market scale and intensified competition prompt firms to agglomerate their R&D investments in pursuit of cost-effective and energy-efficient technologies (De Marchi et al., 2013; Wu et al., 2024; Lee & Wen, 2025). Third, compliance with stricter foreign environmental standards throughout the entire value chain push firms to enhance their green competitiveness by upgrading their industrial structure, reducing their carbon intensity, and refining their energy mix (Wang et al., 2022; Bai & Wu, 2024; Siewers et al., 2024).

1.4. GVC and environmental performance across income groups and GVC positionings

A growing body of research is increasingly citing income-based diversities of environmental performance among GVC firms, reflecting unequal distributed gains, regulatory schemes and access to necessitated technology and expertise along the chains. Empirical results remain inconclusive, providing three different perspectives on how GVC participation affects firms’ environmental performance in developing countries. First, some evidence supports the arguments of factor endowment theory and the pollution haven hypothesis, according to which developed countries with more stringent regulations tend to have a comparative disadvantage in pollution-intensive industries. Firms located in developed economies are highly inclined to offshore the production of energy-intensive and polluting intermediate goods to developing countries with laxer environmental regulations (Li & Zhou, 2017; Duan et al., 2021), resulting in higher carbon emission intensities embodied in the exports of developing (Su & Thomson, 2016; Wang et al., 2021a). Accordingly, high-income economies exhibit greater environmental gains in terms of reduced carbon emissions, from GVC involvement due to their technological and capital advantages compared to their middle and low-income counterparts (Chen et al., 2022; Zheng et al., 2024). Conversely, less-developed regions like MENA economies reap environmental sustainability benefits conditional on their engagement in forward value linkages (Elmassah, & Hassanein, 2023). Second, another stream of findings supports the pollution halo hypothesis, stating that GVC-integrated firms in developing countries can reduce their energy intensity and pollution emissions owing to the benefits they reap from environmental management and clean technological spillovers (Liu & Zhao, 2021; Chen et al., 2022; Bai & Wu, 2024). Third, some conclusions exhibit a more complex inverted U-relationship between GVC and carbon emissions, implying that technological progress increases emissions in developing countries up to a certain threshold value of GVC participation, after which pollution emissions decrease (Wang et al., 2021b).

In parallel, the discussion on firm-level GVC-environment linkages is enriched by another body research delving into the effect of GVC positioning. When firms integrate into GVCs, they tend to meet the international demand for their product while striving to improve their GVC embedding position and deepen their embeddedness degree. This implies the movement from the downstream to the upstream and from the low value-added to the high value- added link of the industry. This repositioning along the chain implies improvements in firms' production efficiency and energy utilization and minimization in carbon emissions, yet only in the short run. In the long term, a country may be locked in a low GVC embedding position, namely in pollution-intensive processing and manufacturing industries. One explanation can be the emission intensive effect of GVC-induced production efficiency that is attributed to higher total energy consumption, and more carbon emissions. Thus, the relationship between carbon emission intensity and GVC positioning is U-shaped (Huang et al., 2022). One must also acknowledge the fact that GVC firms with a shallow degree of embedding have limited absorptive capacity for advanced technology and management systems, due to their reliance on unskilled labor and basic technology (Cohen & Levinthon, 1989). Hence, they are unable neither to cope with the intensified competition nor to adapt to stricter foreign regulations, implying locked-in position within carbon-intensive phase with deteriorated environmental performance and higher energy consumption. But beyond a critical threshold, deeper GVC embeddedness can shift industries' technological progress toward energy conservation, encouraging firms to reduce their energy consumption per output unit (Huang et al., 2022; Yang et al., 2022; Bai & Wu, 2024).

1.5. GVC and energy efficiency innovation

As such, it seems that the literature suffers from limited examination concerning the impact of GVC participation on energy innovation. To draw a theoretical foundation to the relationship, one need to briefly examine the literature tackling the determinants of firm-level energy innovation. The existing academic work on environmental innovation identifies energy innovation as a sub-category of environmental process innovation that aims at enhancing energy efficiency, that is "reducing energy and/or material use" and/or boosting the employment of renewable energy (Agostino et al., 2023; Clementi & Garofalo, 2023; Dzwigol et al., 2023). Energy innovation is triggered by a wide array of internal and external factors. Internal drivers primarily reflect firms' structural characteristics, financial resource accessibility, intensive energy consumption, internationalization, R&D investment, innovative and technological capacities, green awareness and environmental management systems (Garrone et al., 2014; Costa- Campi et al., 2015; Song & Oh, 2015; Sun et al., 2021; Zhang & Fu, 2022; Clementi & Garofalo, 2023; Zaghdoud, 2025). External drivers relate to stakeholder pressure factors, such as functioning within an enforceable regulatory scheme, subjection to environmental regulations, demand-pull factors, sectoral environmental practices and agreements, and industry-level energy intensity (Song & Oh, 2015; Woerter et al., 2017; Hille et al., 2020; Capozza et al., 2021; Šūmakaris et al., 2021; Zhu et al., 2021; Du et al, 2022; Dzwigol et al., 2023). Based on relevant literature bodies, it seems that many of energy innovation drivers are interlinked and stimulated by engagement in GVCs, rationalizing the drawn linkage between both variables.

Upon reviewing the relevant body of literature, we intend to test two main hypotheses: Ho: GVC participation increases firm-level energy efficient innovation, and H1: GVC participation decreases firm-level energy efficient innovation

2. Data & Methodology

2.1: Data and Stylized Facts

Microdata is sourced from the Business Environment and Enterprise Performance Survey (BEEPS), jointly developed by the World Bank Group and the European Bank for Reconstruction and Development[4]. The survey has a comprehensive green economy module that provides a set of environmental business indicators and green management practices. We specifically use the latest survey spanning the period 2018-2020 to deliver the most recent and updated conclusions for around 28,000 firms[5] in 41 global countries[6]. For the measurement of main variables of interest, we rely on the basic criteria of business involvement in direct importing and exporting activities for identifying firm-level GVC participation (Dovis & Zaki,

[4] Source of data: European Bank for Reconstruction and Development, https://www.beeps-ebrd.com/data/.

[5] The effective sample after dropping all missing values

[6] The sample includes countries from Central & Eastern Europe, the former Soviet Union, and the MENA region. The sampled countries are: Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, the Czech Republic, Egypt, Estonia, Georgia, Greece, Hungary, Italy, Jordan, Kazakhstan, Kosovo, the Kyrgyz Republic, Latvia, Lebanon, Lithuania, Malta, Moldova, Mongolia, Montenegro, Morocco, North Macedonia, Poland, Portugal, Romania, Russia, Serbia, the Slovak Republic, Slovenia, Tajikistan, Tunisia, Turkey, Ukraine, Uzbekistan, and the West Bank and Gaza.

2020). Energy efficiency innovation is measured in consistence with the proposed definition of Rennings (2000), Capozza et al (2021) and Wu (2023) pertaining to the introduction of new process facilities that reduce energy consumption or replace fossil-fuel consumption with renewable energy resources. We use the available information on energy efficiency measures and upgrades to classify firms as energy innovative if they undertake at least one of the following production process-specific energy activities: heating and cooling improvements; lighting system improvements; machinery and equipment upgrades; vehicle upgrades; climate-friendly energy generation on site; and use of renewable energy resources.

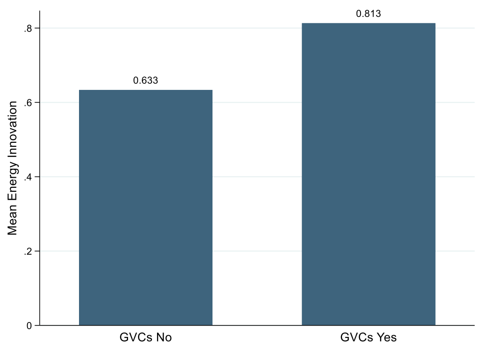
In Table (1), descriptive patterns point to clear association between GVC involvement and innovation in proactive energy efficiency measures. Across the sample, most firms are not integrated into GVCs, yet the share of businesses engaging in innovation for reducing their energy intensity remains relatively higher than those that do not. Depicting the shares of GVC involvement against energy innovation, GVC firms report higher uptake of energy efficient technological and machinery upgrades and installations compared to their non-participant counterparts. Around 74% of GVC-integrated firms exhibit energy efficiency innovative practices in the overall sample[7]. However, more than half of GVC-unintegrated firms don't have the tendency to initiate any of such measures. At sectoral level, presented data in Table (2) indicates that energy innovation is prevalent among GVC firms operating in manufacturing sectors, followed by service and retail industries. Graphical representation in figure (1) further affirms that GVC manufacturing firms record the largest concentration of innovative firms, on average.

Table (1): Cross frequencies share of firm-level GVC participation and energy efficiency

Energy efficiency innovation	**GVC**		
	No	Yes	Total
No	95.15	4.85	100.00
	47.78	26.23	45.95
Yes	88.41	11.59	100.00
	52.22	73.77	54.05
Total	91.51	8.49	100.00
	100.00	100.00	100.00

Source: Constructed by the authors using WBES-BEEPS dataset. First row has row percentages and second row has column percentages Sample weights are accounted for.

Figure (1): Firm-level energy innovation and GVC



[7] We display the same descriptive statistics yet while using simultaneously stricter criteria alongside the typical tow-way trade for defining firms' involvement in GVCS. Advanced definitions include exporting and importing combined with having either an international quality certificate, a positive share of foreign owned capital, or both (Dovis & Zaki, 2020). Statistics shows that the share of GVC participants innovating in energy efficiency is increasing as criteria gets stricter (80%, 82% and 90%, respectively) (See Appendix A)

Table (2): Firm-level GVC participation and energy efficiency by industry type

Energy innovation	GVC participants				GVC non-participants			
	Manufacturing	Retail services	Other services	Total	Manufacturing	Retail services	Other services	Total
0	42.22	2.61	55.17	100.00	19.53	19.09	61.38	100.00
	22.60	11.66	32.07	26.23	42.62	51.35	48.60	47.78
1	51.42	7.02	41.56	100.00	24.06	16.55	59.39	100.00
	77.40	88.34	67.93	73.77	57.38	48.65	51.40	52.22
Total	49.01	5.86	45.13	100.00	21.90	17.77	60.34	100.00
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Source: Constructed by the authors using WBES-BEEPS dataset. First row has row percentages, and second row has column percentages Sample weights are accounted for.

On the regional and income-tier dimension, data patterns in Table (3) clearly reflect that European and high-income countries are the forerunners, standing out with the highest energy efficiency innovation shares. More than 90% and 80% of GVC-engaged firms that are energy innovative are originated in either Europe or high-income economies, respectively. Apparently, developed countries are more agile in deriving greater energy innovation benefits from trading across global chains to mitigate their ecological challenges (Ignatenko et al., 2019). They exploit their persistent innovation dynamics, where "past innovation achievements strongly influence current performance" to shift their energy mix towards less carbon-intensive alternative resources (Nguyen, et al., 2025). Yet, the same trend persists within each other region and income group, where firms involved in GVCs display higher tendency for transitioning to processes with lower fossil-fuel consumption compared to domestically oriented enterprises. Visual evidence in figures (2) and (3) illustrate that, on average, the share of firms that undertake energy efficient innovation is higher among GVC participants than non-participant, regardless of the specified country income or regional classification. Notably, non-participant GVC firms still show higher levels of energy innovation in most regions, except for the case of MENA firms. Only 40% of firms record adoption of clean energy production process improvements, shedding light on the distinctive importance of internationalism for energy transition among MENA firms.

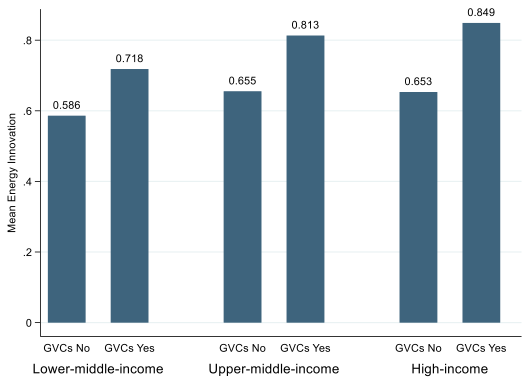
Table (3): Firm-level GVC participation and energy efficiency by income tiers and regions

Income Groups								
Energy innovation	GVC participants				GVC non-participants			
	Lower-middle-income	Upper-middle-income	High-income	Total	Lower-middle-income	Upper-middle-income	High-income	Total
0	12.51	12.93	74.56	100.00	11.38	5.91	82.70	100.00
	37.24	28.38	24.69	26.23	56.79	40.43	47.36	47.78
1	7.50	11.60	80.90	100.00	7.92	7.97	84.11	100.00
	62.76	71.62	75.31	73.77	43.21	59.57	52.64	52.22
Total	8.81	11.95	79.24	100.00	9.58	6.99	83.44	100.00
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Regions								
Energy innovation	GVC participants				GVC non-participants			
	Central Asia	Europe	MENA	Total	Central Asia	Europe	MENA	Total
0	1.13	86.14	12.69	100.00	1.10	87.76	11.11	100.00
	34.11	24.99	38.42	26.23	39.94	46.85	58.46	47.78
1	0.77	91.96	7.24	100.00	1.51	91.08	7.22	100.00
	65.89	75.01	61.58	73.77	60.06	53.15	41.54	52.22

Total	0.87 100.00	90.43 100.00	8.67 100.00	100.00 100.00	1.31 100.00	89.50 100.00	9.08 100.00	100.00 100.00

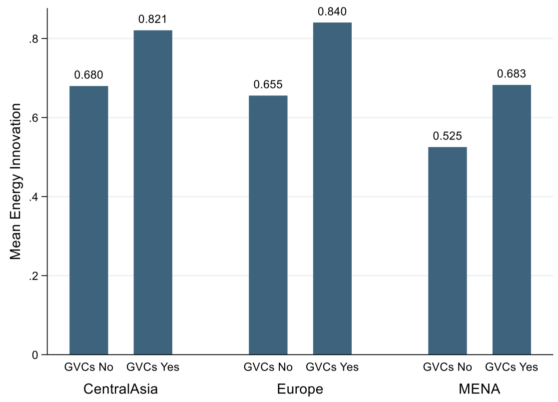
Source: Constructed by the authors using WBES-BEEPS dataset. First row has row percentages, and second row has column percentages Sample weights are accounted for

Figure (2): Firm-level energy innovation and GVC embedding across income groups



Source: Authors' own elaboration   Notes: Weights are use

Figure (3): Firm-level energy innovation and GVC embedding across regions



2.2: Model Specification

Based on the reviewed literature, a multivariate empirical equation is set up to estimate the impact of firm-level GVC participation on energy innovation as follows:

$$\mathbf{Energy\ Innovation_{isct}} = \boldsymbol{\beta_0} + \boldsymbol{\beta_1}\mathbf{GVC_{isct}} + \boldsymbol{\varphi}\mathbf{X_{isct}} + \boldsymbol{\gamma_s} + \boldsymbol{\alpha_c} + \boldsymbol{\Theta_t} + \boldsymbol{\varepsilon_{isct}} \qquad \mathbf{(1)}$$

where i, s, c, and t represent firm, industry, country, and year, respectively. Energy innovation is a dummy variable that takes the value of 1 if the firm undertakes at least one the aforementioned energy-related practices and 0 if it doesn't undertake any of them. The main independent variable of GVC participation is proxied by a binary that is equal to 1 if the firm is a two-way trader, that is, directly exporting and importing at the same time (Dovis & Zaki, 2020). So as not to disregard firms that indirectly import or export via national intermediaries, the variable also considers firms that export (import) a positive share of their sales (inputs and supplies), regardless if they do so directly or indirectly (Siewers et al., 2024). X is the vector of main covariates. $\boldsymbol{\gamma_s}$, $\boldsymbol{\alpha_c}$, and $\boldsymbol{\Theta_t}$ stand for industry, country and time dummies, respectively, and ε_{isct} is the error term.

The vector of control variables is determined in line with prior evidence tackling the determinants of business energy innovation. To limit the effect of omission bias, we break down the main factors of energy efficiency innovation into two main groups that include as much as possible all attainable core influencing variables. The first group entails the typical individual characteristics of firms (size, age, and ownership type). The second is dedicated to resources and capabilities that facilitate setting in-house strategies related to energy efficiency (human and financial capital, knowledge development, technological capacity, and organizational management). Concerning firm structural specificities, the scale of the firm highly affects business management and allocation of its resources. It is generally established that larger firms have more available resources to direct towards innovative investment

(Boeing, 2016). Firm size is included as a dummy variable for different sizes depending on the number of full-time employees. We follow the World Bank Enterprise Survey classification to define small firms as having 5 to 19 employees, medium firms 20 to 99, and large firms 100 or more (Wu, 2023). Firm age plays a notable role in shaping the organization's innovation direction, yet the extent to which it can positively or negatively drive green innovative initiatives reaches no consensus. While younger firms could be more eager to engage in socially responsible practices like energy-efficient activities for enhancing their market reputation, older firms can be highly adaptable to environmentally evolving stakeholder concerns (Agostino et al., 2018; Zhang et al., 2020; Wang et al., 2021; Zhou et al., 2021). Age is calculated as the natural logarithmic of the subtracted value of the firm's establishment from the survey year (Du & Li, 2019; Li et al., 2021; Ren et al., 2021; Du et al., 2022; Song et al., 2022; Clementi & Garofalo, 2023). A firm's foreign orientation is cited as one key driver of its energy transition through a smoother pipeline of cutting-edge technologies and expertise that enhance productivity and innovation intensity (Guadalupe et al., 2012; Zhang et al., 2020; Xue & Wang, 2021). Indeed, this is related to how close the enterprise is to the foreign market (De Loecker, 2013); thus, it is captured by the percentage owned by private foreign individuals, organizations, and companies (Lee & Wen, 2025). Moving to core business resources, financial constraints are listed as one of the primary barriers to investment in energy efficiency for its long pay-back periods and high front costs (Šūmakaris et al., 2021; Agostino et al., 2023; Lee & Wen, 2025). We follow the league of Fowowe (2017) to construct a measure of full credit constrained status. The dummy variable takes a value of 1 for firms that have no loans, applied for loans and got rejected and did not use external sources of finance for both working capital and investments during the previous year and 0 if the firm reports successful access to any of the specified criteria. Since the full credit constraint variable captures only firms' external financial flexibility, we also account for firm's internal financial resource streams (Berrone et al., 2010; Dekker & Hasso, 2016; Agostino et al., 2023). Profitable firms are expected to have more assets at hand for environmental innovation, and so firms' total annual sales is added to reflect the potential effect of their revenues[8]. As another essential input to eco-innovation, human capital is reflected by whether the firm provides its permanent full-time employees with professional training programs (Agostino et al., 2023). Previous innovative experience and absorptive capacity of the firm are commonly referred to as knowledge development capabilities of the firm. Solnørdal and Thyholdt (2019) and Arranz et al. (2021) argue that knowledge accumulation is crucial for developing clean energy innovation. Knowledge development is added as a dichotomous variable that is equal to 1 if the firm spent on either inside/outside R&D or acquired external knowledge (Šūmakaris et al., 2021). Organizational innovation in terms of developing energy management systems is a decisive determinant for energy-efficient innovation. It reflects the firm's green capabilities relative to the pertinent environmental knowledge and self-regulatory measures for developing new eco-friendly processes and products (Rennings et al., 2006; Costa-Campi et al., 2015). This paper applies the same approach as Karplus and Grover (2020) to construct an energy management score measure. The measure includes energy auditing, energy monitoring, energy management,

[8] A typical total profit proxy is not added since data on cost variables is only available for a limited number of observations

energy efficiency enhancement measures, and energy consumption targets. It is essential to pinpoint that all variables in monetary units are deflated and converted into the 2015 US dollars.

Aside from firms' internal indicators, we account for external institutional and environmental constraints that can pressure businesses to shift their technological and intellectual productivity towards rationing their dirty energy consumption. Environmental regulatory challenges can reduce negative externalities and adverse selection among enterprises, triggering business investment in new less energy-intensive technologies (Huang & Chen, 2015; Hille et al., 2020; Agostino & Ruberto, 2021; Du et al., 2022). An energy regulation dummy variable is added with a value of 1 if an enterprise is subjected to at least one of two energy-related regulatory tools: energy tax and energy performance standards in operation and 0 if it isn't exposed to any regulation. Another relevant determinant of innovative environmental performance is the quality of the institutional environment where enterprises operate. Corruption degree and fairness of the legal system not only affect the enforcement of environmental regulations but also the implementation of energy-saving investments (Alam et al., 2019; Lee & Wen, 2025). We follow the proposed methodology by Fogel et al. (2006), Chadee and Roxas (2013), and Barasa et al. (2017) to construct a measure of national institutional quality based on firm-level governance perceptions[9]. Energy innovation can be triggered by demand-pull factors related to evolving customer preferences for products with a low carbon footprint (Russo & Perrini 2010; Chao & Hong, 2019; Capozza et al, 2021). As such, a variable of whether a firm's customers require environmental certifications or adherence to certain environmental standard factors in environmental market dynamics is added (Wu, 2023).

2.3: Identification Strategy

The earlier-specified empirical equation is estimated using probit regression to consistently fit the binary nature of the energy-efficient innovation variable. Since the latest BEEPS survey comprises independently sampled observations across each period, pooled cross-sectional estimation modelling is the best fit for the analysis. It allows for the combination of different cross-sectional units from different time periods (2018-2020). Year-fixed effects are added to control for time-specific attributes of the outcome and an interaction between industry and country fixed effects is included to alleviate the cofounding effect of different industrial structures in each country. Since energy innovation variables can't be assumed to be statistically independent, we also deploy the multivariate probit approach to model the situation where a firm might simultaneously innovate in more than one facet of energy innovation. The model serves as robustness validation of the baseline results while accounting for the correlation of the unobservable factors related to energy innovation. We conduct a likelihood ratio test to checked for the relevance of estimating a multivariate probit model by testing the hypothesis that correlation coefficients are jointly equivalent to zero.

[9] We make use of the institutional matters section of the Enterprise Survey to construct the measure which is composed of three main dimensions: corruption, regulatory quality, and rule of law. The variables used for each dimension, along with the approach followed to aggregate the indicators into a composite measure, are explained in Appendix B

Prominently, all regressions are run while taking into account the complex nature of survey data by including weights and stratum identifiers.

It is important to take notice of the potential biasedness of probit estimation that is caused by selection and endogeneity biases. On one hand, the dependent variable of interest is only observed for non-randomly selected sample of firms that participate in GVCs. Firms' involvement is highly affected by both unobservable and observable business factors that can be correlated with energy efficiency innovation. For instance, internationally recognized quality certification, like ISO 14001, is posed as a facilitator input to introducing environmental management structures for governing eco-friendly process innovation (Kammerer, 2009) and at the same time, it is one of the requirements in a vertically fragmented production process (Dovis & Zaki, 2020). On the other hand, reverse causality can contaminate the direction of association between our two main variables of interest. Firms that are relatively more energy efficient have higher capacity to integrate into GVCs and be selected by multinationals for their adaptability to labor divisions and imposed global environmental standards across the chains (Agostino et al., 2023; Aghion et al., 2023; Gao et al., 2024; Paschoaleto & Martínez-Zarzoso, 2024).

To tackle the selectivity concerns due to observables, we employ the propensity score matching (PSM) technique, where the treatment is the likelihood of a firm to participate in GVC. Firms are matched with a set of selection observable variables, including size, industry type, age, foreign and state ownership share, financial constraints, human capital and possession of internationally recognized quality certification (Agostino et al., 2023; Eissa & Zaki, 2025; Lee & Wen, 2025). Although PSM assumes exogeneity of treatment variables, there is still a propensity that estimates can be confounded by unobservables. So, we resort to the instrumental variable two-stage least squares estimation approach, where GVC involvement is instrumented by firms' customs and trade obstacles. The rationale behind the instruments' selection is that the variable directly affects energy-saving innovation behaviour only through trading within value chains (Eissa & Zaki, 2023). Another commonly used instrument is the average GVC participation value at the country-sectoral level. The variable is an econometrically sound tool for isolating the true effect of GVCs on energy innovation. Firm-level GVC embedding is directly correlated with the diffusion of GVC within their operating national industry but enterprise individual characteristics cannot impact the average value at a higher level (Agostino et al., 2023; Lee & Wen, 2025). The baseline analysis is extended in two ways. First, a mechanism analysis is conducted to uncover the mediator factors that explain the baseline effect. Second, a sub-sampling regression is conducted to unveil heterogeneous effects and draw inferences on moderator factors at firm, industry, country, and global region levels.

3. Main Results

3.1: Baseline Results

Results of regressing energy efficiency innovation on firm-level GVC participation are reported in Table (4). Column (1) include GVC estimates while controlling only for country and year fixed effects, whereas column (2) augments the specification with industry-fixed effect to limit the cofounding effect of industry-specific differences. In both cases, the coefficient of GVC is significant at 5% level with slight increase in GVC's coefficient after adding industry fixed effects. We then account for the time-invariant sectoral variations within countries by incorporating the country-sector fixed effect in column (3). Once the model considers multidimensional fixed effects, GVC participation exhibits a significant positive effect with even higher impact magnitude[10]. According to multivariate probit output, GVC participation induce businesses to specifically innovate in lighting system improvements, machinery and equipment upgrades, vehicle upgrades, and use of renewable energy resources[11] (See Appendix C). As such, the baseline findings validate this paper's first hypothesis, that is GVC participation drives interlinked innovative forms of reducing firms' energy intensity. Most importantly, the results are concurrent with prior research validating that GVC participation is effectively conductive to reducing a firm's energy intensity (Meng et al., 2022; Jin et al., 2022; Siewers et al., 2024; Lee & Wen, 2025). Business integration within the international production chains smooths the innovative upgrading process of existing production systems for less energy consumption, enhancing energy productivity and reducing heavy reliance on fossil-fuel energy. A coherent explanation is that GVCs facilitate the transmission of sustainable management experience, green action plans, and modern technologies throughout the trading networks. Novel practices and technologies encourage GVC-engaged firms to adapt, on energy usage basis, to the ongoing trend of green production and technologies within a wider market with more concerned consumers and leading suppliers on the environmental footprint of offered products (Li et al., 2019; Pahl & Timmer, 2020; Ha & Thanh, 2022; Meng et al., 2022; Bai & Yu, 2024). On this basis, the extent to which the positive innovative effect can be explained by market scale and knowledge sharing is a matter that is extensively examined through the mechanism analysis in section (3.3)

Concerning the impact of covariates, in most cases, they coincide with theoretical expectation, verifying the reasonability of our model setting. Most coefficients for firm age, annual sales, institutional quality, internal energy management, knowledge development, financial constraint, customer environmental demand, and foreign ownership are positively significant at the 1% level. Older firms are more likely to adopt energy innovation given that they are less opaque, more exposed to stakeholders' control and less indulged in financial constraints (Horbach et al., 2012; Dekker & Hasso, 2016; Agostino et al., 2023). Knowledge development activities reinforce a firm's absorptive and adaptable capacity, encouraging eco-

[10] To a certain extent, these results verify that unobserved heterogeneity at the country-sector level underestimates the true effect of GVC parameter.
[11] Likelihood ratio test strongly rejects the null hypothesis, supporting the appropriateness of applying multivariate probit and confirming the interdependence between energy innovation outcomes

innovation propensities (Solnørdal & Thyholdt, 2019; Arranz et al., 2021; Capozza et al., 2021). Installing energy management systems is proactive for shaping new business procedures and investments in resource efficiency, including energy innovation (Rehfeld et al., 2007; Wagner, 2008; Kammerer, 2009; Segarra-Blasco & Jove-Llopis, 2019). The higher the perceived quality of the institutional environment, the more likely firms are to consider investment in long-run clean energy (Lee & Wen, 2025). Firms that are constrained to access traditional financial resources are highly unlikely to approach green and resource-efficient investment opportunities (Cruz et al., 2014; Moreno-Mondéjar & Cuerva, 2020). Unlike the case for lucrative firms with high revenues, they are financially robust to cover the high upfront costs of green energy innovation (Berrone et al., 2010; Dekker & Hasso, 2016). As the share of foreign-owned capital increases, the link between the organization's green innovation and positive influence of foreign investors on R&D investment and productive capacity becomes more vivid (Kong et al., 2020; Wu, 2023). Finally, businesses are more inclined to alter their energy consumption structure under increased pressure from environmentally-considerable customers (He et al., 2016; He et al., 2018; Andries & Stephan, 2019; Capozza et al., 2021; Agostino et al., 2023). Surprisingly, firm size, energy regulation and employee training variables reveal no significant effect.

Table (4): Baseline Results

Variables	(1)	(2)	(3)
GVC	0.0904**	0.0941**	0.139***
	(-0.0456)	(-0.0421)	(-0.0482)
Small firm	0.102	0.115	0.129
	(-0.0959)	(-0.101)	(-0.106)
Large firm	-0.062	-0.0903	-0.0982
	(-0.0739)	(-0.0848)	(-0.0936)
Ln age	0.206***	0.217**	0.243***
	(-0.0672)	(-0.0852)	(-0.0911)
Financial constraint	-0.269***	-0.280***	-0.291***
	(-0.0639)	(-0.0519)	(-0.0483)
Ln annual sales	0.0751**	0.0824**	0.0834**
	(-0.0333)	(-0.0391)	(-0.0396)
Knowledge development	0.485***	0.486***	0.465***
	(-0.154)	(-0.161)	(-0.161)
National institutional quality	0.594***	0.578***	0.571***
	(-0.17)	(-0.174)	(-0.175)
Employee training	0.0437	0.061	0.058
	(-0.0727)	(-0.0739)	(-0.0751)
Energy management	2.229***	2.221***	2.194***
	(-0.3)	(-0.306)	(-0.294)
Energy regulation	0.084	0.0674	0.107
	(-0.229)	(-0.232)	(-0.251)
Environmental demand	0.488*	0.513*	0.546*
	(-0.275)	(-0.307)	(-0.313)
Foreign ownership	0.377***	0.379***	0.360***
	(-0.125)	(-0.127)	(-0.127)
Industry Fixed effect	No	Yes	Yes
Year Fixed effect	Yes	Yes	Yes
Country Fixed effect	Yes	Yes	Yes

Industry Country Fixed effect	No	No	Yes
Constant	-2.200***	-2.274***	-2.185**
	(-0.683)	(-0.778)	(-0.866)
Observations	22,888	22,888	22,888

Robust and clustered standard errors in parentheses *** is for p -value <0.01, ** p-value <0.05, * p-value <0.1

3.2: Robustness Checks

While the previous section puts forward empirical evidence on the contribution of GVC participation on energy efficiency innovation, this section tests the validity of baseline results to self-selection, endogeneity biases, and sensitivity analyses.

3.2.1: Addressing Endogeneity & Selectivity concerns

To verify the exogeneity of the baseline results, we adopt instrumental variable and PSM estimation approaches. Table (14) in Appendix D presents the empirical results of instrumenting GVC with customs and trade obstacles in column (1) and average GVC values in column (2). Instrumented GVC still exerts a significant positive effect on business decisions to innovate in energy efficiency at the 1% level. GVC coefficients exhibit a higher impact compared to baseline results, indicating the underestimated GVC effect by endogeneity bias. Correcting for selection bias, we run PSM using the specified vector of selection variables to eliminate the GVC confounding effect by firm pre-existing disparities. We run a balanced test to ensure that treated and controlled groups are, on average, similar with respect to a set of common support covariates and consistently attribute differences in energy efficiency innovation adoption to GVC participation. For robustness, the treatment effect is estimated using both the kernel matching algorithm and the 5 nearest neighbors (NN) matching method. Moreover, we re-estimate the baseline equation (1) on the matched sample while accounting for all explanatory variables that are not used in the selection model to ensure that the matching removes all differences. Across all specifications, average treatment effects are statistically significant at the 1% level. The magnitude of the effect does not deviate much after adding the rest of the covariates to GVC participation, affirming that the treatment is consistent and the matching process successfully eliminates confounding bias. (see Tables 15-18 in Appendix D). Once again, the robustness of the paper's main story is reinforced.

3.2.2: Alternative measures of covariates and extended model specification

This paper verifies the reliability of its conclusions by checking for its sensitivity to using different proxies for the main independent variable and other controls. Given non-conclusive definition of firm's GVC participation, we re-estimate the baseline model with a tighter criterion based on foreign ownership that functions as an exporting channel for foreign destinations (Dovis & Zaki, 2020). Results of proxying GVC integration as firms that export and import and maintain a positive share of foreign ownership continue are still significantly and positively associated with a higher probability of energy efficiency innovation[12]. As such,

[12] In line with Dovis and Zaki (2020) approach to defining firm-level GVC participation, we consider the other stricter facets of qualifying firms for GVC integration upon two-way trade and ownership of international quality certification as well as the combination of all strict aspects of exporting, importing, foreign ownership and certified quality in the robustness analysis. We find no significant effect on energy innovation using the stricter proxies, suggesting that more selective criterion limit the attributed energy innovation variation to GVC participation. This can be because the more advanced definition captures a smaller subset of highly internationalized firms that are already

our main findings are not limited to a sole definition of key outcome variable. For covariates, alternative proxy measures are considered for financial access, energy management, and human capital. The fully credit constraint measure is replaced by another proposed measure by Zhang et al. (2020) that defines a financially restrained firm as one that has been denied access to a credit line or loan or discouraged from applying for a loan. We follow Wu (2023) in constructing another binary measure for firm-level internal energy management that takes a value of 1 if a firm has any of the following organizational factors: appointment of an environmental manager, and monitoring and setting targets for energy consumption over the past three years. Human capital is redefined as the proportion of skilled employees in total production employees[13] (Lee & Wen, 2025). The reported results in Table (19) in Appendix D show that modified specifications of some variables endorse a stable positive impact of GVCs.

For more reliable baseline findings, we extend the main empirical model to account for further firm-level energy innovation drivers. Six additional variables are concurrently added to the primary model: innovation capabilities[14] (Stephenson et al., 2015; Arranz et al., 2019), natural logarithm of country-level fossil fuel subsidy in USD[15] (Yang et al., 2022), percentage of a firm's shares owned by the same family[16] (Agostino et al., 2023), informal competition (Wu, 2023), and good management practices (Delera et al., 2022). The outcome of expanding the baseline model specification is listed in Table (20) in Appendix D. Across all specifications, GVC retains its positive significant impact with similar coefficients to what is previously elucidated in the baseline analysis. Against this robust backdrop, it becomes evident that the main conclusion holds true regardless of variations in either model or variable specifications.

3.3: Mechanism Analysis

A firm's ability to innovate in energy efficiency is determined by its resource use (Lopez et al., 2015), as well as its knowledge and technological absorptive capacity (Solnørdal & Thyholdt, 2019). As far as GVC participation is concerned, the aforementioned energy innovation drivers are mostly generated by the market scale and learning effects. In this section, we delve into analyzing their mechanism role in encouraging firms' decisions to take up energy-related innovative upgrades. Since both market scale and learning effects are, at their core, broad in definition, we rely on the work of Lee and Wen (2025) to define their indirect effect through specific mediator factors of stimulated revenue streams, enhanced productivity and technological capabilities. Remarkably, we follow the firm-level technological capacity definition of Capozza et al. (2021), Šūmakaris et al. (2021), and Eissa and Zaki (2023b) as a combination of both the intangible knowledge development and the tangible innovation experience. In other words, the variable measures whether firms conduct any type of R&D, acquire external knowledge, innovate in a new product or new process, and use a licensed

technologically competent. Yet, substantial effect, that is even higher than that reported in the baseline analysis, persists only among large firms, validating the view that the energy innovative impact of GVC integration is more reliant on firm-level internal resources and capacities than on specific definition.

[13] The alternative human capital measure suffers from a lot of missing values, reducing the re-estimated sample size

[14] Innovation capabilities are measured upon a firm's adoption of any product or process innovation (Lorenz & Pommet, 2021).

[15] Subsidy data is sourced from OECD and IISD fossil fuel subsidy tracker

[16] According to the socioemotional wealth and affective endowment conceptualization, family-owned businesses are more inclined to be environmentally-oriented as a means of preserving the family's social legacy (Berrone et al., 2012; Kellermanns et al., 2012).

technology from a foreign-owned company. Labor productivity is annual sales per employee (Costa-Campi et al., 2015; Wu, 2023).

Mediation analysis typically unfolds over three main steps, starting with the baseline estimation as reported in Table (4). In the second stage, the mediation variables are regressed on GVC participation in columns (1)-(3) in Table (5). The results imply that GVC participation drives a significant positive impact on sales, productivity, and technological capacity at the 1% level. However, once all mediating factors have been added along with GVC in the third step in column (4), the coefficient on annual sales becomes less significant, labor productivity turns insignificant, and technological capacity retains its highly significant impact on energy innovation. Most essentially, the magnitude of GVC impact on energy efficiency innovation declined, highlighting the partial explanation of the GVC effect through market scale and learning effects, particularly technological advancements. In conclusion, GVC firms have lower trade costs to access global factors and end-product markets, enabling them to broaden their market scale and scope (Shu & Steinwender, 2019; Li et al., 2023). A wider competitive market scale not only upscales their production and increases their productivity, but facilitates their outreach to networks of upstream and downstream producers with a lower cost of information sharing per output unit (Gereffi & Lee, 2012). The easily accessible channels of advanced technological and production practices entail a transnational spillover effect of energy efficiency. This effect is mainly explained by the fact that optimizing energy-efficient technologies and techniques is induced by technology transfer, international investment, and the importing and exporting of intermediate inputs (Tran, 2022). Accordingly, GVC competition stimulates the main factors (technological knowledge and productivity) that contribute the most to firm-level structural energy efficiency transformation of its production process (Reddy, 1991; Jalo et al., 2021).

Table (5): Mechanism Analysis

Variables	**(1) Ln annual sales**	**(2) Ln labor productivity**	**(3) Technological capacity**	**(4) Energy innovation**
GVC	0.630***	0.432***	0.502***	0.110**
	(0.112)	(0.102)	(0.0838)	(0.0445)
Small firm	-0.998***	0.106*	0.00418	0.172**
	(0.130)	(0.0581)	(0.112)	(0.0805)
Large firm	1.659***	0.306**	0.0660	-0.163*
	(0.134)	(0.126)	(0.111)	(0.0887)
Ln age	0.252***	0.135***	0.0162	0.232**
	(0.0462)	(0.0450)	(0.0205)	(0.0987)
Financial constraint	-0.0926*	-0.137**	-0.208**	-0.286***
	(0.0523)	(0.0580)	(0.0827)	(0.0518)
National institutional quality	-0.546**	-0.486***	0.0457	0.554***
	(0.218)	(0.162)	(0.365)	(0.168)
Ln annual sales			-0.0305	**0.143***
			(0.0359)	**(0.0757)**
Employee training	0.459***	0.240**	0.831***	-0.0869
	(0.0960)	(0.108)	(0.0769)	(0.0780)
Energy management	0.340**	0.0476	0.789***	2.119***
	(0.142)	(0.0798)	(0.228)	(0.306)

Energy regulation	-0.414	-0.475	0.0621	0.124
	(0.275)	(0.324)	(0.139)	(0.260)
Environmental demand	0.451*	0.223	0.717***	0.439
	(0.225)	(0.193)	(0.173)	(0.282)
Foreign ownership	0.263	0.142	0.413***	0.288***
	(0.238)	(0.241)	(0.128)	(0.108)
Ln labor productivity				**-0.0636**
				(0.130)
Technological capacity				**0.632*** **
				(0.0686)
Constant	12.41***	10.43***	1.416***	-2.840***
	(0.196)	(0.222)	(0.497)	(0.924)
Year FE	Yes	Yes	Yes	Yes
Industry Country FE	Yes	Yes	Yes	Yes
Observations	9,924	10,100	22,909	22,840

Robust and clustered standard errors in parentheses *** is for p -value <0.01, ** p-value <0.05, * p-value <0.1

3.4: Heterogeneity Analysis

While it has been established that GVC can positively increase firm's innovation in energy efficiency practices, its impact may hinge on key moderators. On one hand, a firm's energy efficiency innovation is highly reliant on the enterprise resource and capabilities (Šumakaris et al., 2021). On the other hand, GVC is an evolutionary process of cross-sector and cross-country resource integration and production process fragmentation (Ayadi et al., 2020; Rigo, 2021; Wang et al., 2022). This implies that GVC participation may differently prompt energy innovation, warranting sub-sample analysis across firm-, industry-, country-, and regional levels.

3.4.1. Firm Heterogeneity

The first source of heterogeneity is firm-level internal aspects and external pressures, like size, capacity to easily access finances, and subjection to environmental policy instruments. Columns (1) and (2) in Table (6) are dedicated to subsample regression of financially constrained versus non-constrained firms. According to literature on energy innovation and eco-innovation investment, installing energy-saving materials, machines and equipment primarily require a sufficient flow of financial sources (Moreno-Mondéjar & Cuerva, 2020). GVC significantly infers energy innovation only among firms encountering no obstacles while accessing any of the typical external financial resources. Conversely, financing constraints hinder the likelihood of energy efficiency innovation by discouraging resource allocation toward strategic investments, such as R&D, thereby limiting firms' ability to leverage knowledge and technology transfer (Elshaarawy & Ezzat, 2022). Reported estimates in columns (3) and (4) make it clear that our baseline conclusions are pronounced among SMEs, yet the effect is insignificant for their larger counterparts[17]. Indeed, this can be depicted as an

[17] We are aware that reporting no significant effect on large firms is surprisingly against well-known evidence that they are the hub of GVC knowledge transfer and founders of GVC inter-firm networks (De Marchi et al., 2014). Against this, we interestingly underwent a heterogenous analysis for the large sampled firms and find that GVC significantly triggers energy efficiency innovation only for those operating in high- or upper-middle-income countries or those who have their own internal energy management system. It seems that large firms solely leverage their economies of scale and their structural network effect for their innovative energy transition if they are backed by a resilient doing-business environment and internal sustainable managerial experience.

extension to the work of Lee and Wen (2025) who prove that GVC embedding significantly promotes SMEs' energy efficiency. Penetrating oversea markets enables smaller firms to reinforce their market position, induces their learning effects through embedded environmental expertise in imported inputs, offsets their R&D fixed costs, and helps them avert their technology trap (Eissa & Zaki, 2025). Accordingly, SMEs embrace higher production scale and less costly innovation activities, which eventually can be translated into lower energy consumption (Ranasinghe et al., 2024). Among the external determinants of energy innovation is the exposure to environmental regulations, like performance standards and taxation. In columns (5) and (6), GVC significantly encourages energy innovation among both, subjected and non-subjected firms to energy regulations. But the magnitude of effect is higher for firms that are bound by environmental regulatory obligations and is even considerably higher than the baseline effect. A combination of integration in international production networks and mandatory compliance with national environmental regulations highly motivate cost-effective resource allocation and eco-friendly technological investments (Hille et al., 2020; Du et al, 2022).

Table (6): Firm-level GVC heterogenous effect on energy efficiency innovation

Variables	**(1) Financially constrained firms**	**(2) Non-Financially constrained firms**	**(3) Large Firms**	**(4) SMEs**	**(5) Subjected to energy regulations**	**(6) Non-Subjected to energy regulations**
GVC	-0.148	0.332***	-0.141	0.149**	0.457***	0.114*
	(0.176)	(0.122)	(0.241)	(0.0610)	(0.154)	(0.0590)
Small firm	0.316*	0.0296			0.0875	0.160
	(0.191)	(0.104)			(0.257)	(0.109)
Large firm	-0.271	0.000289			0.187	-0.205
	(0.193)	(0.176)			(0.154)	(0.141)
Ln age	0.239	0.261***	-0.207*	0.246***	0.292	0.240***
	(0.159)	(0.0594)	(0.118)	(0.0900)	(0.201)	(0.0810)
Financial constraint			-0.393***	-0.290***	-0.279***	-0.277***
			(0.133)	(0.0474)	(0.0973)	(0.0468)
Ln annual sales	0.182**	0.0150	0.106	0.0775*	0.00637	0.111***
	(0.0718)	(0.0268)	(0.0749)	(0.0396)	(0.0448)	(0.0403)
Knowledge development	0.489**	0.508**	0.391	0.467***	0.609***	0.439***
	(0.214)	(0.220)	(0.404)	(0.166)	(0.185)	(0.170)
National institutional quality	0.937***	0.262	0.550**	0.560***	-0.942***	0.506***
	(0.296)	(0.238)	(0.251)	(0.175)	(0.284)	(0.172)
Employee training	0.288**	-0.117	-0.131	0.0598	0.309	0.0515
	(0.124)	(0.0916)	(0.174)	(0.0770)	(0.190)	(0.0604)
Energy management	1.739***	2.617***	2.221***	2.203***	1.949**	2.246***
	(0.474)	(0.181)	(0.317)	(0.296)	(0.772)	(0.278)
Energy regulation	-0.248	0.331	0.419***	0.0968		
	(0.183)	(0.220)	(0.150)	(0.252)		
Environmental demand	0.843**	0.241	0.0289	0.564*	0.000790	0.667*
	(0.341)	(0.315)	(0.195)	(0.327)	(0.229)	(0.353)
Foreign ownership	0.477**	0.266	0.515*	0.345**	0.235**	0.541***
	(0.240)	(0.203)	(0.302)	(0.139)	(0.101)	(0.139)
Constant	-3.408**	-1.705***	-0.408	-2.098**	-1.684	-2.161***
	(1.452)	(0.547)	(1.166)	(0.816)	(1.210)	(0.737)

Year Fe	Yes	Yes	Yes	Yes	Yes	Yes
Industry Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	10,302	12,579	4,515	18,143	5,723	16,943

Robust and clustered standard errors in parentheses *** is for p -value <0.01, ** p-value <0.05, * p-value <0.1

3.4.2. Industry Heterogeneity

The following heterogeneity analysis gauges sectoral differences while differentiating the sampled firms upon industry type, as well as the sector's intensity of technological employment and energy consumption. We first focus on manufacturing and non-manufacturing firms. Taking the results in columns (1) and (2) in Table (7), GVCs incur its significant effect for both types of industries. The size effect for manufacturing firms is markedly higher than for others specialized in retail and service production[18]. According to Siewers et al. (2024), the manufacturing sector is arguably more relevant when it comes to exploring the relation between GVC and core variables relating to decarbonizing energy consumption. That is because the nature of the industry entails multiple stages, including procurement, production, logistics sales, and after-sales, each with high potential exposure and vulnerability to climate transitional and physical risks (Guo et al., 2024). The subsequent sectoral differentiation is focused on the degree of an industry's technological intensity where the firm operates. Columns (3) and (4) present the split of enterprises into two classifications: high-tech and medium high-tech against medium low- and low-tech firms[19]. The propensity of innovation in sustainable energy practices is significant among both technologically heterogenous groups. Compared to lower technologically intensive industries, high-tech and medium-high manufacturers have a higher GVC coefficient. In their essence, higher-tech industries are endowed with intensive capabilities like R&D investment and technological resources (Liu et al., 2018a, 2018b). They accordingly have a stronger innovation pipeline and higher technology absorption capacity (Baldwin & Lopez-Gonzalez, 2014) that will not only transfer it to lower-end industries in the chain but also streamline its energy-efficient transition. Our results can be posed as an extension to the suggested evidence of Bai and Yu (2024) about the heterogenous effect of GVC on firm's carbon emission reduction in technological intensive industries. It seems that GVC-induced learning spillovers fuel innovation momentum in tangible energy efficiency, which ultimately contributes to a firm's emission pollution reduction. As one last sector-related aspect, we find it imperative to examine industry-specific energy intensity heterogeneity of GVC impact on energy efficiency innovation. We run separate regressions on two subsamples of energy-intensive and less energy-intensive industries[20] and display the probit results in columns (5) and (6). While regressing energy efficiency innovation on GVC participation of less energy-intensive businesses reveals a similar positive significant conclusion as benchmark estimation, the effect shows no significance for firms operating in high energy-intensive sectors. Innovation in relatively energy-efficient sectors is commonly flexible given its easy installation of new eco-technologies, non-reliance on heavy infrastructure and low-needed capital. Conversely, higher energy-intensive sectors are ultimately pollution-intensive with critical need of complex technological innovation processes for its green transformation. In

[18] Notably, the effect is mostly significant among retail sectors.
[19] We use the Eurostat high-tech classification of manufacturing industries based on NACE Rev. 2 3-digit level.
[20] We define energy-intensive sectors using the median value of the energy intensity ratio (i.e., energy costs per dollar of sales) as a threshold (Agostino et al., 2023).

general, eco-friendly innovation typically comprises two main sub-processes: green technology R&D for developing intermediate output and conversion of innovative inputs into environmentally friendly economic output. These innovative processes differ among firms within energy-intensive sectors upon its green technological capacity and efficiency (Zhu et al., 2021). Exposure and interaction with foreign technological knowledge solidify this efficient energy-saving technological progress, but that depends on firm's GVC embedding method, direction and position (Yang et al., 2022). Unless the firm is positioned within the GVC in a way that enables it to channel adequate energy-saving technologies compatible with its existing energy-intensive processes, it will remain reliant on dirty energy production (Garrone & Mrkajic, 2018; Shahbaz et al., 2018). In other words, the reported insignificant coefficient may be triggered by the underlying heterogeneity in firms' ability to access, channel, absorb, and apply the needed cutting-edge know-how to shift their technological trajectory. Against this backdrop, we delve into examining to what extent the differences in countries' developmental status and their sectoral structures can affect our main propositions.

Table (7): Industry-level heterogenous effect on energy efficiency innovation

Variables	**(1) Manufacturing**	**(2) Non-manufacturing**	**(3) Medium low & Low-tech**	**(4) High tech & Medium high tech**	**(5) Energy Intensive**	**(6) Less Energy Intensive**
GVC	0.164**	0.138*	0.362**	0.786**	0.0229	0.176***
	(0.0807)	(0.0731)	(0.182)	(0.381)	(0.0956)	(0.0642)
Small firm	-0.0191	0.207*	0.271	-0.0713	0.00192	0.188
	(0.106)	(0.119)	(0.197)	(0.257)	(0.113)	(0.120)
Large firm	0.0144	-0.147	0.0520	-0.374	0.0628	-0.300***
	(0.205)	(0.0893)	(0.242)	(0.276)	(0.0676)	(0.0668)
Ln age	0.123	0.292***	0.140	0.536**	0.0767	0.354***
	(0.129)	(0.0748)	(0.0973)	(0.226)	(0.0881)	(0.0681)
Financial constraint	-0.302***	-0.304***	-0.0918	-0.660***	-0.420***	-0.237***
	(0.0567)	(0.0793)	(0.0740)	(0.132)	(0.0419)	(0.0215)
Ln annual sales	0.0467	0.0940**	0.111*	0.0342	0.00834	0.139***
	(0.0453)	(0.0392)	(0.0637)	(0.0503)	(0.0376)	(0.0417)
Knowledge development	0.237*	0.596***	0.351	0.841***	0.496***	0.504**
	(0.136)	(0.182)	(0.266)	(0.224)	(0.127)	(0.203)
National institutional quality	0.886***	0.440**	1.147***	0.628***	0.593**	0.483***
	(0.258)	(0.218)	(0.402)	(0.213)	(0.248)	(0.156)
Employee training	0.290**	-0.0197	-0.0491	-0.0350	-0.0423	0.0612
	(0.129)	(0.0751)	(0.124)	(0.151)	(0.114)	(0.0590)
Energy management	1.676***	2.464***	1.915***	3.158***	2.120***	2.321***
	(0.537)	(0.179)	(0.467)	(0.557)	(0.655)	(0.146)
Energy regulation	0.260	0.0366	0.363	-0.128	-0.0198	0.467
	(0.174)	(0.337)	(0.317)	(0.208)	(0.232)	(0.306)
Environmental demand	0.124	0.662	0.783**	-0.00704	-0.0884	0.858**
	(0.185)	(0. .313)	(0.365)	(0.189)	(0.157)	(0.402)
Foreign ownership	0.674	-0.689**	0.465***	-0.245	0.307***	0.593***
	(0.785)	(0.271)	(0.131)	(0.243)	(0.118)	(0.158)
Constant	-5.961**	-0.0311	-2.998**	-1.795	-0.466	-3.185***
	(2.846)	(1.133)	(1.451)	(1.522)	(0.344)	(0.746)

Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes				
Industry Country FE	No	No	Yes	Yes	Yes	Yes
Observations	818	3,283	13,401	4,155	11,942	10,922

Robust and clustered standard errors in parentheses *** is for p -value <0.01, ** p-value <0.05, * p-value <0.1. Non-manufacturing firms are those operating either in retail or service sectors.

3.4.3. Income Group Heterogeneity

Table (8) presents the country-level heterogenous results. We divide the sample into high- and low-income economies using the UN income classification. Then we run a baseline estimation for subsampled firms from low- and high-income countries in columns (1) and (2). The baseline positive significant GVC impact holds true for firms from low- and high-income countries. Compared to higher-income countries, the GVC coefficient depicts a higher effect for firms originating in lower-income economies. Existing evidence argues that exposure to learning-by-doing opportunities and technological spillover streams can allow developing countries to upgrade their industries and enhance their GVC position, moving away from backward chain levels (Ivarsson & Alvstam, 2010; De Marchi et al., 2018; Amendolagine et al., 2019). Throughout the process of escalating to GVC upper reaches, firms secure cooperative alliances with master business partners, trade high-quality intermediate inputs, learn more advanced environmental management and technologies, and match sustainable production modes (Ghisetti & Quatraro, 2017). Moreover, direct interactions with lead firms stimulate knowledge transfer via multiple channels, including the establishment of local subsidiaries, engagement with expatriates, and the provision of capacity building training aimed at upskilling local technological capabilities to ensure adequate quality. Such engagement also encompasses technical support that is associated with ultimate pressure to comply with international environmental standards through consistent innovation and technology-adaptive approach to production (De Marchi et al., 2018). Such an international realm leads to emergence of local environmental upgrading to mitigate the ecological consequences of operational processes and meet the growing global awareness of environmental stewardship (Ha & Thanh, 2022). It is then possible for low-income firms to advance their product structure, shift to cleaner energy production patterns and optimize more their energy consumption than higher-income ones (Zhong, 2018; Sun et al., 2019; Hu et al., 2020).

Owing to substantial variation in industrial energy structure between developed and developing countries, we further investigate the impact in energy-intensive and less energy-intensive countries across both income groups. Columns (3)-(6) show that GVC can increase the propensity of a firm to carry out energy-conservative innovation among higher-income firms, regardless of the intensity of their operational industry energy consumption. On the contrary, firms from developing countries benefit from the cross-border spillover flows and innovate in their energy decarbonization only if their production is classified as relatively energy efficient. In other terms, firms classified as operating in energy intensive sectors don’t exhibit any green innovation gains from their participation in GVCs. This validates the evidence of the pollution haven hypothesis and chiefly its firm-level adaptation: pollution offshoring hypothesis (Cherniwchan et al., 2017; Forslid et al., 2018; Najjar & Cherniwchan, 2021). If GVC participation is based mostly on exploiting unskilled, low-cost labor or natural resources, the opportunities for learning and upgrading are generally limited, and it won't necessarily draw innovative spillovers (Shi et al., 2022). Within global production fragmentation, developed economies preserve their energy-efficient consumption trend and less disruptive energy supply by transferring the most pollution-intensive stages of production to developing countries (Wang et al., 2020; Zhou et al., 2022; Li et al., 2023). This offshoring behavior makes it more likely for low-income, energy-intensive firms to be trapped on the periphery of the GVC, where they heavily rely on comparative advantages of abundant energy factors and undertake energy-consuming tasks (Huang et al., 2022; Yang et al., 2022). Such conditions enlarge the gap between peripheral and core countries' technologies, inhibiting the energy-saving technology and knowledge overflow (Yang et al., 2022). Putting it differently, their locked-in GVC embeddedness position biases their technological progress towards more energy-intensive comparative advantage production through the path dependency effect and technological barrier upgrade. It seriously retards their sustainable industrial energy development (Huang et al., 2022; Yang et al., 2022). On the opposite evolutionary side of the chain, more developed industries master their upward position with forward production segments, advanced technology, high profitability (Koopman et al., 2010; Wang et al., 2013), and wider scope for improving their energy efficiency (Jin et al., 2022; Yang et al., 2022). In this view, our results verify that the locked-in effect of production in high energy consumption and low value-added links catalyzes energy security inequality and unequal sharing of energy costs in global production divisions (Li et al., 2021; Huang et al., 2022; Ji et al., 2022) through unequal green innovation opportunities. One relevant proposition in this regard is posed by Bartley (2010) and Tsoi (2010) who reveal that the lack of robust sanctions and regulations further demotivates adherence to environmental requirements and green technology adoption by less competitive GVC firms. Enterprises essentially need to be guided by some environmental regulatory policies so that they can be compelled under the influence of the government to alter the direction of their technology application. Upon this, we are inspired to explore whether the adverse GVC locked-in effect on low-income firm-level energy-saving innovation can be mitigated if the heterogeneous impact accounts for firms' governed by energy regulations (Noailly & Smeets, 2015; Wu et al., 2024). Interestingly, columns (7) and (8) back the view that firms from developing countries that participate in GVC and at the same time are subjected to pay energy taxes and adhere to energy performance standards are encouraged to restructure the allocation of their technology and R&D knowledge to reduce their energy consumption.

Table (8): Heterogenous effect on energy efficiency innovation across different income classifications

Variables	**(1) High income**	**(2) Low income**	**(3) High income energy intensive sectors**	**(4) High income energy efficient sectors**	**(5) Low income energy intensive sectors**	**(6) Low income energy efficient sectors**	**(7) Low income subjected to energy regulation**	**(8) Low income non subjected to energy regulation**
GVC	0.139***	0.244***	0.142**	0.151***	-0.369	0.347***	0.521***	0.114**
	(0.0482)	(0.0220)	(0.0576)	(0.0521)	(0.443)	(0.0131)	(0.134)	(0.0445)
Small firm	0.129	-0.0160	0.218**	0.176	-0.0366	0.0162	-0.383***	0.0545
	(0.106)	(0.0270)	(0.108)	(0.108)	(0.0690)	(0.0438)	(0.0885)	(0.0603)
Large firm	-0.0982	-0.000845	-0.132	-0.108	-0.110	0.0331	0.431***	-0.235*
	(0.0936)	(0.0857)	(0.126)	(0.103)	(0.129)	(0.132)	(0.152)	(0.135)
Ln age	0.243***	-0.0609***	0.292***	0.273***	-0.178***	-0.0585***	0.00902	-0.0781***
	(0.0911)	(0.00683)	(0.0722)	(0.0835)	(0.0199)	(0.0111)	(0.0153)	(0.0178)

Financial constraint	-0.291***	-0.392***	-0.261***	-0.281***	0.0579	-0.512***	-0.00602	-0.516***
	(0.0483)	(0.0652)	(0.0370)	(0.0460)	(0.106)	(0.0555)	(0.156)	(0.0300)
Ln annual sales	0.0834**	0.120***	0.108**	0.0965***	0.242***	0.116**	-0.0536***	0.162***
	(0.0396)	(0.0456)	(0.0466)	(0.0369)	(0.0475)	(0.0538)	(0.00752)	(0.0604)
Knowledge development	0.465***	0.647***	0.450**	0.407***	0.176	0.747***	0.925***	0.539***
	(0.161)	(0.137)	(0.196)	(0.152)	(0.212)	(0.149)	(0.229)	(0.161)
National institutional quality	0.571***	0.520***	0.496**	0.687***	1.152***	0.329***	-0.605**	0.664***
	(0.175)	(0.120)	(0.204)	(0.143)	(0.334)	(0.127)	(0.247)	(0.106)
Employee training	0.0580	-0.0191	0.0247	0.132***	0.360**	-0.100	0.252	0.00476
	(0.0751)	(0.200)	(0.0793)	(0.0338)	(0.179)	(0.258)	(0.260)	(0.217)
Energy management	2.194***	0.701**	2.450***	2.315***	0.572	0.789**	-0.201	0.846***
	(0.294)	(0.341)	(0.209)	(0.288)	(0.469)	(0.380)	(0.509)	(0.314)
Energy regulation	0.107	-0.440***	0.527***	0.00231	0.156	-0.572***		
	(0.251)	(0.0647)	(0.204)	(0.288)	(0.338)	(0.105)		
Environmental demand	0.546*	-0.0587	0.722**	0.532	0.322	-0.0394	-0.238*	0.533***
	(0.313)	(0.145)	(0.363)	(0.349)	(0.285)	(0.117)	(0.131)	(0.105)
Foreign ownership	0.360***	0.291**	0.504***	0.449***	-0.0570	0.374***	0.0798	0.481***
	(0.127)	(0.116)	(0.182)	(0.133)	(0.142)	(0.106)	(0.0645)	(0.158)
Constant	-2.185**	-1.358***	-2.997***	-3.012***	-2.384***	-2.136***	-0.634***	-1.168**
	(0.866)	(0.333)	(0.840)	(0.862)	(0.471)	(0.734)	(0.0742)	(0.539)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	22,888	5,965	14,252	17,843	1,731	4,234	1,787	4,178

Robust and clustered standard errors in parentheses *** is for p -value <0.01, ** p-value <0.05, * p-value <0.1

3.4.4. Region Heterogeneity

The last differential analysis focuses on untangling the effect of GVC participation on energy innovation within global regions is presented in Table (9). We split firms according to whether they are based in Europe, MENA, and Central Asia. Evidently, the highest and most significant effect is observed among MENA firms. GVCs also substantially encourage energy efficiency innovation within European firms, whereas no significant effect is observed in Central Asia. The prominent responsiveness in MENA suggests contextual-specific dynamics that warrants further moderation examination.

Table (9): Heterogenous effect on energy efficiency innovation across global regions

Variables	**(1) Central Asia**	**(2) MENA**	**(3) Europe**
GVC	-0.226	0.232***	0.140**
	(0.152)	(0.0254)	(0.0569)
Small firm	-0.239**	-0.00600	0.226**
	(0.0960)	(0.0221)	(0.104)
Large firm	-0.0987	-0.0431	-0.136
	(0.0685)	(0.114)	(0.119)
Ln age	-0.0866*	-0.0645***	0.298***
	(0.0451)	(0.00474)	(0.0701)
Financial constraint	0.0826	-0.394***	-0.261***
	(0.104)	(0.0777)	(0.0382)
Ln annual sales	0.0964***	0.127***	0.0991**

	(0.0222)	(0.0472)	(0.0491)
Knowledge development	0.377***	0.739***	0.461**
	(0.122)	(0.0804)	(0.185)
National institutional quality	1.135***	0.475***	0.486**
	(0.237)	(0.150)	(0.208)
Employee training	0.373**	-0.0639	0.0250
	(0.189)	(0.195)	(0.0794)
Energy management	2.652***	0.601**	2.479***
	(0.246)	(0.276)	(0.200)
Energy regulation	0.378	-0.483***	0.519**
	(0.301)	(0.0282)	(0.218)
Environmental demand	0.166	-0.0592	0.702**
	(0.262)	(0.159)	(0.346)
Foreign ownership	0.0174	0.329**	0.524***
	(0.163)	(0.131)	(0.169)
Constant	-3.788***	-0.791	-3.010**
	(0.572)	(0.514)	(1.253)
Year FE	Yes	Yes	Yes
Industry Country FE	Yes	Yes	Yes
Observations	2,600	4,726	15,205

Robust and clustered standard errors in parentheses *** is for p -value <0.01, ** p-value <0.05, * p-value <0.1

Centering on the MENA economies is grounded in their chronically unsatisfactory and limited GVC participation and their exposure to the intertwined challenge of economic expansion and environmental deterioration. On the GVC side, structural barriers, like fragmented regulatory frameworks and limited firm capabilities, constrain the region's positioning within low value-added, upstream phases. It lacks the massive cohort of large, globally competitive firms at the top of the distribution and suffers from marginal involvement of the smaller firms. Yet, the region's untapped potential in terms of logistic Mediterranean positioning, abundant resource endowments, proximity to the markets, and specialization in intermediate trade unlock prospects for export dynamism and productive upgrading across the chain (Aboushady & Zaki, 2018; Del Prete et al., 2018; Ayadi et al., 2020). Broadening GVC linkages of MENA firms acts as a lever for boosting their growth, productivity, innovation, and adoption of more eco-friendly technologies and practices (Ayadi et al., 2020; Dovis & Zaki, 2020; Siewers et al., 2024). On the environmental sustainability front, Middle Eastern economies stand out in their distinctive stance regarding the economic diversification-environmental sustainability intersection. While the region's intensive dependence on natural capital reserves has conferred economic gains, it has inflated its environmental degradation and exposure to extreme weather episodes and climatic adversities (Lionello et al., 2014; Ulucak & Ozcan, 2020; Li et al., 2023; Elkebti & Khalifa, 2025). In this context, innovation-led green transition has become imperative to mitigate environmental pressures. More specifically, innovation in low-carbon and energy-efficient technologies has gained traction as a key strategic mechanism in fostering competitive advantage in market accessibility and emboldening adherence to global sustainability standards (Moghadam, 2023; Elkebti & Khalifa, 2025). Nonetheless, the regional share of green innovation remains modest and unstable, steering the region off the climate-aligned growth trajectory and jeopardizing its energy decarbonisation pathway (Yu et al., 2016; Elkebti & Khalifa, 2025). MENA countries still grapple with persistent structural and economic challenges, including weak regulatory frameworks, entrenched dependency on non-clean energy sources, inadequate infrastructure, technological limitations, political turmoil and conflicts, like in Lebanon and Gaza and West Bank (Akhmat et al., 2014; Usman & Hammar, 2021; Ghanem & Alamri, 2023; Baffour Gyau et al., 2024; Elkebti & Khalifa, 2025). Amid this setting, we extend the existing GVC participation evidence to gauge the extent to which it can help cushion the regional impediments to green energy transition.

In Table (10) and (11), we probe into the dynamics between GVCs and energy innovation in MENA by decomposing the effect across firms and industry attributes to capture variations in firms' innovative behavior. Results show that the positive association between GVC participation and energy efficiency innovation is markedly heterogenous across firms. At the firm level, the significant impact is more apparent among SMEs, non-financially constrained firms and businesses operating under energy regulatory pressure. This pattern flags the tandem relevance of internal capacities and external pressures in enabling firms to capitalize on their GVC exposure for tangible eco-innovation gains. Restraints to smooth access to external finance impede MENA firms from covering the upfront costs of technological investments in upgrading their energy efficiency even if they are part of the value chains (Elshaarawy & Ezzat, 2022). Constituting the largest share of the regional total number of businesses (Jaud & Freund, 2015; Sharma, 2018), the stronger effect among SMEs reflects their transformative green potential amid integration in the internationalization mode. This serves as their strategic signal of agility and readiness to adapt to stricter environmental and quality standards, sustain their business relationships, and intensify their competitiveness across the trading chain. National environmental regulations are often viewed by firms as the baseline from which they structure their proactive environmental management systems and nurture their technological innovation capacity (investment in R&D). This regulatory foundation reinforces their productive and adaptive capacity, which in turn reinforces their competitive edge to join GVCs (Ayouni & Zouiri, 2024; Hazem & Zaki, 2025; Ramzy, 2025). Exposure to domestic and global environmental standards makes it indispensable for MENA firms to leverage their GVC participation to absorb international knowledge and technologies and drive pollution control innovation, specifically related to sustainable energy consumption. At the sectoral level, the positive impact is mostly evident among Middle Eastern enterprises in retail, energy-efficient, and low-technological-intensity sectors. This is plausible and consistent with the region's structural realities, viewed across three lenses. First, the MENA's low-technology-intensive and retail GVC-integrated businesses often disproportionately have more room for improving their productivity and competitiveness since their operational approaches are far from global standardized practices (Ledezma & Lopez-Villavicencio, 2024). Seemingly, their technological gap triggers their catch-up in environmental upgrading to meet the sustainability requirements of their foreign partners through basic know-how transfers and imports of high-quality inputs and machinery. Second, activities that are intensively reliant on sophisticated technologies are relevantly less effective in driving green innovation among MENA firms because they require deep levels of green absorptive capacity (Eissa & Zaki, 2020). That is, firms should have adequate internal competencies to pinpoint their operational-based sustainability gap areas and assimilate, identify, exploit and apply the available technological knowledge and experience flows from the global lead firms (Zhang et al., 2020).

Alternatively, less technologically intensive sectors are more adept to capitalize on environmental opportunities from their peers and turning them into internal eco-reforms and competitive advantages (Eissa & Zaki, 2020), strengthening the GVC effect on energy-efficient innovation. Third, energy-intensive sectors may encounter diminishing returns to efficiency, where they need substantial technological and financial assistance and spillovers to invest in less energy-intensive processes. As long as their GVC positioning lacks meaningful engagement with environmental know-how and innovation case studies, they are pressured to scale up their production with higher net emissions (Del Prete et al., 2018). As such, it can be deduced that MENA firms operating in high-emission-intensive sectors are structurally locked into peripheral segments of GVCs, limiting their chances of upgrading and access to cleaner technologies.

Table (10): Firm-Level Heterogeneity-MENA

Variables	**(1) Financially constrained firms**	**(2) Financially non-constrained firms**	**(3) Large Firms**	**(4) SMEs**	**(5) Subjected to energy regulations**	**(6) Non- Subjected to energy regulations**
GVC	0.218***	0.291**	-0.0674	0.247***	0.544***	0.0975***
	(0.0725)	(0.140)	(0.246)	(0.0340)	(0.137)	(0.0329)
Small firm	0.334*	-0.0187	-	-	-0.403***	0.0714
	(0.176)	(0.0201)	-	-	(0.0769)	(0.0492)
Large firm	-0.0988	0.0499	-	-	0.483***	-0.291*
	(0.134)	(0.142)	-	-	(0.164)	(0.175)
Ln age	0.0981***	-0.123***	0.0631	-0.0650***	0.0217	-0.0858***
	(0.0321)	(0.0125)	(0.114)	(0.00420)	(0.0192)	(0.0127)
Financial constraint	-	-	-0.600*	-0.391***	-0.0116	-0.532***
	-	-	(0.354)	(0.0741)	(0.179)	(0.0388)
Ln annual sales	0.234**	0.0980***	0.0603	0.128***	-0.0582***	0.169***
	(0.117)	(0.0345)	(0.0408)	(0.0464)	(0.00480)	(0.0618)
Knowledge development	0.569*	0.787***	0.243	0.746***	0.938***	0.651***
	(0.321)	(0.0720)	(0.193)	(0.0790)	(0.245)	(0.130)
National institutional quality	1.037***	-0.0242	-0.168	0.469***	-0.669**	0.634***
	(0.177)	(0.138)	(0.654)	(0.151)	(0.317)	(0.124)
Employee training	-0.407	-0.0176	0.172	-0.0667	0.197	-0.0306
	(0.517)	(0.107)	(0.261)	(0.193)	(0.258)	(0.220)
Energy management	2.278***	0.517***	1.335**	0.586**	-0.291	0.758***
	(0.455)	(0.185)	(0.528)	(0.264)	(0.487)	(0.251)
Energy regulation	-0.836***	-0.430***	0.450**	-0.492***	-	-
	(0.0328)	(0.0444)	(0.199)	(0.0248)	-	-
Environmental demand	-0.766	0.119	1.316***	-0.0881	-0.252**	0.592***
	(0.566)	(0.118)	(0.135)	(0.163)	(0.124)	(0.0678)
Foreign ownership	0.354***	0.107	0.390*	0.332**	0.0891	0.532***
	(0.0974)	(0.118)	(0.232)	(0.139)	(0.0692)	(0.187)
Constant	-2.980**	-0.464*	-0.0482	-0.809	1.113***	-1.260*
	(1.442)	(0.244)	(0.567)	(0.496)	(0.116)	(0.665)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,240	2,998	789	3,937	1,319	3,407

Robust and clustered standard errors in parentheses *** is for p -value <0.01, ** p-value <0.05, * p-value <0.1

Table (11): Industry-Level Heterogeneity-MENA

Variables	**(1) Manufacturing**	**(2) Service**	**(3) Retail**	**(4) High and Medium-high Technological intensive**	**(5) Medium-low and Low technological intensive**	**(6) Energy Intensive**	**(7) Energy Efficient**
GVC	0.126	0.0708	1.544***	-0.0568	0.167**	-0.449	0.330***

	(0.107)	(0.130)	(0.169)	(0.329)	(0.0796)	(0.487)	(0.0423)
Small firm	-0.134	0.177	-0.0757	-0.404**	-0.160***	-0.0783	0.0323
	(0.0965)	(0.114)	(0.108)	(0.171)	(0.0489)	(0.0493)	(0.0373)
Large firm	-0.213***	0.261	-1.520***	-0.434***	-0.0655	-0.120	-0.00157
	(0.0353)	(0.208)	(0.391)	(0.120)	(0.111)	(0.138)	(0.172)
Ln age	-0.150***	-0.153***	0.491***	0.0478***	-0.139***	-0.193***	-0.0613***
	(0.0161)	(0.0421)	(0.0476)	(0.0176)	(0.00808)	(0.0113)	(0.0110)
Financial constraint	-0.151**	-0.808***	0.209	-0.624***	-0.234***	0.0645	-0.513***
	(0.0667)	(0.0223)	(0.360)	(0.142)	(0.0824)	(0.109)	(0.0707)
Ln annual sales	0.177***	0.0821	-0.0583	0.130	0.143***	0.249***	0.124**
	(0.00551)	(0.0733)	(0.0586)	(0.140)	(0.0187)	(0.0492)	(0.0587)
Knowledge development	0.728***	0.815***	0.763	0.611***	0.880***	0.0228	0.850***
	(0.116)	(0.101)	(0.714)	(0.0665)	(0.158)	(0.179)	(0.0657)
National institutional quality	0.361***	0.568	-0.0324	0.249	0.158	1.135***	0.291*
	(0.0172)	(0.357)	(0.248)	(0.534)	(0.148)	(0.388)	(0.162)
Employee training	0.523***	-0.159	1.737***	-0.687	0.364***	0.403*	-0.152
	(0.0687)	(0.240)	(0.559)	(0.481)	(0.0816)	(0.214)	(0.266)
Energy management	-0.117	1.583***	2.251***	0.336	0.0636	0.516	0.668**
	(0.138)	(0.399)	(0.608)	(0.738)	(0.187)	(0.501)	(0.314)
Energy regulation	-0.381***	-0.832***	-0.848***	-0.280***	-0.435***	0.167	-0.631***
	(0.0312)	(0.0306)	(0.161)	(0.0740)	(0.0442)	(0.366)	(0.0530)
Environmental demand	-0.162**	-0.0987	1.474***	-0.279	-0.108	0.122	-0.0112
	(0.0733)	(0.244)	(0.501)	(0.275)	(0.0887)	(0.206)	(0.150)
Foreign ownership	0.0463	0.0427	2.817***	-0.0942	0.266	-0.103	0.423***
	(0.124)	(0.326)	(0.504)	(0.349)	(0.296)	(0.139)	(0.125)
Constant	-1.011***	-0.906	-1.642	-0.294	-0.665***	-2.339***	-1.662*
	(0.0851)	(0.878)	(1.077)	(1.372)	(0.229)	(0.508)	(0.986)
Observations	2,823	1,586	317	902	2,995	1,502	3,224

Robust and clustered standard errors in parentheses *** is for p -value <0.01, ** p-value <0.05, * p-value <0.1

Conclusion and policy implications

GVC integration is commonly known for its associated technological transfer effects, productivity enhancement, division of labor gains, and market expansions. It can thus induce firms to upgrade their production system in a timely manner so that they employ new production technologies that either consume less energy or increase energy productivity. This study examines the association between GVC embedding and energy innovation. Using the latest firm-level WB-EBRD BEEPS dataset from 41 global countries, our findings depict that GVC embedding draws a positive significant impact on firm-level energy innovation. Our mechanism analysis reveals that the positive energy innovative impact is indirectly explained by market scale and induced learning externalities. The main results are heterogenous, where the favorable baseline effect is prevalent among firms that are small and medium-sized, are not financially constrained, and are subjected to stricter environmental regulations. Moreover, the evidence shows that firms operating in medium-high and high-tech industries, energy-efficient sectors, and in low-income countries are the most benefitting from GVC integration in terms of deploying innovative energy-saving equipment and machinery. On regional level, GVC participation mostly increases the probability of implementing energy efficiency innovation across MENA firms. The observed findings are prominent among SMEs, energy efficient firms, as well as financially unconstrained, energy regulated and low-technologically intensive businesses. Thus, our regionally-specific examination makes it clear how international trading networks can help mitigate firm-level barriers to innovation in energy efficiency. It corroborates that taking part in global trading networks confer technological upgrading and environmental spillovers on MENA firms conditional not only on external environmental incentives but also on internal absorptive capacities and sectoral configurations.

From a policy standpoint, our findings support the global call for developing an international trading system that facilitates the diffusion of energy-saving technologies. Hence, governments need to develop their own salient regulatory frameworks to promote firms' GVC embedding, specifically in context of developing countries. First, public agencies need to improve their trading policies and reduce trade barriers (tariffs and non-tariff ones) to support firms' embeddedness in GVC. Second, developing economies' governments need to enforce a rigorous environmental regulatory framework, especially those reliant on market-based instruments, such as environmental taxation/energy taxation. Stricter and enforced environmental regulations ensure enterprises' responsible operation and investment. Regulatory systems could also embrace the development of voluntary carbon markets to reallocate the use of proceeds of sold carbon credits towards the articulation of energy-saving technologies or to the replacement of decarbonisation costs. Third, governments need to put in place more favourable innovation policies (i.e., enforcement of intellectual property rights IPRs) and industrial policies that encourage the industrial restructuring by shifting to low-carbon and environmentally friendly technologies. Fourth, regulators need to support firms' GVC embedding by providing the private sector players with technical and financial support to incentivize their uptake of green technologies and formulation of environmental management systems. Fifth, governmental entities in developing countries should work on enhancing the businesses' competitiveness by raising awareness of the relevance of aligning their internal management practices with international quality standards for smooth access to foreign markets. Developing firms' measure, report and verification (MRV) system is also highly imperative and required. The external evaluation of energy consumption and information disclosure for all firms across the supply chains should be reinforced. Sixth, there is a great need to improve the access of SMEs to external finance and to reduce the cost of green innovation. This could also be coupled with the provision of crafted public financial incentives (i.e. tax credits, exemptions, etc.) for SMEs to encourage their green R&D investments in energy-related fields. Finally, it is crucial that governments at the global and regional levels collaborate for the development of green partnerships, like the ongoing cooperation between the European Union and Southern Mediterranean countries and platforms for a green dialogue facilitating the exchange of knowledge and best energy innovation practices.

For the MENA region, given that our findings confirm the hypothesis that GVCs embedding promote energy innovation among MENA firms, governments in the region need to deepen their firms embedding in GVCs. In essence, they need to remove persistent structural barriers to trade and foreign direct investment (FDI) by streamlining administrative procedures and removing discriminatory practices, improving governance, enforcing property rights, and enhancing transport and logistics. The creation of a business-friendly environment would attract FDI, favoring the transfer of know-how, foreign technologies, and informational assets (product specification and quality standards) and fostering energy-specific innovative capabilities. Also, since GVC firms that are liable to energy regulation are more likely to improve their energy efficiency, it is crucial for governments to strengthen and to harmonize the stringency of environmental regulations and energy-efficiency standards both regionally and with their EU standards. The regulatory alignment would help mitigating the lock-in effect that contrain firms' environmental upgrading, especially those operating in energy-intensive and low-technological-intensity sectors. It is also crucial to improve the access to finance especially for SMEs and energy-intensive firms to cover upfront costs of energy efficiency investments and low-carbon technologies. Improving access to finance must also be coupled with financial incentives (e.g. tax credits, green subsidies, etc.) to foster green energy-specific innovation and R&D efforts. It is also important to build firm absorptive capacity in order to firms' assimilation and adaptation to imported and more sophisticated green technologies, thereby mitigating the lock-in effect among low-technological-intensity firms. In this regard, it is also important to invest in green human capital and to enhance labor skills through on-the-job training that is focused on using green technologies and on implementing energy management practices. At the regional level, it is recommended for government to cooperate on building regional innovation hubs and to promote industrial cluster-based knowledge diffusion. These hubs would act as a platform for knowledge sharing and collective learning on energy-saving practices. It is also recommended to establish a regional voluntary carbon markets that would facilitate the trading of carbon markets, generate stable revenues, and thereby support firms' adoption of green practices and energy-saving technologies. Finally, MENA governments must leverage this neighbourhood with EU countries and their environmental programs because aligning MENA green practices with those of EU would help the former to unlock greater potential to deepen their GVC embedding and to upgrade their positioning toward higher-value and more environmentally friendly sectors.

Further avenues of upcoming research can resort to tackling the relationship while using panel data instead of pooled cross-section to better reveal the time-changing impact of GVC on energy innovation. Since there is no consensus regarding the definition of energy efficiency, future analysis can base its measurement on physical energy consumption units, rather than energy expenditure, for accurate interpretation. Other measures of energy efficiency can be evaluated, such as the total factor energy efficiency that accounts for various productive structures by reflecting on not only energy sources but also all production inputs.

References

Aboushady, N., & Zaki, C. (2024). *Are Global Value Chains for Sale? On Business-State Relations in the MENA Region*. https://doi.org/10.2139/ssrn.4972018

Aghion, P., Bergeaus, A., Gigout, T., Lequien, M., & Melitz, M. (2021). *Exporting ideas: knowledge flows from expanding trade in goods.* Documents de Travail de l'Insee - INSEE Working Papers 2024-04, Institut National de la Statistique et des Etudes Economiques.

Agostino, M., Ruberto, S., & Trivieri, F. (2018). Lasting lending relationships and technical efficiency: Evidence on European SMEs. *Journal of Productivity Analysis, 50*(1), 25–40. https://doi.org/10.1007/s11123-018-0532-z

Agostino, M., & Ruberto, S. (2021). Environment-friendly practices: Family versus nonfamily firms. *Journal of Cleaner Production, 329*, 129689. https://doi.org/10.1016/j.jclepro.2021.129689

Agostino, M., Giunta, A., Ruberto, S., & Scalera, D. (2023). Global value chains and energy-related sustainable practices. Evidence from Enterprise Survey data. *Energy Economics*, *127*, 107068. https://doi.org/10.1016/j.eneco.2023.107068

Akhmat, G., Zaman, K., Shukui, T., & Sajjad, F. (2014). Does energy consumption contribute to climate change? Evidence from major regions of the world. *Renewable and Sustainable Energy Reviews*, *36*, 123-134. https://doi.org/10.1016/j.rser.2014.04.044

Alam, Md. S., Atif, M., Chien-Chi, C., & Soytaş, U. (2019). Does corporate R&D investment affect firm environmental performance? Evidence from G-6 countries. *Energy Economics*, *78*, 401–411. https://doi.org/10.1016/j.eneco.2018.11.031

Amendolagine, V., Presbitero, A. F., Rabellotti, R., & Sanfilippo, M. (2019). Local sourcing in developing countries: The role of foreign direct investments and global value chains. *World Development*, *113*, 73-88. https://doi.org/10.1016/j.worlddev.2018.08.010

Andries, P., & Stephan, U. (2019). Environmental Innovation and Firm Performance: How Firm Size and Motives Matter. *Sustainability*, *11*(13), 3585. https://doi.org/10.3390/su11133585

Antràs, P. (2020). Conceptual Aspects of Global Value Chains, *The World Bank Economic Review,* 34(3), 1-24. https://scholar.harvard.edu/files/antras/files/conceptualaspectsgvcsfinal.pdf

Antràs, P., & De Gortari, A. (2020). On the geography of global value chains. *Econometrica*, *88*(4), 1553-1598. https://doi.org/10.3982/ECTA15362

Avenyo, E. K.; Mensah, E. B.; Ndubuisim G.; Sakyi, D. (2022). *Global Value Chain Participation and Innovation: Firm-Level Evidence from Africa*, AERC Working Paper GVC-012 African Economic Research Consortium, Nairobi.

Ayadi, R., Giovannetti, G., Marvasi, E., & Zaki, C. (2020). *Global Value Chains and the Productivity of Firms in MENA countries: Does Connectivity Matter?*. DISEI, Università degli Studi di Firenze.

Ayouni, O., & Zouiri, L. (2024). Proactive Environmental Management's Drive for Green Technology Adoption in MENA Firms: Regulatory Mediation and Financial Moderation. *Procedia Computer Science*, *236*, 101–110. https://doi.org/10.1016/j.procs.2024.05.010

Baffour Gyau, E., Adu, D., Darko, R. O., & Adomako, M. O. (2024). Green energy dynamics: exploring the nexus between renewable energy utilization and environmental quality in the middle east and North Africa. *International Journal of Environmental Research*, *18*(5), 84. https://doi.org/10.1007/s41742-024-00634-1

Bai, J., & Yu, X. (2024). The impact of global value chain embedment on energy conservation and emissions reduction: Theory and empirical evidence. *China Finance and Economic Review*, *13*(2), 46-66. https://doi.org/10.1515/cfer-2024-0009

Baldwin, R., & Lopez-Gonzalez, J. (2014). Supply-Chain Trade: A Portrait of Global Patterns and Several Testable Hypotheses. *The World Economy*, 38(11), 1682–1721. https://doi.org/10.1111/twec.12189

Barasa, L., Knoben, J., Vermeulen, P., Kimuyu, P., & Kinyanjui, B. (2017). Institutions, resources and innovation in East Africa: A firm level approach. *Research Policy*, *46*(1), 280–291. https://doi.org/10.1016/j.respol.2016.11.008

Bartley, T. (2010). Transnational private regulation in practice: The limits of forest and labor standards certification in Indonesia. *Business and Politics, 12*(3), 1–34. https://doi.org/10.2202/1469-3569.1321

Berrone, P., Cruz, C., Gomez-Mejia, L. R., & Larraza-Kintana, M. (2010). Socioemotional wealth and corporate responses to institutional pressures: Do family-controlled firms pollute less? *Administrative Science Quarterly, 55*(1), 82–113. https://doi.org/10.2189/asqu.2010.55.1.82

Bodas-Freitas, I. M., & Corrocher, N. (2019). The use of external support and the benefits of the adoption of resource efficiency practices: An empirical analysis of european SMEs. *Energy Policy*, *132*, 75-82. https://doi.org/10.1016/j.enpol.2019.05.019

Boeing, P. (2016). The allocation and effectiveness of China's R&D subsidies-Evidence from listed firms. *Research policy*, *45*(9), 1774-1789. https://doi.org/10.1016/j.respol.2016.05.007

Capozza, C.; Divella, M.; & Rubino, A. (2021), Exploring Energy Transition in European Firms: The Role of Policy Instruments, Demand-pull Factors and Cost-saving Needs in Driving Energy-efficient and Renewable Energy Innovations, *Energy Sources*, *Part B: Economics, Planning, and Policy,* 16(11-12), 1094-1109, https://doi.org/10.1080/15567249.2021.1939462

Cevik, S., & Miryugin, F. (2022). *Rogue waves: Climate change and firm performance* (IMF Working Paper No. 22/102). International Monetary Fund. https://www.greenfinanceplatform.org/sites/default/files/downloads/resource/Rogue%20Waves%20Climate%20Change%20and%20Firm%20Performance_IMF.pdf

Chadee, D., & Roxas, B. (2013). Institutional environment, innovation capacity and firm performance in Russia. *Critical perspectives on international business*, *9*(1/2), 19-39. https://doi.org/10.1108/17422041311299923

Chao, A. C., & Hong, L. (2019). Corporate Social Responsibility Strategy, Environment and Energy Policy. *Structural Change and Economic Dynamics*, *51*, 311–317. https://doi.org/10.1016/j.strueco.2018.11.010

Chen, H., Zhang, C., & Yin, K. (2022) The Impact of Global Value Chain Embedding on Carbon Emissions Embodied in China's Exports. *Front. Environ. Sci*. 10:950869. https://doi.org/10.3389/fenvs.2022.950869

Cherniwchan, J., Copeland, B. R., & Taylor, M. S. (2017). Trade and the environment: New methods, measurements, and results. *Annual Review of Economics*, *9*(1), 59-85. https://doi.org/10.1146/annurev-economics-063016-103756

Clementi, E. L. & Garofalo, G. (2023). Determinants of Renewable Energy Adoption: Evidence from Italian Firms, *Journal of Innovation Economics & Management,* 42(3), 201-234. https://doi.org/10.3917/jie.pr1.0143

Costa-Campi, M. T., García-Quevedo, J., & Segarra, A. (2015). Energy efficiency determinants: An empirical analysis of Spanish innovative firms. *Energy Policy*, *83*, 229–239. https://doi.org/10.1016/j.enpol.2015.01.037

Cowling, M., & Dvouletý, O. (2023). UK government-backed start-up loans: Tackling disadvantage and credit rationing of new entrepreneurs. *International Small Business Journal, 41*(7), 714–733. https://doi.org/10.1177/02662426221124733

Cruz, C., Larraza–Kintana, M., Garcés–Galdeano, L., & Berrone, P. (2014). Are family firms really more socially responsible?. *Entrepreneurship Theory and Practice*, *38*(6), 1295-1316. https://doi.org/10.1111/etap.12125

De Marchi, V. & Di Maria, E. (2019). Environmental Upgrading and Suppliers' Agency in the Leather Global Value Chain, *Sustainability*, 11(23) 6530, 1-17, https://doi.org/10.3390/su11236530.

De Marchi, V., Di Maria, E., & Micelli, S. (2013). Environmental Strategies, Upgrading and Competitive Advantage in Global Value Chains, *Business Strategy and the Environment*, Volume 22, 62-72. https://doi.org/10.1002/bse.1738

De Marchi, V., Di Maria, E., & Ponte, S. (2014). Multinational Firms and the Management of Global Networks: Insights from Global Value Chain Studies. In T. Pedersen, M. Venzin, T. M. Devinney, & L. Tihanyi (Eds.), *Advances in International Management* (Vol. 27, pp. 463–486). Emerald Group Publishing Limited. https://doi.org/10.1108/S1571-502720140000027009

De Marchi, V., E. Giuliani, and R. Rabellotti. (2018). Do Global Value Chains Offer Developing Countries Learning and Innovation Opportunities. *The European Journal of Development Research* 30 (3), 389–407.

Dekker, J., & Hasso, T. (2016). Environmental performance focus in private family firms: The role of social embeddedness. *Journal of Business Ethics*, *136*, 293-309. https://doi.org/10.1007/s10551-014-2516-x

Del Prete, D., Giovannetti, G., & Marvasi, E. (2018). Global value chains: New evidence for North Africa. *International Economics*, *153*, 42–54. https://doi.org/10.1016/j.inteco.2017.03.002

Delera, M., Pietrobelli, C., Calza, E., & Lavopa, A. (2022). Does value chain participation facilitate the adoption of industry 4.0 technologies in developing countries?. *World Development*, *152*, 105788. https://doi.org/10.1016/j.worlddev.2021.105788.

Dovis, M., & Zaki, C. (2020). Global Value Chains and Local Business Environments: Which Factors Really Matter in Developing Countries? *Review of Industrial Organization*, *57*(2), 481–513. https://doi.org/10.1007/s11151-020-09768-w

Du, W., & Li, M. (2019). Can environmental regulation promote the governance of excess capacity in China's energy sector? The market exit of zombie enterprises. *Journal of Cleaner Production*, *207*, 306-316. https://doi.org/10.1016/j.jclepro.2018.09.267

Du, W., Li, M., & Wang, Z. (2022). The impact of environmental regulation on firms' energy-environment efficiency: Concurrent discussion of policy tool heterogeneity. *Ecological Indicators*, *143*, 109327. https://doi.org/10.1016/j.ecolind.2022.109327

Dzwigol, H., Kwilinski, A., Lyulyov, O., & Pimonenko, T. (2023). Renewable energy, knowledge spillover and innovation: capacity of environmental regulation. *Energies*, *16*(3), 1117. https://doi.org/10.3390/en16031117

Eissa, Y. & Zaki, C. (2023a). GVC and Innovation: Evidence from MENA Firm-Level Data, available at https://theforum.erf.org.eg/2024/03/04/global-value-chains-and-domestic-innovation-evidence-from-mena-firms/

Eissa, Y., & Zaki, C. (2023b). On GVC and innovation: The moderating role of policy. *Journal of Industrial and Business Economics*, *50*(1), 49–71. https://doi.org/10.1007/s40812-022-00255-9

Eissa, Y., & Zaki, C. (2025). Leveraging global value chains for innovation: The case of SMEs. *International Economics*, *182*, 100599. https://doi.org/10.1016/j.inteco.2025.100599

Elkebti, O. A. M., & Khalifa, W. M. S. (2025). Assessing the Saudi and Middle East Green Initiatives: The Role of Environmental Governance, Renewable Energy Transition, and Innovation in Achieving a Regional Green Future. *Sustainability*, *17*(12), 5307. https://doi.org/10.3390/su17125307

Elmassah, Suzanna and Hassanein, Eslam A., "GVCs and environmental sustainability in MENA: Do digitalization and institutions make a difference?" (2023). *All Works*. 6180. https://zuscholars.zu.ac.ae/works/6180

Elshaarawy, R. & Ezzat, R. (2022). Global value chains, financial constraints, and innovation, *Small Bus Econ*, 61 (1), 223–257. https://doi.org/10.1007/s11187-00685-8

Fan, J. L., Zhang, X., Wang, J. D., & Wang, Q. (2019). Measuring the Impacts of International Trade on Carbon Emissions Intensity: A Global Value Chain Perspective. *Emerging Markets Finance and Trade*, *57*(4), 972–988. https://doi.org/10.1080/1540496X.2019.1662783

Fogel, K., Hawk, A., Morck, R., & Yeung, B. (2009). Institutional obstacles to entrepreneurship. In A. Basu, M. Casson, N. Wadeson, & B. Yeung (Eds.), *The Oxford handbook of entrepreneurship* (pp. 540-570). Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199546992.003.0020

Fowowe, B. (2017). Access to finance and firm performance: Evidence from African countries. *Review of Development Finance*, *7*(1), 6–17. https://doi.org/10.1016/j.rdf.2017.01.006

Gao, Y., Yu, A., Jiang, J., & Pei, J. (2024). Will global value chain participation reduce environmental emissions? Evidence from Chinese firm-level data. *Structural Change and Economic Dynamics*, *69*, 512–526. https://doi.org/10.1016/j.strueco.2024.01.006

Garrone, P., Grilli, L., & Mrkajic, B. (2014). Determinants of energy-efficient innovation: Induction mechanisms and stakeholders pressures. *Available at SSRN 2527925*. http://dx.doi.org/10.2139/ssrn.2527925

Garrone, P., Grilli, L., & Mrkajic, B. (2014). Determinants of energy-efficient innovation: Induction mechanisms and stakeholders pressures. *Available at SSRN 2527925*. http://dx.doi.org/10.2139/ssrn.2527925

Garrone, P.; Grilli, L.; & Mrkajic, B. (2018). The role of institutional pressures in the introduction of energy- efficiency innovations. *Business Strategy and the Environment*, *27*(8), 1245- 1257. https://doi.org/10.1002/bse.2072

Geng, D., & Kali, R. (2021). Trade and innovation: Unraveling a complex nexus. *International Journal of Innovation Studies*, *5*(1), 23-34. https://doi.org/10.1016/j.ijis.2021.01.001

Gentile, E., Xing, Y., Rubínová, S., & Huang, S. (2021). Productivity growth, innovation, and upgrading along Global Value Chains. *Global Value Chain Development Report 2021: Beyond Production, Oecd 2021*, 106-138. https://doi.org/10.30875/e0f3a76e-en

Gereffi, G., & Lee, J. (2012). Why the world suddenly cares about global supply chains. *Journal of supply chain management*, *48*(3), 24-32. https://doi.org/10.1111/j.1745-493X.2012.03271.x

Ghanem, A. M., & Alamri, Y. A. (2023). The impact of the green Middle East initiative on sustainable development in the Kingdom of Saudi Arabia. *Journal of the Saudi Society of Agricultural Sciences*, *22*(1), 35-46. https://doi.org/10.1016/j.jssas.2022.06.001

Ghisetti, C., & Quatraro, F. (2017). Green technologies and environmental productivity: A cross-sectoral analysis of direct and indirect effects in Italian regions. *Ecological Economics*, *132*, 1-13. https://doi.org/10.1016/j.ecolecon.2016.10.003

Guadalupe, M., Kuzmina, O., & Thomas, C. (2012). Innovation and foreign ownership. *American Economic Review*, *102*(7), 3594-3627. https://doi.org/10.1257/aer.102.7.3594

Guo, J., Xie, J., Liu, X., & Yang, T. (2024). How do global value chains respond to climate change? A case study of Chinese manufacturing firms. *Journal of Environmental Management*, *368*, 122083. https://doi.org/10.1016/j.jenvman.2024.122083

Ha, L. T., & Thanh, T. T. (2022). Global value chains and energy security: Evidence from global sample. *Energy Strategy Reviews*, *42*, 100870. https://doi.org/10.1016/j.esr.2022.100870

Hazem, Nada & Zaki, Chahir. (2025). Environmental Stringency and Firms' Participation in Global Value Chains: Evidence for MENA Countries. *Policy Research Working Paper Series 11161*, The World Bank. https://documents1.worldbank.org/curated/en/099727106302516985/pdf/IDU-61c759bc-1029-4248-85d0-ee103f0e6cb7.pdf

He, Z. X., Shen, W. X., Li, Q. B., Xu, S. C., Zhao, B., Long, R. Y., & Chen, H. (2018). Investigating external and internal pressures on corporate environmental behavior in papermaking enterprises of China. *Journal of Cleaner Production*, *172*, 1193-1211.

He, Z. X., Xu, S. C., Shen, W. X., Long, R. Y., & Chen, H. (2016). Factors that influence corporate environmental behavior: Empirical analysis based on panel data in China. *Journal of Cleaner Production*, *133*, 531-543. https://doi.org/10.1016/j.jclepro.2016.05.164

Hille, E., Althammer, W., & Diederich, H. (2020). Environmental regulation and innovation in renewable energy technologies: Does the policy instrument matter? *Technological Forecasting and Social Change*, *153*, 119921. https://doi.org/10.1016/j.techfore.2020.119921

Horbach, J., Rammer, C., & Rennings, K. (2012). Determinants of eco-innovations by type of environmental impact—The role of regulatory push/pull, technology push and market pull. *Ecological economics*, *78*, 112-122. https://doi.org/10.1016/j.ecolecon.2012.04.005

Hovhannisyan, N., & Keller, W. (2015). International business travel: an engine of innovation?. *Journal of Economic Growth*, *20*, 75-104. https://doi.org/10.1007/s10887-014-9107-7
https://doi.org/10.1016/j.jclepro.2017.10.115.

Hu, D., Jiao, J., Tang, Y., Han, X., & Sun, H. (2021). The effect of global value chain position on green technology innovation efficiency: From the perspective of environmental regulation. *Ecological Indicators*, *121*, 107195. https://doi.org/10.1016/j.ecolind.2020.107195
Hu, D., Jiao, J., Tang, Y., Xu, Y., & Zha, J. (2022). How global value chain participation affects green technology innovation processes: A moderated mediation model. *Technology in Society*, *68*, 101916. https://doi.org/10.1016/j.techsoc.2022.101916
Hua, Y., Lu, Y., & Zhao, R. (2022). Global value chain engagement and air pollution: Evidence from Chinese firms. *Journal of Economic Surveys*, *36*(3), 708–727. https://doi.org/10.1111/joes.12447
Huang, H., Zhang, Z., & Jiang, F. (2022). Environmental effects of global value chain embedding in manufacturing industry in countries along the Belt and Road. *Frontiers in Environmental Science*, *10*, 1039358. https://doi.org/10.3389/fenvs.2022.1039358
Humphrey, J.(2004). *Upgrading in Global Value Chains*, Working Paper No. 28, International Labor Organization, Geneva.
Humphrey, J., & Schmitz, H. (2002). How does insertion in global value chains affect upgrading in industrial clusters? *Regional Studies, 36*(9), 1017–1027. https://doi.org/10.1080/0034340022000022198
Ignatenko, A.; Raei, F.; & Mircheva, B. (2019). Global Value Chains: What are the Benefits and Why Do Countries Participate? IMF Working Paper No.19/18, International Monetary Fund, Washington, D.C.
International Energy Agency. (2024). Greenhouse Gas Emissions from Energy Data Explorer, available online at https://www.iea.org/data-and-statistics/data-tools/greenhouse-gas-emissions-from-energy-data-explorer
Ivarsson, I., & Alvstam, C. G. (2010). Supplier upgrading in the home-furnishing value chain: an empirical study of IKEA's sourcing in China and South East Asia. *World Development*, *38*(11), 1575-1587. https://doi.org/10.1016/j.worlddev.2010.04.007
Jalo, N., Johansson, I., Kanchiralla, F. M., & Thollander, P. (2021). Do energy efficiency networks help reduce barriers to energy efficiency? A case study of a regional Swedish policy program for industrial SMEs. *Renewable and Sustainable Energy Reviews*, *151*, 111579. https://doi.org/10.1016/j.rser.2021.111579
Jaud, M., & Freund, C. (2015). *Champions Wanted: Promoting Exports in the Middle East and North Africa*. World Bank Publications.
Ji et al. (2022). Global value chain participation and trade-induced energy inequality, *Energy Economics*, 112:106175. https://doi.org/10.1016/j.eneco.2022.106175
Jin, Z., Wang, J., Yang, M., & Tang, Z. (2022). The effects of participation in global value chains on energy intensity: Evidence from international industry-level decomposition. *Energy Strategy Reviews*, *39*, 100780. https://doi.org/10.1016/j.esr.2021.100780
Kallini, M. & Zaki, C. (2024). *Are Global Value Chains Women Friendly in Developing Countries? Evidence from Firm-Level Data,* Policy Research Working Paper No. 10667, World Bank, Washington D.C.
Kammerer, D. (2009). The effects of customer benefit and regulation on environmental product innovation. *Ecological Economics*, *68*(8–9), 2285–2295. https://doi.org/10.1016/j.ecolecon.2009.02.016
Karplus, V. J., & Grover, A. (2020). *The Energy-Management Nexus in Firms: Which Practices Matter, how Much and for Whom ?* World Bank, Washington, DC. https://doi.org/10.1596/1813-9450-9397
Kellermanns, F.W., Eddleston, K.A., Zellweger, T., (2012). Extending the socioemotional wealth perspective: a look at the dark side. *Entrepreneurship Theory and Practice*. 36 (6), 1175–1182. https://doi.org/10.1111/j.1540-6520.2012.00544.x.
Koirala, S. (2019). SMEs: Key drivers of green and inclusive growth. *OECD Green Growth Papers*, (2019/03). OECD Publishing.
Kong, D., Zhu, L., & Yang, Z. (2020). Effects of foreign investors on energy firms' innovation: Evidence from a natural experiment in China. *Energy Economics*, *92*, 105011. https://doi.org/10.1016/j.eneco.2020.105011
Koopman, R., Powers, W., Wang, Z., & Wei, S. J. (2010). *Give credit where credit is due: Tracing value added in global production chains* (No. w16426). National Bureau of Economic Research.
Krishnan, A., De Marchi, V., & Ponte, S. (2023). Environmental Upgrading and Downgrading in Global Value Chains: A Framework for Analysis, *Economic Geography*, 99:1, 25-50. https://doi.org/10.1080/00130095.2022.2100340
Ledezma, I., & Lopez-Villavicencio, A. (2024). "Global Value Chains and Productivity: Causal Evidence for Firms Worldwide." *EconomiX Working Paper 2024–4*. University of Paris Nanterre, EconomiX. https://economix.fr/pdf/dt/2024/WP_EcoX_2024-4.pdf
Lee, C. & Wen, H. (2025). Global value chain embedding and enterprise energy efficiency: A worldwide firm-level analysis, *Renewable and Sustainable Energy Reviews*, 207: 114955. https://doi.org/10.1016/j.rser.2024.114955
Li, C. J., Razzaq, A., Irfan, M., & Luqman, A. (2023). Green innovation, environmental governance and green investment in China: Exploring the intrinsic mechanisms under the framework of COP26. *Technological Forecasting and Social Change*, *194*, 122708. https://doi.org/10.1016/j.techfore.2023.122708

Li, H.; Zheng, Q.; Zhang, B.; & Sun, C. (2021). Trade policy uncertainty and improvement in energy efficiency: Empirical evidence from prefecture-level cities in China. *Energy Economics*, *104*, 105691. https://doi.org/10.1016/j.eneco.2021.10569

Li, J., Wang, L., Cheng, X., Luo, D., Huang, B., Sun, S., ... & Yang, Z. (2023). Low-temperature and high-sensitivity Au-decorated thin-walled SnO2 nanotubes sensor for ethanol detection. *Materials Today Communications*, *37*, 107217. https://doi.org/10.1016/j.mtcomm.2023.107217

Li, Q., Zhao, J., Gong, Y., & Zhang, Q. (2019). Energy-efficient computation offloading and resource allocation in fog computing for Internet of Everything. *China Communications,* *16*(3), 32–41. https://doi.org/10.12676/j.cc.2019.03.004

Li, Y., Wang, Y., Li, J., & Huang, Q. (2023). Global value chain embedding mode and carbon emission efficiency: evidence from China's manufacturing industry. *Technological Forecasting and Social Change*, *194*, 122661. https://doi.org/10.1016/j.techfore.2023.122661

Lionello, P., Abrantes, F., Gacic, M., Planton, S., Trigo, R., & Ulbrich, U. (2014). The climate of the Mediterranean region: research progress and climate change impacts. *Regional Environmental Change*, *14*(5), 1679-1684. https://doi.org/10.1007/s10113-014-0666-0

Liu, Y., Li, Z., & Yin, X. (2018b). Environmental regulation, technological innovation and energy consumption---a cross-region analysis in China. *Journal of Cleaner Production*, *203*, 885-897. https://doi.org/10.1016/j.jclepro.2018.08.277.

Liu, Z., Chen, X., Chu, J., & Zhu, Q. (2018a). Industrial development environment and innovation efficiency of high-tech industry: analysis based on the framework of innovation systems. *Technology Analysis & Strategic Management*, *30*(4), 434-446. https://doi.org/10.1080/09537325.2017.1337092

Loecker, J. D. (2013). Detecting learning by exporting. *American Economic Journal: Microeconomics*, *5*(3), 1-21. https://doi.org/10.1257/mic.5.3.1

Lorenz, E., & Pommet, S. (2021). Mobile money, inclusive finance and enterprise innovativeness: An analysis of East African nations. *Industry and Innovation*, *28*(2), 136–159. https://doi.org/10.1080/13662716.2020.1774867

Marslev, K., Staritz, C., & Raj-Reichert, G. (2022). Rethinking social upgrading in global value chains: Worker power, state–labour relations and intersectionality. *Development and Change*, *53*(4), 827-859. https://doi.org/10.1111/dech.12705

Meng B, Liu Y, Gao Y, Li M, Wang Z, Xue J, Andrew R, Feng K, Qi Y, Sun Y, Sun H, Wang K. (2023a). Developing countries' responsibilities for CO2 emissions in value chains are larger and growing faster than those of developed countries. *One Earth*. 6, 167- 181. https://doi.org/10.1016/j.oneear.2023.01.006

Meng, B., Ye, M., & Wei, S. J. (2020). Measuring smile curves in global value chains. *Oxford Bulletin of Economics and Statistics*, *82*(5), 988-1016. https://doi.org/10.1111/obes.12364

Meng, B.; Wang, R.; & Li, M. (2023b). *Tracing Carbon Dioxide Emissions along Global Value Chains, WTO report, https://www.wto.org/english/res_e/booksp_e/08_gvc23_ch5_dev_report_e.pdf*

Meng, S., Yan, H., & Yu, J. (2022). Global Value Chain Participation and Green Innovation: Evidence from Chinese Listed Firms. *International Journal of Environmental Research and Public Health*, *19*(14), 8403. https://doi.org/10.3390/ijerph19148403

Moghadam, H. E. (2023). Can ETFs mitigate stock Co-movement? An analysis of an emerging market. *Heliyon*, *9*(10).

Moreno-Mondéjar, L. & Cuerva, M. C. (2020), Fostering Investment in Resource Efficiency Actions: The Case of European SMEs. *Energy Efficiency*, 13. https://doi.org/10.1007/s12053-020-09888-y

Nguyen, P. H., Van Nguyen, D., Nguyen, T. P., Nguyen, L. A. T., Nguyen, T. H. T., Vu, T. G., & Le Hoang, H. G. (2025). Income-dependent variations in innovation performance: Insights from sustainable economic development indicators. *Journal of Open Innovation: Technology, Market, and Complexity*, *11*(1), 100478.https://doi.org/10.1016/j.joitmc.2025.100478

Noailly, J., & Smeets, R. (2015). Directing technical change from fossil-fuel to renewable energy innovation: An application using firm-level patent data. *Journal of Environmental Economics and Management*, *72*, 15-37. https://doi.org/10.1016/j.jeem.2015.03.004

OECD. (2024). *Global Value and Supply Chains*, available online at https://www.oecd.org/en/topics/policy-issues/global-value-and-supply-chains.html.

Orsato, R. (2003). Competitive Environmental Strategies: When Does It Pay to be Green? *California Management Review,* 48(2), 127-143, https://doi.org/10.2307/41166341

Pahl, S., & Timmer, M. P. (2020). Do global value chains enhance economic upgrading? A long view. *Journal of Development Studies, 56*(9), 1683–1705. https://doi.org/10.1080/00220388.2019.1702159

Paschoaleto, L. & Martinez-Zarzoso, I. (2024). Environmental Regulations and Firms' Integration in Global Markets: Using a New Environmental Performance Index, Empirica, 51, 829-876, https://doi.org/10.1007/s10663-024-09612-4

Piermartini, R. & Rubínová, S. (2014). *Knowledge spillovers through international supply chains,* WTO Working Paper ERSD-2014-11, World Trade Organization Economic Research and Statistics Division Geneva.

Pietrobelli. C. & Rabellotti, R. (2010). *Global Value Chains Meet Innovation Systems: Are There Learning Opportunities for Developing Countries?* IDB Working Paper Series No IDB-WP-232, Italy.
Porter, E. and Van der Linde, C. (1995). Green and Competitive: Ending the Stalemate, *Harvard Business Review*, 73(5) 120-134. https://hbr.org/1995/09/green-and-competitive-ending-the-stalemate
Ramzy, M. (2025). Exploring the Role of Environmental Regulations and Green Practices in Global Value Chains (GVCs) Participation: Evidence from Firms in the Euro-Mediterranean Region, FEMISE Conference Paper No.13.
Ranasinghe, U. C., Ennis, S. F., Monteiro, J., & Malagueño, R. (2025). Global value chains, trade facilitation and the use of environmental management practices in SMEs. *International Journal of Operations & Production Management*. https://doi.org/10.1108/IJOPM-03-2024-0261
Reddy, A. K. (1991). Barriers to improvements in energy efficiency. *Energy policy*, *19*(10), 953-961. https://doi.org/10.1016/0301-4215(91)90115-5
Rehfeld, K. M., Rennings, K., & Ziegler, A. (2007). Integrated product policy and environmental product innovations: An empirical analysis. *Ecological economics*, *61*(1), 91-100. https://doi.org/10.1016/j.ecolecon.2006.02.003
Ren, S., Sun, H., & Zhang, T. (2021). Do environmental subsidies spur environmental innovation? Empirical evidence from Chinese listed firms. *Technological Forecasting and Social Change*, *173*, 121123. https://doi.org/10.1016/j.techfore.2021.121123
Rennings, K. & Rexhäuser, S. (2010). *Long-Term Impacts of Environmental Policy and Eco-Innovative Activities of Firms,* ZEW Discussion Paper No.10-074, Center for European Economic Research, Mannheim.
Rennings, K., Ziegler, A., Ankele, K., & Hoffmann, E. (2006). The influence of different characteristics of the EU environmental management and auditing scheme on technical environmental innovations and economic performance. *Ecological Economics*, *57*(1), 45-59. https://doi.org/10.1016/j.ecolecon.2005.03.013
Rigo, D. (2021). Global value chains and technology transfer: new evidence from developing countries. Rev. *World Economy*. 157, 271–294. https://doi.org/10.1007/s10290-020-00398-8
Russo, A., & Perrini, F. (2010). Investigating Stakeholder Theory and Social Capital: CSR in Large Firms and SMEs. *Journal of Business Ethics*, *91*(2), 207–221. https://doi.org/10.1007/s10551-009-0079-z
Santacreu-Vasut, E. & Kensuke T. (2016). Foreign Employees as Channel for Technology Transfer: Evidence from MNC's Subsidiaries in Mexico. *Journal of Development Economics*. 122. 92–112. https://doi.org/10.1016/j.jdeveco.2016.05.001
Segarra-Blasco, A., & Jove-Llopis, E. (2019). Determinants of Energy Efficiency and Renewable Energy in European SMEs, *Economics of Energy & Environmental Policy*, *8*(2). https://doi.org/10.5547/2160- 5890.8.2.aseg
Shahbaz, M., Nasir, M. A., & Roubaud, D. (2018). Environmental degradation in France: the effects of FDI, financial development, and energy innovations. *Energy economics*, *74*, 843-857. https://doi.org/10.1016/j.eneco.2018.07.020
Sharma, N. (2018). Management of Innovation in Micro, Small and Medium Enterprises in the Middle East and North Africa (MENA). In *Entrepreneurship Ecosystem in the Middle East and North Africa (MENA) Dynamics in Trends, Policy and Business Environment* (pp. 611-626). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-75913-5_23
Shi, Q., Zhao, Y., Qian, Z., Zheng, L., & Wang, S. (2022). Global value chains participation and carbon emissions: Evidence from Belt and Road countries. *Applied Energy*, *310*, 118505. https://doi.org/10.1016/j.apenergy.2021.118505
Shu, P., & Steinwender, C. (2019). The impact of trade liberalization on firm productivity and innovation. *Innovation Policy and the Economy*, *19*(1), 39-68. https://doi.org/10.1086/699932
Siewers, S., Martínez-Zarzoso, I., & Baghdadi, L. (2024). Global value chains and firms' environmental performance. *World Development*, *173*, 106395. https://doi.org/10.1016/j.worlddev.2023.106395
Song, C. & Oh, W. (2015). Determinants of innovation in energy intensive industry and implications for energy policy, *Energy Policy*, *81*, 122–130. https://doi.org/10.1016/j.enpol.2015.02.022
Song, M., & Wang, S. (2016). Participation in global value chain and green technology progress: evidence from big data of Chinese enterprises. *Environmental Science and Pollution Research*, *24*, 1648-1661. https://doi.org/10.1007/s11356-016-7925-1
Šūmakaris, P. Korsakienė, R. & Ščeulovs, D. (2021). Determinants of Energy Efficient Innovation: A Systematic Literature Review, *Energies*, *14*(22), 7777. https://doi.org/10.3390/en14227777
Sun, C., Li, Z., Ma, T., & He, R. (2019). Carbon efficiency and international specialization position: Evidence from global value chain position index of manufacture. *Energy Policy*, *128*, 235–242. https://doi.org/10.1016/j.enpol.2018.12.058
Sun, H., Edziah, B. K., Kporsu, A. K., Sarkodie, S. A., & Taghizadeh-Hesary, F. (2021). Energy efficiency: The role of technological innovation and knowledge spillover. *Technological Forecasting and Social Change*, *167*, 120659. https://doi.org/10.1016/j.techfore.2021.120659
Tian, P., & Lin, B. (2019). Impact of financing constraints on firm's environmental performance: Evidence from China with survey data. *Journal of Cleaner Production*, *217*, 432-439. https://doi.org/10.1016/j.jclepro.2019.01.209
Tran, T. M. (2022). Environmental benefit gain from exporting: Evidence from Vietnam. *The World Economy*, *45*(4), 1081-1111. https://doi.org/10.1111/twec.13177

Tsoi, J. (2010). Stakeholders' perceptions and future scenarios to improve corporate social responsibility in Hong Kong and mainland China. *Journal of Business Ethics, 91*(3), 391–404. https://doi.org/10.1007/s10551-009-0091-3
Ulucak, R., & Ozcan, B. (2020). Relationship between energy consumption and environmental sustainability in OECD countries: the role of natural resources rents. *Resources Policy*, *69*, 101803. https://doi.org/10.1016/j.resourpol.2020.101803
Usman, M., & Hammar, N. (2021). Dynamic relationship between technological innovations, financial development, renewable energy, and ecological footprint: fresh insights based on the STIRPAT model for Asia Pacific Economic Cooperation countries. *Environmental Science and Pollution Research*, *28*(12), 15519-15536. https://doi.org/10.1007/s11356-020-11640-z
Wagner, M., 2008. Empirical influence of environmental management on innovation: evidence from Europe. *Ecological Economics* 66 (2–3), 392–402. https://doi.org/10.1016/j.ecolecon.2007.10.001
Wang, J., Wan, G., & Wang, C. (2019). Participation in GVCs and CO2 emissions. *Energy Economics, Volume 8* https://doi.org/10.1016/j.eneco.2019.104561
Wang, L., Yue, Y., Xie, R., & Wang, S. (2020). How global value chain participation affects China's energy intensity. *Journal of environmental management*, *260*, 110041. https://doi.org/10.1016/j.jenvman.2019.110041
Wang, S., He, Y., & Song, M. (2021b). Global value chains, technological progress, and environmental pollution: Inequality towards developing countries. *Journal of Environmental Management*, *277*, 110999. https://doi.org/10.1016/j.jenvman.2020.110999
Wang, S., Wang, X., & Chen, S. (2022). Global value chains and carbon emission reduction in developing countries: Does industrial upgrading matter? *Environmental Impact Assessment Review*, *97*, 106895. https://doi.org/10.1016/j.eiar.2022.106895
Wang, Z. ; Zhang, Y. ; Liao, C. ; Ai, H. ; & Yang, X. (2021a). What contributes to the growth of China's embodied CO2 emissions? Incorporating the global value chains concept. Applied Economics, 54(12), 1335–1351. https://doi.org/10.1080/00036846.2021.1976382
Wang, Z., Wei, S. J., & Zhu, K. (2013). *Quantifying international production sharing at the bilateral and sector levels* (No. w19677). National Bureau of Economic Research.
Wu, R. (2023). Environmental management, environmental innovation, and productivity growth: a global firm- level investigation, *Environment and Development Economics* (2023),28, 449–468 https://doi.org/10.1080/15435075.2017.1381612
Wu, X., Li, Y., & Zhang, H. (2024). How does global value chain embeddedness affect environmental pollution? Evidence from Chinese enterprises. *Journal of Cleaner Production, 434*, 140232.https://doi.org/10.1016/j.jclepro.2023.140232
Xue, X., &Wang, Z. (2021). Impact of finance pressure on energy intensity: Evidence from China's manufacturing sectors, *Energy*, *226*, 120220. https://doi.org/10.1016/j.energy.2021.120220
Yang, B., Liu, B., Peng, J., & Liu, X. (2022). The impact of the embedded global value chain position on energy-biased technology progress: Evidence from chinas manufacturing. *Technology in Society*, *71*, 102065. https://doi.org/10.1016/j.techsoc.2022.102065
Yu, F., Guo, Y., Le-Nguyen, K., Barnes, S. J., & Zhang, W. (2016). The impact of government subsidies and enterprises' R&D investment: A panel data study from renewable energy in China. *Energy policy*, *89*, 106-113. https://doi.org/10.1016/j.enpol.2015.11.009
Zaghdoud, O. (2025). Technological Progress as a Catalyst for Energy Efficiency: A Sustainable Technology Perspective, *Sustainable Technology and Entrepreneurship,* 4(1),1-9. https://doi.org/10.1016/j.stae.2024.100084
Zhang, D., Li, J., & Ji, Q. (2020). Does better access to credit help reduce energy intensity in China? Evidence from manufacturing firms. *Energy Policy*, *145*, 111710.https://doi.org/10.1016/j.enpol.2020.111710
Zhang, J., Liang, G., Feng, T., Yuan, C., & Jiang, W. (2020). Green innovation to respond to environmental regulation: How external knowledge adoption and green absorptive capacity matter? *Business Strategy and the Environment*, *29*(1), 39–53. https://doi.org/10.1002/bse.2349

Zhang, R., & Fu, Y. (2022). Technological progress effects on energy efficiency from the perspective of technological innovation and technology introduction: An empirical study of Guangdong, China. *Energy Reports*, *8*, 425-437. https://doi.org/10.1016/j.egyr.2021.11.282
Zheng, M., Ni, J., & Wen, D. (2024). Has GVC participation exacerbated inequality of the embodied carbon in fossil energy industry export trade? *Frontiers in Environmental Science*, *11*, 1293462. https://doi.org/10.3389/fenvs.2023.1293462
Zhong, S. (2018). Structural decompositions of energy consumption between 1995 and 2009: Evidence from WIOD. *Energy Policy*, *122*, 655-667. https://doi.org/10.1016/j.enpol.2018.08.017
Zhou, F., & Wang, X. (2022). The carbon emissions trading scheme and green technology innovation in China: A new structural economics perspective. *Economic Analysis and Policy*, *74*, 365-381. https://doi.org/10.1016/j.eap.2022.03.007

Zhou, Q., Fu, C., Ni, H., & Gong, L. (2021). What are the main factors that influence China's energy intensity? Based on aggregate and firm-level data. *Energy Reports*, *7*, 2737–2750. https://doi.org/10.1016/j.egyr.2021.04.037
Zhu, L., Luo, J., Dong, Q., Zhao, Y., Wang, Y., & Wang, Y. (2021). Green technology innovation efficiency of energy-intensive industries in China from the perspective of shared resources: Dynamic change and improvement path. *Technological Forecasting and Social Change*, *170*, 120890. https://doi.org/10.1016/j.techfore.2021.120890

Appendix

Appendix A: Descriptive Statistics

Table (12): Cross frequencies share of firm-level GVC participation and energy efficiency

	GVC Strict1			**GVC Strict2**			**GVC Strictest**		
Energy innovation	0	1	Total	0	1	Total	0	1	Total
0	98.96	1.04	100.00	99.76	0.24	100.00	99.94	0.06	100.00
	46.63	19.17	45.95	46.12	18.07	45.95	46.04	10.21	45.95
1	96.26	3.74	100.00	99.07	0.93	100.00	99.56	0.44	100.00
	53.37	80.83	54.05	53.88	81.93	54.05	53.96	89.79	54.05
Total	97.50	2.50	100.00	99.39	0.61	100.00	99.73	0.27	100.00
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Source: Constructed by the authors using WBES-BEEPS dataset. First row has row percentages and second row has column percentages Sample weights are accounted for. GVC Strict1 is defined upon two-way trading and possession of international quality certificate, GVC Strict 2 stands for two-way trading along with positive ownership, and GVC Strictest is the most advanced combining the three dimensions.

Appendix B: Definition of institutional quality measure

The availability of a wide array of institutional indicators in the Enterprise Survey database allows for the construction of institutional quality measures of firm-level governance perceptions within each country. Following Barasa et al. (2017), Chadee and Roxas (2013), and Fogel et al. (2006), this study uses multiple items from the Enterprise Survey reflecting firms's viewpoints on corruption, rule of law, and regulatory quality to develop the main three dimensions of the composite measure. Two main variables are used for measuring corruption. The first item asks firms whether they discern the court system as fair, impartial, and uncorrupted and report their responses using a four-point scale (1 = strongly disagree, 4 = strongly agree). The second one focuses on the degree to which firms perceive corruption as an obstacle to their current operations. The respondents' identification of corruption degree is captured by a five-point scale (0 = not an obstacle, 4 = very severe obstacle). To measure the rule of law, three Enterprise Survey items that ask the firms to what degree they regard courts, political instability, crime, theft, and disorder as institutional barriers to their operations are used. For each element, firms' responses are shown using a five- point scale (0 = not an obstacle, to 4 = very severe obstacle). Lastly, regulatory quality encompasses firms' perceptions about to what extent the quality of tax rates, tax administration, customs and trade regulations, and business permits and licensing set back their business transactions. Responses to these four questions are entered on a five-point scale (0 = not an obstacle, to 4 = very severe obstacle). Subsequently, the individual items within each dimension are standardized then the average firm-level scores are computed within each country to have country-level measures of corruption, rule of law and regulatory quality. The composite measure of institutional quality is calculated upon taking the mean value of three main pillars for each economy. Due to standardisation, scores range between 0 and 1 with higher values indicating above average institutional quality (Barasa et al., 2017).

Appendix C: Multivariate probit results

Table (13): Multivariate probit estimation of GVC impact on individual energy innovation types

Variables	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
	Lightening system improvement	**Heating and cooling system improvement**	**Machinery upgrades**	**Vehicle upgrades**	**Energy saving onsite generation**	**Renewable energy**
GVC	0.132***	0.0580	0.213***	0.0927**	0.0684	0.140***
	(0.0438)	(0.0406)	(0.0522)	(0.0401)	(0.0462)	(0.0381)
Small firm	-0.0216	-0.0420	-0.112*	-0.156**	-0.120***	-0.106**
	(0.0373)	(0.0325)	(0.0648)	(0.0756)	(0.0393)	(0.0536)
Large firm	-0.164***	0.0448	0.0225	0.0321	0.0929*	0.0358
	(0.0430)	(0.0508)	(0.0394)	(0.0416)	(0.0508)	(0.0558)
Ln age	-0.0300	-0.0286	-0.0123	-0.0233	0.0330	0.0768***
	(0.0276)	(0.0240)	(0.0220)	(0.0205)	(0.0305)	(0.0286)
Financial constraint	-0.146	-0.149***	-0.178***	-0.216***	-0.0807	-0.181***
	(0.109)	(0.0548)	(0.0388)	(0.0367)	(0.0600)	(0.0620)
Ln annual sales	0.0228**	0.00433	0.00978	0.0180**	-0.00355	0.00489
	(0.0106)	(0.00681)	(0.00692)	(0.00768)	(0.00838)	(0.00861)
Knowledge development	0.254***	0.293***	0.442***	0.270***	0.163***	0.166***
	(0.0623)	(0.0331)	(0.0424)	(0.0393)	(0.0400)	(0.0556)
National institutional quality	-0.261	-0.0815	-0.0194	0.0321	0.363***	0.0568
	(0.273)	(0.152)	(0.184)	(0.158)	(0.134)	(0.210)
Employee training	0.141*	0.158*	0.133***	0.194***	0.115*	0.166***
	(0.0798)	(0.0878)	(0.0425)	(0.0398)	(0.0640)	(0.0522)
Foreign ownership	0.0200	0.0515	-0.0434	-0.122**	-0.00146	-0.0831
	(0.0534)	(0.0468)	(0.0470)	(0.0534)	(0.0534)	(0.0618)
Energy management	1.823***	1.419***	1.215***	0.734***	1.245***	0.958***
	(0.143)	(0.0922)	(0.161)	(0.155)	(0.126)	(0.112)
Energy regulation	0.00843	0.0972	0.0102	0.182**	0.00407	0.107
	(0.0717)	(0.0598)	(0.0703)	(0.0827)	(0.0626)	(0.0670)
Environmental demand	0.0557	0.192**	0.242***	0.233***	0.312***	0.350***
	(0.0880)	(0.0761)	(0.0603)	(0.0418)	(0.0681)	(0.0669)
Constant	299.6	321.6*	-142.5	21.88	476.3	37.91
	(232.2)	(191.6)	(111.8)	(98.01)	(314.2)	(358.6)
Year Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes
Industry Country Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes

LR $x^2(6)$	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***
Observations	19,804	19,804	19,804	19,804	19,804	19,804

Robust and clustered standard errors in parentheses *** is for p -value <0.01, ** p-value <0.05, * p-value <0.1

Appendix D: Robustness Checks

I. Addressing endogeneity concerns

Table (14): instrumental variable estimates

Variables	**(1)**	**(2)**
GVC	0.820***	0.653***
	(0.253)	(0.243)
Small firm	0.114	0.119
	(0.104)	(0.106)
Large firm	-0.0922	-0.0914
	(0.0883)	(0.0905)
Ln age	0.219***	0.223***
	(0.0814)	(0.0830)
Financial constraint	-0.257***	-0.260***
	(0.0596)	(0.0610)
Ln annual sales	0.0947**	0.0963**
	(0.0408)	(0.0409)
Knowledge development	0.431***	0.440***
	(0.129)	(0.126)
National institutional quality	0.553***	0.583***
	(0.141)	(0.135)
Employee training	0.0794**	0.0817**
	(0.0331)	(0.0333)
Foreign ownership	0.386***	0.381***
	(0.148)	(0.146)
Energy management	2.260***	2.292***
	(0.357)	(0.346)
Energy regulation	0.0607	0.0633
	(0.199)	(0.200)
Environmental demand	0.666*	0.676*
	(0.349)	(0.355)
Constant	-2.476***	-2.700***
	(0.815)	(0.790)
Year Fixed Effect	Yes	Yes
Industry Country Fixed Effect	Yes	Yes
Observations	20,100	20,100

Robust and clustered standard errors in parentheses *** is for p -value <0.01, ** p-value <0.05, * p-value <0.1

II. Addressing selection bias

Table (15): PSM results- Balanced Test

	Mean			
Variable	**Treated**	**Control**	**t-stat**	**p-value**
Large size	0.3758	0.37217	0.4	0.691
Small size	0.26263	0.27581	-1.57	0.115
Medium size	0.36157	0.35202	1.06	0.291
Retail	0.0605	0.0737	-2.8	0.005
Manufacturing	0.76922	0.72998	4.81	0
Services	0.17028	0.19632	-3.57	0

Ln age	2.9374	2.9252	0.89	0.375
Financial constraint	0.32705	0.3219	0.58	0.56
Employee training	0.43808	0.44246	-0.47	0.64
Foreign ownership	15.475	16.258	-1.21	0.228
State ownership	0.95534	0.87035	0.56	0.577
International quality certification	0.50231	0.50653	-0.45	0.655

Table (16): PSM results- kernel matching

Variable	**Sample**	**Treated**	**Controls**	**Difference**	**S.E.**	**T-stat**	**R-squared**	**Observations**
Energy Innovation	Unmatched	0.81726	0.633162	0.184097	0.006984	26.36	0.1724	25,697
	ATT	0.81726	0.711454	0.105806	0.008307	12.74		

Table (17): PSM results- 5 nearest neighbouring matching

Variable	Sample	Treated	Controls	Difference	S.E.	T-stat	R-squared	Observations
Energy innovation	Unmatched	0.81726	0.633162	0.184097	0.006984	26.36	0.1724	25,697
	ATT	0.81726	0.721815	0.095445	0.009624	9.92		

Table (18): Results of adding covariates on matching sample

Variables	**(1)**
GVC	0.171***
	(0.0613)
Ln sales	0.0883**
	(0.0366)
Knowledge development	0.443**
	(0.200)
National institutional quality	0.518**
	(0.203)
Employee training	0.0400
	(0.0719)
Energy management	2.175***
	(0.291)
Energy regulation	0.121
	(0.251)
Environmental demand	0.553*
	(0.336)
Constant	-1.691***
	(0.541)
Year Fixed Effect	Yes
Industry Country Fixed Effect	Yes
Observations	23,306

Robust and clustered standard errors in parentheses *** is for p -value <0.01, ** p-value <0.05, * p-value <0.1

III. Alternative variable measurement and model specification

Table (19): Alternative measures of key variables

	(1)	(2)	(3)	(4)
GVC weak	0.157***	0.258***	0.151***	
	(0.0454)	(0.0762)	(0.0385)	
GVC strict				0.393*
				(0.205)
Small firm	0.133	0.0239	0.0624	0.140
	(0.108)	(0.146)	(0.0792)	(0.113)
Large firm	-0.0908	0.101	-0.0605	-0.0642
	(0.0853)	(0.206)	(0.115)	(0.0822)
Ln age	0.253***	-0.00760	0.226***	0.243***
	(0.0943)	(0.0549)	(0.0796)	(0.0938)
Fully financial		-0.225***	-0.301***	-0.287***

constrained				
		(0.0296)	(0.0473)	(0.0482)
Financial constraint	0.123			
	(0.0759)			
Ln annual sales	0.0831**	0.0700	0.0773**	0.0850**
	(0.0386)	(0.0638)	(0.0364)	(0.0401)
Knowledge development	0.503***	0.203	0.529***	0.494***
	(0.149)	(0.194)	(0.134)	(0.159)
National institutional quality	0.649***	1.012***	0.601***	0.561***
	(0.185)	(0.278)	(0.200)	(0.186)
Employee training	0.0257		0.0436	0.0474
	(0.0747)		(0.0699)	(0.0738)
Skilled workers		-0.129		
		(0.108)		
Energy management score measure	2.179***	1.760***		2.192***
	(0.298)	(0.599)		(0.298)
Energy regulation	0.124	0.305*	0.201	0.110
	(0.254)	(0.174)	(0.272)	(0.247)
Environmental demand	0.515*	0.0414	0.586**	0.596*
	(0.300)	(0.147)	(0.282)	(0.326)
Foreign ownership	0.325***	0.358***	0.285**	0.330***
	(0.124)	(0.135)	(0.138)	(0.115)
Energy management			0.897***	
			(0.132)	
Constant	-2.382***	-1.239	-1.866**	-2.098**
	(0.840)	(0.976)	(0.735)	(0.867)
Year Fixed effect	Yes	Yes	Yes	Yes
Industry Country Fixed effect	Yes	Yes	Yes	Yes
Observations	22,736	12,115	22,895	23,037

Robust and clustered standard errors in parentheses *** is for p -value <0.01, ** p-value <0.05, * p-value <0.1

Table (20): Extended model specification

Variables	(1)	(2)	(3)	(4)	(5)
GVC	0.136***	0.104**	0.134***	0.141***	0.146***
	(0.0503)	(0.0412)	(0.0498)	(0.0523)	(0.0442)
Small firm	0.107	0.119	0.132	0.127	0.121
	(0.0957)	(0.0992)	(0.108)	(0.115)	(0.101)
Large firm	-0.0940	-0.0722	-0.0949	-0.103	-0.0835
	(0.0957)	(0.0871)	(0.0959)	(0.102)	(0.0833)
Ln age	0.247***	0.251***	0.246***	0.242**	0.163**
	(0.0901)	(0.0967)	(0.0907)	(0.101)	(0.0703)
Financial constraint	-0.281***	-0.281***	-0.295***	-0.287***	-0.272***
	(0.0447)	(0.0450)	(0.0488)	(0.0424)	(0.0515)
Ln annual sales	0.0908**	0.0851**	0.0836**	0.0825**	0.0788**
	(0.0409)	(0.0399)	(0.0400)	(0.0351)	(0.0400)
Knowledge development	0.470***	0.311	0.459***	0.468***	0.455***
	(0.145)	(0.212)	(0.163)	(0.156)	(0.158)
National institutional quality	0.551***	0.580***	0.566***	0.571***	0.686***
	(0.190)	(0.168)	(0.176)	(0.176)	(0.170)
Employee training	0.0392	0.00754	0.0570	0.0624	0.0634

	(0.0754)	(0.0752)	(0.0761)	(0.0711)	(0.0754)
Energy management	2.193***	2.151***	2.196***	2.200***	2.178***
	(0.293)	(0.296)	(0.300)	(0.305)	(0.299)
Energy regulation	0.115	0.121	0.105	0.113	0.0761
	(0.257)	(0.255)	(0.256)	(0.249)	(0.245)
Environmental demand	0.462*	0.510*	0.570*	0.545	0.519*
	(0.271)	(0.301)	(0.317)	(0.336)	(0.303)
Foreign ownership	0.340**	0.362***	0.383***	0.354***	0.368**
	(0.154)	(0.126)	(0.133)	(0.123)	(0.150)
Informal competition	0.0960				
	(0.0696)				
Innovative capacity		0.429***			
		(0.0300)			
Ln subsidy			0.373		
			(0.245)		
Family business				-0.000320	
				(0.00184)	
Manager experience					0.0101**
					(0.00400)
Constant	-2.377***	-2.393***	-4.352**	-2.155***	-2.179**
	(0.857)	(0.888)	(1.826)	(0.704)	(0.888)
Year Fixed effect	Yes	Yes	Yes	Yes	Yes
Industry Country Fixed effect	Yes	Yes	Yes	Yes	Yes
Observations	21,827	22,867	21,495	22,635	22,593

Robust and clustered standard errors in parentheses *** is for p -value <0.01, ** p-value <0.05, * p-value <0.1

Appendix E: Average Marginal Effects

Table (21): Baseline with country and year fixed effects

Variables	dy/dx	std.error	z-stat	P>z
GVC	0.028	0.014	1.960	0.050
Small firm	0.031	0.028	1.100	0.272
Large firm	-0.019	0.023	-0.850	0.398
Ln age	0.063	0.019	3.360	0.001
Financial constraint	-0.083	0.022	-3.810	0.000
Ln annual sales	0.023	0.010	2.330	0.020
Knowledge development	0.149	0.049	3.040	0.002
National institutional quality	0.182	0.052	3.530	0.000
Employee training	0.013	0.022	0.610	0.545
Energy management	0.684	0.068	10.010	0.000
Energy regulation	0.026	0.069	0.370	0.710
Environmental demand	0.150	0.082	1.820	0.069
Foreign ownership	0.117	0.035	3.340	0.001

Table (22): Baseline with country, year and industry fixed effects

Variables	dy/dx	std.error	z-stat	P>z
GVC	0.029	0.013	2.220	0.027
Small firm	0.035	0.030	1.190	0.235
Large firm	-0.028	0.025	-1.080	0.280

Ln age	0.066	0.024	2.770	0.006
Financial constraint	-0.086	0.019	-4.600	0.000
Ln annual sales	0.025	0.011	2.200	0.028
Knowledge development	0.148	0.052	2.870	0.004
National institutional quality	0.177	0.053	3.310	0.001
Employee training	0.019	0.022	0.830	0.405
Energy management	0.678	0.071	9.490	0.000
Energy regulation	0.021	0.070	0.290	0.769
Environmental demand	0.157	0.090	1.730	0.084
Foreign ownership	0.116	0.035	3.320	0.001

Table (23): Baseline with multidimensional fixed effects

Variables	**dy/dx**	**std.error**	**z-stat.**	**P>z**
GVC	0.042	0.015	2.880	0.004
Small firm	0.039	0.031	1.270	0.204
Large firm	-0.030	0.028	-1.060	0.288
Ln age	0.073	0.025	2.900	0.004
Financial constraint	-0.088	0.017	-5.080	0.000
Ln annual sales	0.025	0.012	2.180	0.029
Knowledge development	0.141	0.051	2.780	0.005
National institutional quality	0.172	0.053	3.250	0.001
Employee training	0.017	0.022	0.780	0.437
Energy management	0.662	0.066	9.990	0.000
Energy regulation	0.032	0.075	0.430	0.666
Environmental demand	0.165	0.091	1.810	0.071
Foreign ownership	0.109	0.035	3.110	0.002

Appendix F: Country-level income and region classification

Country	**Region**	**Income Group**
Albania	EU	Upper-middle-income
Armenia	EU	Upper-middle-income
Azerbaijan	CA	Upper-middle-income
Belarus	EU	Upper-middle-income
Bosnia and Herzegovina	EU	Upper-middle-income
Bulgaria	EU	High-income
Croatia	EU	High-income
Cyprus	EU	High-income
Czechia	EU	High-income
Egypt, Arab Rep.	MENA	Lower-middle-income
Estonia	EU	High-income
Georgia	EU	Upper-middle-income
Greece	EU	High-income
Hungary	EU	High-income
Italy	EU	High-income
Jordan	MENA	Lower-middle-income
Kazakhstan	CA	Upper-middle-income
Kosovo	EU	Upper-middle-income
Kyrgyz Republic	CA	Lower-middle-income
Latvia	EU	High-income
Lebanon	MENA	Upper-middle-income

Lithuania	EU	High-income
Malta	EU	High-income
Moldova	EU	Lower-middle-income
Mongolia	EAP	Upper-middle-income
Montenegro	EU	Upper-middle-income
Morocco	MENA	Lower-middle-income
North Macedonia	EU	Upper-middle-income
Poland	EU	High-income
Portugal	EU	High-income
Romania	EU	High-income
Russian Federation	EU	High-income
Serbia	EU	Upper-middle-income
Slovak Republic	EU	High-income
Slovenia	EU	High-income
Tajikistan	CA	Lower-middle-income
Tunisia	MENA	Lower-middle-income
Turkey	EU	Upper-middle-income
Ukraine	EU	Upper-middle-income
Uzbekistan	CA	Lower-middle-income
West Bank and Gaza	MENA	Lower-middle-income

MENA stands for Middle East & North Africa. CA stands for Central Asia. EU stands for Europe.