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Nancy Barakat Rodulf and Myriam Ramzy

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POWERING THE ENERGY TRANSITION IN ENTERPRISES: EMPIRICAL INSIGHTS INTO THE GLOBAL VALUE CHAIN–ENERGY INNOVATION NEXUS

Nancy Barakat Rodulf[1] and Myriam Ramzy[2]

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Send correspondence to:
Myriam Ramzy
Cairo University
myriamgad@feps.edu.eg

[1] Faculty of Economics and Political Science, Cairo University, email: nancy.barakat2018@feps.edu.eg
[2] Assistant Professor of Economics at Faculty of Economics and Political Science, Cairo University, and Research Associate at the Economic Research Forum (ERF), email: myriamgad@feps.edu.eg

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Abstract

Global value chain (GVC) embedding can induce businesses' energy efficiency and decarbonization 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 enterp0rises' 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 Classifications: F1 ; F14 ; O3 ; Q4 ; Q5

ملخص

يمكن أن يُحفّز الاندماج في سلاسل القيمة العالمية (GVC) الشركاتِ على تسريع التحول نحو كفاءة الطاقة وخفض الانبعاثات الكربونية. ومع ذلك، يُمثل هذا التحول الأثر النهائي؛ إذ لا تزال التحسينات الطاقوية الدقيقة على مستوى العمليات التشغيلية—والتي تُشكل الأساس لهذا التحول واسع النطاق—غير مستكشفة بما يكفي. وتُعد هذه الدراسة أول فحص على مستوى المنشأة للعلاقة بين الانخراط في سلاسل القيمة العالمية والابتكار في كفاءة استخدام الطاقة. بالاعتماد على بيانات مسح بيئة الأعمال وأداء المشاريع (WBES-BEEPS)عبر 41 دولة، تُظهر النتائج أن المشاركة في سلاسل القيمة العالمية ترفع بشكل ملحوظ من قابلية الشركات لتبني الابتكارات الطاقوية. ويكشف تحليل الآليات عن دور وسيط محوري لكل من حجم السوق وتأثيرات التعلم بالبحث والتجربة (Research and Learning Spillovers)في تفسير هذه العلاقة. كما أُجري تحليل تباين متعمق لمراعاة الفروق المرتبطة بخصائص المنشأة، والسمات القطاعية، والتوزيع الجغرافي، وفئات الدخل القُطرية. يتجلى هذا الأثر الإيجابي بوضوح أكبر لدى الشركات الصغيرة والمتوسطة، والمنشآت الأقل تقييداً من الناحية التمويلية، وتلك الخاضعة للتشريعات البيئية، فضلاً عن الشركات العاملة في قطاعات الصناعات التحويلية، والقطاعات المتوسطة وعالية التكنولوجيا، والأنشطة ذات الكفاءة الطاقوية العالية نسبياً. وعلى صعيد المقارنات الدولية القائمة على مستويات الدخل، تُشير النتائج إلى دور محتمل لسلاسل القيمة العالمية في تعميق التفاوت العالمي في استهلاك الطاقة؛ إذ تبتكر شركات البلدان منخفضة الدخل في كفاءة الطاقة بوتيرة لافتة ولكن بشرط انتمائها لقطاعات موفرة للطاقة بالأساس. كما تبدو الفروق الإقليمية أكثر وضوحاً بين شركات منطقة الشرق الأوسط وشمال أفريقيا(MENA) ، وتحديداً ضمن الشركات الصغيرة والمتوسطة، والمؤسسات الميسورة مالياً، وتلك العاملة في قطاعات متوسطة إلى منخفضة الكثافة التكنولوجية والخاضعة لتنظيمات كفاءة الطاقة. وقد أكدت سلسلة من اختبارات المتانة (Robustness Checks) موثوقية النتائج وصمودها أمام إشكاليات المتغيرات الداخلية (Endogeneity) وتحيزات الاختيار (Selection Bias). وتختتم الورقة بحزمة من التوصيات العملية لواضعي السياسات تهدف إلى تعظيم مكاسب الاندماج في سلاسل القيمة العالمية، وتحسين الأداء البيئي للشركات، بما يدعم جهود الاستدامة على المستوى الكلي.

1. 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. GVCs is a complex web of interactions among firms from different countries, which reshape 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. Participants are allowed to 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). They accordingly unlock productivity and efficiency spillovers, allowing them to take up upgrading approaches for higher value added (Humphrey & Schmitz, 2002; Meng et al., 2020; Gentile et al., 2021; Krishnan et al., 2022).

Relevant research stream identifies 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 upgrading and innovation in new organizational mechanisms, products and processes through complex inter- and intra-firm interaction, international quality-compliance pressures, and peer knowledge and technology transfer (Pietrobelli & Rabellotti, 2010; Eissa & Zaki, 2023b). Fourth, the environmental upgrading by minimizing the environmental footprint of business operations across the value chains. GVC firms can optimize their production system in a way that avoids and/or reduces their pollution and resource use (soil, energy, etc.) (Krishnan et al., 2022). Existing evidence documents the environmental gains associated with businesses' GVC participation, including ecological footprint reduction (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), green innovation (Hu et al., 2021; Meng et al., 2022), and energy efficiency (Agostino et al., 2023; Lee & Wen, 2025).

Despite the drawn environmental benefits of GVC integration, concerns are raised on the extent to which its interlinkages drive higher production scale, and so higher greenhouse gas (GHG) emissions (Cevik & Miryugin, 2022; Meng et al., 2023a, 2023b). Such prompting scrutiny is specifically pressing at energy-intensive production stages, since energy is the principal production and consumption source of heating and lighting, making up for more than 75% of global GHG emissions (International Energy Agency, 2024). Scholars stress that decoupling energy consumption from environmental pollution requires firms to refine their energy mix. Rationing energy consumption is particularly expedited by reducing used materials and increasing resource savings, which materialized through energy efficiency innovation. In principle, energy efficiency 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, this requires 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, the integration in international markets reinforces firms' know-how and technological absorptive expertise and capacity for restructuring their energy-intensive consumption patterns. Exposure to international environmental protection standards and carbon neutrality targets, and eco-friendly best-practices induce them to embed energy-efficient upgrades within their operational processes for environmental competitive advantage (Song & Wang, 2016; Hu et al., 2021; Agostino et al., 2023; Siweres et al., 2024). In other words, GVC participation can serve as a catalyst of energy efficiency innovation by unleashing its activating its underlying drivers (technological development, green technical and managerial awareness, environmental market demand (Garrone et al., 2014; Costa-Campi et al., 2015; Song & Oh, 2015; Clementi & Garofalo, 2023)). However, GVCs can still draw an adverse energy efficiency effect 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). Against this backdrop, we aim to add to the extant research work by empirically unveiling the unexamined impact of enterprises' GVC embedment on propensity of adopting innovative measures for enhancing their energy efficiency.

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' GVC participation and energy innovation related to energy efficiency. This research intends to fill in the gap of four relevant bodies of literature by referring to areas on: (1) GVC embedding and firms' general environmental performance (Siewers et al., 2024). (2) GVC forward and backward participation and embodied carbon emissions in exports and imports (Song & Wang, 2016). (3) 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). (4) GVC embedding and enterprise-level energy efficiency (Agostino et al., 2023; Lee & Wen, 2025). 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 enhanced technological knowledge development and innovation experience. The baseline findings are heterogeneous; they are more evident for SMEs, manufacturing businesses, and financially flexible enterprises and liable firms to energy regulations. One of our most compelling results is that our country-level heterogeneous estimation aligns with the pollution haven hypothesis. The results suggest that 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 lower-income countries. Another salient finding is the particularly strong effect observed in the MENA region compared to other regions. We move beyond the assumption of firm-level uniform effect by further disaggregating the impact across MENA

firms to align GVC exposure with firm and sector-specific readiness. Among MENA firms, 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.

2. Literature review

2.1. GVCs and transfer of knowledge, productivity and technology

Embedding in GVCs alters firms' operational scheme by expanding its access to foreign markets and intensifying their exposure to domestic competition from foreign entrants (Shu & Steinwender, 2019). When developed-economies' lead firms outsource components or intermediate input production to developing-countries suppliers, operational synergies are unfolded through effective interaction, labour movements, and fluid transfer of tacit knowledge and technologies (Hovhannisyan & Keller, 2015; Santacreu-Vasut & Teshima, 2016). In this setting, reciprocal gains are generated 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 and 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 are further agglomerated when they consider the country-sectoral influence of higher connectivity and central positioning within the intermediate trade network.

2.2. GVCs and firm-level innovation

Anchored in economic upgrading from low to high-value added specialisation, existing evidence points to the influence of GVC involvement on firm-level product and process innovation. The positive association is evident 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 these innovative gains: product market competition, knowledge spillovers, and 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 occur as firms leverage the technological value and learning potential of imported intermediate goods to catch up with the technology frontier, thereby activating their learning-by-exporting and triggering innovative behavior (Eissa & Zaki, 2025). Yet, some scholars propose that GVC embedding can bias

the reallocation of technological and know-how spillovers away from developing countries that have a comparative disadvantage in technology production (Aghion et al., 2021; Eissa & Zaki, 2023b; Lee & Wen, 2025). Eissa and Zaki (2023a) show that innovative firms in developing countries possess higher absorptive capacity and operate in low- skilled labor and medium-low technology-intensive activities. Third, the integration in a broader market scale allows domestic firms to garner higher sales revenues and profits, and so more feasibility to undertake R&D activities and innovate to improve their competitiveness in the new markets (Aghion et al., 2021; Geng & Kali, 2021). Lee and Wen (2025) identify GVCs as a key driver to enhance the innovation capabilities of SMEs, in particular, by inducing large-scale production and promoting lower costs of overseas information sharing. 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 systemic constraints, such as economies of scale and financial accessibility (Elshaarawy & Ezzat, 2022; Cowling & Dvouletý, 2023). Other scholars specify the main mediating factors of GVC-induced innovation gains, like 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). But, some firm- or context-specific factors may outweigh this positive innovation impact, such as firm size, where only larger and more productive firms handle the hefty upfront costs and participate in forward GVC linkages (Antràs, 2020; Gentile et al., 2021). There are also the limited local absorptive capacity and low learning effects (Pietrobelli & Rabellotti, 2010; Piermartin & Rubínová, 2014; De Marchi et al., 2018), and financing constraints, especially among firms operating in middle-income countries[3] (Elshaarawy & Ezzat, 2023).

2.3. GVCs and firm-level environmental performance

Although GVC embeddedness provides domestic firms with expanded market access and growth prospects, it simultaneously bears environmental implications due to increased production scale and intensive use of fossil-fuel-based energy (i.e. coal and crude oil, etc.) (Bai & Wu, 2025; Lee & Wen, 2025). A strand of recent studies increasingly examines how 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. The emission-reduction 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). Some scholars thus view 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). It encourages firms to adopt eco-efficiency strategies that translate environmental investments into competitive gains by lowering costs, enhancing resource productivity (i.e. material savings), and improving process yields

[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.

and by-product management (Orsato, 2006). Two dimensions of eco-efficiency are particularly salient: green innovation and energy efficiency. First, GVCs effectively trigger eco-friendly technology innovation, which commonly addresses businesses' environmental pollution through resource-efficient technologies, goods, services and production processes (Porter & Van Der Linde, 1995). Findings show that green innovation is especially promoted among firms subject to regulatory pressures, facing financing constraints, publicly owned enterprises, those operating in pollution- and capital- intensive sectors, and firms locating in developing countries (Meng et al., 2022; Wu et al., 2025). Second, GVC participation catalyzes the adoption of clean energy technologies and sustainable energy management measures. GVCs heterogeneously encourage greener energy aptitude among SMEs and less endowed firms in terms of human capital or financial resources (Agostino et al., 2023; Lee & Wen, 2025). The GVC-environment nexus is typically explained by three mechanisms. 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 increase their R&D and innovation investments in pursuit of cost-effective and energy-efficient technologies (De Marchi et al., 2013; Wu et al., 2024; Lee & Wen, 2025; Huang et al., 2026). Third, compliance with stricter foreign environmental standards across the value chains pushes firms to enhance their green competitiveness by upgrading their production process structure, reducing their carbon intensity, and refining their energy mix (Wang et al., 2022; Bai & Wu, 2024; Siewers et al., 2024).

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

A growing body of research uncovers the heterogeneity in environmental performance of GVC firms across different country income groups, reflecting unequal access to regulatory support, technology, and expertise along value chains. Existing evidence remains inconclusive and provides three different perspectives on how GVC participation disproportionately influences environmental performance of firms originating from 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 countries (Su & Thomson, 2016; Wang et al., 2021a). Accordingly, high-income economies exhibit greater environmental gains in terms of reduced carbon emissions from GVC involvement compared to their middle and low-income counterparts (Chen et al., 2022; Zheng et al., 2024). In contrast, less-developed regions like MENA economies reap environmental sustainability benefits conditional on their engagement in forward value linkages

(Elmassah & Hassanein, 2023). Second, other findings corroborate 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, another research stream examines the linkages between GVC participation, emissions and energy consumption while delving into the effect of country-level GVC positioning. Huang et al. (2022) shows that GVC firms strive to improve their GVC positioning and deepen their embeddedness degree to move from the downstream to the upstream and from the low value-added to the high value-added link of the industry. As firms reposition within GVCs, they are inclined to improve their production efficiency, energy utilization and carbon emission reduction. Yet, these improvements aren't realised if a country is locked in a low GVC-embedding position, namely in pollution-intensive processing and manufacturing industries. This can be due to GVC-induced production growth that results in higher total energy consumption and more carbon emissions. Thus, the relationship between carbon emission intensity and GVC positioning is U-shaped. GVC firms with a shallow degree of participation have limited absorptive capacity for advanced technology and management systems, given their reliance on unskilled labor and basic technology (Cohen & Levinthon, 1989). They are therefore unable either to cope with the intensified competition or to adapt to stricter foreign regulations, which in turn places them in a locked-in position within a carbon-intensive phase with high 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).

2.5. GVC and energy efficiency innovation

Energy efficiency innovation has not been investigated as one of the firm-level eco-strategies that GVC participation can incentivize in pursuit of competitive advantage. To fill in this gap, we scrutinize the relevant literature on enterprise-level energy innovation to set up the theoretical foundation of the potential linkage between energy efficiency innovation and GVC integration. Earlier evidence 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). Following the established propositions on how GVCs can induce product and process innovation, green innovation and higher energy efficiency, similar rationalization and mechanisms can be extended to the case of energy innovation. GVC participation can affect the participants' process management and induce their innovative energy behavior through expansion into broader overseas markets and acquisition of energy-saving knowledge and technology. Yet, these eco-efficient benefits may not occur because of uncertain sustainable competitiveness and the realization of lock-in and technology-path dependence effects with high energy consumption and low added value. So, this study proposes the following hypotheses for empirical testing:

H1: GVC participation increases the firm-level propensity to adopt energy efficiency innovation

H2: GVC participation decreases the firm-level propensity to adopt energy efficiency innovation

H3: GVC participation encourages firms to innovate in their energy efficiency through exposure to broader market scale and learning spillovers.

While GVC participation provides firms with a range of opportunities and spillovers that can be translated into energy innovation, these opportunities are realised depending on firms' initial capabilities and the technological and industrial environment within which it operates. We rely on the heterogeneous-firm perspective to view GVC participation as generating variant energy innovation effect across firms. This particularly aligns with consequences for energy-efficient transition, which commonly requires modifications in technology, capital equipment, and management practices (Agostino et al., 2023; Lee & Wen, 2025). Beyond firm- and industry-specific characteristics, firms may encounter fragmented incentives and constraints for energy efficiency depending on the broader national and regional institutional and development context. On one hand, weaker environmental regulation and specialization in resource-, or energy-intensive stages of production may generate a pollution-haven effect, offsetting innovation incentives in energy savings (Duan et al., 2021). On the other hand, the larger technological and regulatory gap between domestic firms and international lead firms may generate the pollution-halo effect. GVCs can incrementally increase the pressure and scope for energy-efficient upgrading through changes in production processes, technologies and organizational practices undertaken in response to value-chain requirements (Chen et al., 2022; Bai & Wu, 2024).

H4: The effect of GVC participation on firm-level energy efficiency innovation varies with firms' individual characteristics and with the nature of the industries in which they operate.

H5: GVC participation may generate different energy efficiency innovation outcomes across countries and regions

3. Data & methodology

3.1. Data and stylized facts

Our data 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 features a comprehensive green economy module that provides a set of environmental business indicators and green management practices, enabling empirical configurations of firm-level green behavior. We use the most recent available survey spanning the period 2018-2020 for around 28,000 firms[5] in 41 global countries[6]. We construct the main variables of our analysis as follows. First, we follow Dovis and Zaki (2020) in defining the likelihood of firm-level GVC participation based on the business involvement in direct importing and exporting. Second, energy efficiency innovation is measured in line with the proposed definitions of Rennings (2000), Capozza et al. (2021), and Wu (2023), which pertain to the introduction of new process facilities that reduce energy consumption or replace fossil fuel consumption with renewable energy resources. The propensity of enterprises' innovation in energy efficiency depends on business adoption of at least one of the following production process-specific energy measures and upgrades: 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 a potential association between firms' GVC involvement and innovation in proactive energy efficiency measures. Across the sample, most firms are not integrated into GVCs, while energy-innovative firms account for a relatively larger share than those that do not innovate. Taking by the distribution of GVC involvement across energy-innovative and non-innovative firms, GVC firms report higher uptake of energy-efficient upgrades and installations compared to their non-participant counterparts. Around 74% of GVC-integrated firms exhibit energy-efficient innovative practices, yet more than half of non-GVC-integrated firms don't have the tendency to initiate any energy-efficient measures. At the sectoral level, Table 2 indicates that energy innovation is prevalent among GVC firms operating in manufacturing sectors, followed by service and retail industries.

[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.

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.

Notes: First row has row percentages and second row has column percentages. Sample weights are accounted for.

Figure 1. Firm-level energy innovation and GVC

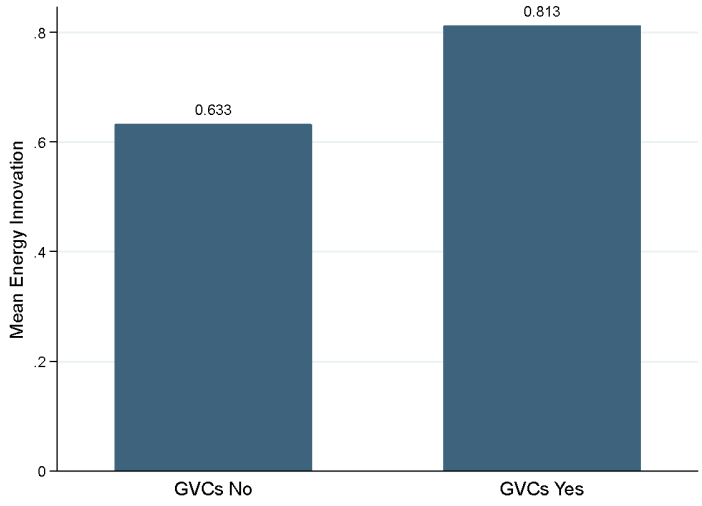


Table 2. Firm-level GVC participation and energy efficiency by industry type

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.

Notes: First row has row percentages, and second row has column percentages Sample weights are accounted for.

On the regional and income-tier dimension, Table 3 shows that surveyed firms in European and high-income countries exhibit the highest energy efficiency innovation shares. More than 90% and 80% of GVC-engaged firms that are energy innovative are operating in either Europe or high-income economies, respectively. Similarly, higher shares of energy-innovative firms are found among firms involved in GVCs compared to domestically oriented enterprises in lower-income groups and less developed regions. Figures 2 and 3 illustrate that, on average, the share of firms that undertake energy-efficient innovation is higher among GVC participants than non-participants, regardless of the

specified country income or regional classification. Interestingly, 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	90.43	8.67	100.00	1.31	89.50	9.08	100.00
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Source: Constructed by the authors using the WBES-BEEPS dataset.

Notes: The first row has row percentages, and the second row has column percentages. Sample weights are accounted for.

Figure 2. Firm-level energy innovation and GVC embedding across income groups

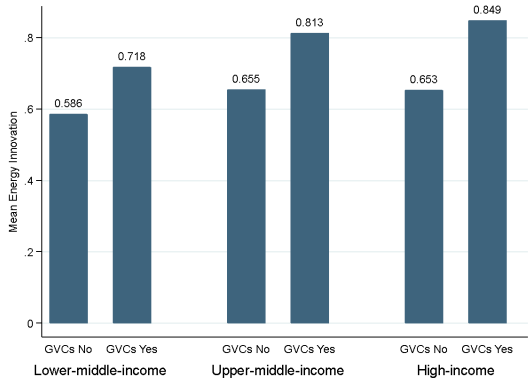
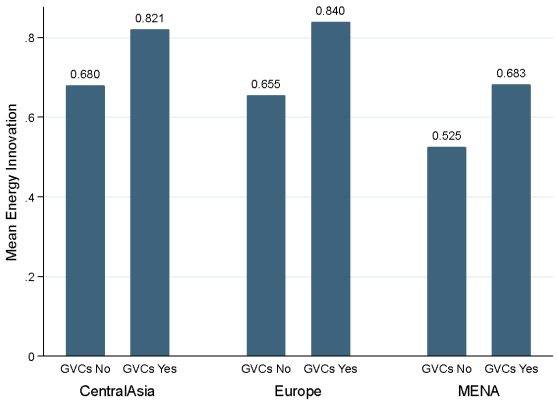


Figure 3. Firm-level energy innovation and GVC embedding across regions



Source: Authors' own elaboration

Notes: Sample weights are used

3.2. Model specification

The impact of firm-level GVC participation on energy innovation is estimated using the following multivariate equation:

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

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 of 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 variable 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). X is the vector of main covariates that is defined in line with prior evidence tackling the determinants of business energy innovation. We account for as many attainable control variables as possible to limit the effect of omission bias, including firms' individual characteristics (size, age, and ownership type) and resources and capabilities (human and financial capital, knowledge development, technological capacity, and organizational management). Table 4 presents the description and measurement of the control variables. γ_s, α_c, and Θ_t stand for industry, country and time dummies, respectively, and ε_{isct} is the error term. Agostino et al., 2018; Zhang et al., 2020; Wang et al., 2021; Zhou et al., 2021; Clementi & Garofalo, 2023).

Table 4. Variable description

Variable	Measurement
Energy innovation	A dummy variable takes a value of 1 if the firm responds (yes) to at least one of the survey questions on energy innovation practices: - Over the last 3 Years, adopt heating and cooling improvements? - Over the last 3 Years, adopt the improvement of lighting systems? - Over the last 3 Years, adopt machinery upgrades? - Over the last 3 Years, adopt upgrades of vehicles, vessels, and aircraft in the fleet? - Over the last 3 Years, adopt more climate-friendly energy generation on-site? - In the last FY, use energy from its own renewable sources?
GVC 1	A binary variable that is equal to 1 if the firm is a two-way trader (directly exports and imports at the same time) (Dovis & Zaki, 2020). The variable considers firms that export (import) a positive share of their sales (inputs and supplies), regardless if they do so directly or indirectly, so as not to disregard firms that indirectly import or export via national intermediaries (Siewers et al., 2024).
GVC 2	A binary variable that is equal to 1 if the firm is a two-way trader and has a positive share of its capital owned by a foreign firm (Dovis & Zaki, 2020).
GVC 3	A binary variable that is equal to 1 if the firm is a two-way trader and has an internationally recognized quality certificate (Dovis & Zaki, 2020).
GVC 4	A binary variable that is equal to 1 if the firm is a two-way trader, has a positive share of its capital owned by a foreign firm, and an internationally recognized quality certificate (Dovis & Zaki, 2020).

Table 4. Variable description (continued)

Variable	Measurement
Firm-level characteristics	
Firm size	Dummy variables for different sizes in line with the World Bank Enterprise Survey classification of small firms with 5 to 19 employees, medium firms 20 to 99, and large firms 100 or more (Wu, 2023).
Firm age	The natural logarithm of the subtracted value of the firm's establishment from the survey year (Du et al., 2022; Song et al., 2022; Clementi & Garofalo, 2023).
Foreign ownership	The percentage owned by private foreign individuals, organizations, and companies (Lee & Wen, 2025)
Business resources and capabilities	
Financial constraint (external financial resources)	A dummy variable that 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 (Fowowe, 2017).
Ln annual sales (internal financial resources)	The natural logarithm of total annual sales over the previous fiscal year (Agostino et al., 2023)
Human capital	A dummy variable hat takes a value of 1 if the firm provides its permanent full-time employees with professional training programs and 0 otherwise (Agostino et al., 2023).
Knowledge development	A dummy variable that takes a value of 1 if the firm spent on either inside/outside R&D or acquired external knowledge (Šūmakaris et al., 2021).
Energy management	A score-based measure of energy auditing, energy monitoring, energy management, energy efficiency enhancement measures, and energy consumption targets in line with Karplus and Grover (2020) approach
External institutional and environmental constraints	
Energy regulation	A dummy variable that takes 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 (Hille et al., 2020; Agostino & Ruberto, 2021; Du et al., 2022)
National institutional quality	A composite measure of national institutional quality based on firm-level governance perceptions of corruption, regulatory quality, and rule of law. We make use of the institutional matters section of the Enterprise Survey to construct the measure, which is composed of three main dimensions: The paper follows Fogel et al. (2006), Chadee and Roxas (2013), and Barasa et al. (2017) in making use of the institutional matters section of the Enterprise Survey to proxy the three sub-dimensions of the measure. - Corruption is measured by firms' reply to two questions: (1) whether firms discern the court system as fair, impartial, and uncorrupted and report their responses using a four-point scale (1 = strongly disagree, 4 = strongly agree). (2) 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). - Rule of law is measured by the degree at which firms regard courts, political instability, crime, theft, and disorder as institutional barriers to their operations. For each element, firms' responses are shown using a five- point scale (0 = not an obstacle, to 4 = very severe obstacle). - Regulatory quality is captured by firms' perceptions of the extent 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). The composite measure is constructed by first standardizing the individual items within each dimension, then computing the country-level measures of corruption, rule of law and regulatory quality by taking the average firm-level scores within each country and finally calculating the value of institutional quality by taking the mean value of the three main pillars for each economy. Due to standardization, scores range between 0 and 1, with higher values indicating above-average institutional quality
Environmental demand	A dummy variable takes a value of 1 if a firm's customers require environmental certifications or adherence to certain environmental standards and 0 otherwise (Wu, 2023).

3.3. Identification strategy

The earlier-specified empirical equation is estimated using probit regression to 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 adopt 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 a 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 check for the relevance of estimating a multivariate probit model by testing the hypothesis that correlation coefficients are jointly equivalent to zero. Prominently, all regressions are run while taking into account the complex nature of survey data by including weights and stratum identifiers.

We acknowledge that the baseline effects can be confounded by endogeneity and selection biases. First, firms' participation in the international fragmentation of production is non-random. GVC integration may be affected by a set of ex-ante factors that are also correlated with the energy innovation outcome, like productivity, human and financial capital management, and others (Del Prete et al., 2017). To tackle this selectivity bias, we employ the propensity score matching (PSM) approach, where the treatment is the likelihood of a firm to participate in GVC, and the outcome is the propensity of taking up energy efficiency innovation. We isolate the main effect by matching GVC participants and non-GVC participants using a set of observable characteristics, 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). Second, Firms' GVC involvement is highly affected by unobservable business factors that in turn can also impact firms' capacity of adopting innovative energy measures. For instance, internationally recognized quality certification, like ISO 14001, guides firms' environmental management structures for governing their 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). Reverse causality may also arise. Firms that are relatively more energy efficient have a higher capacity to integrate into GVCs and be selected by multinationals for their adaptability to labor divisions and capability to comply with the cross-border environmental standards and regulations (Agostino et al., 2023; Aghion et al., 2023; Gao et al., 2024; Paschoaleto & Martínez-Zarzoso, 2024). To address these endogeneity concerns, we opt for an instrumental variable two-stage least squares methodology by instrumenting GVC with the average GVC participation value at the country-sectoral level minus the focal firm's performance[7]. The rationale of the instrument's choice is anchored in the

[7] Notably, we use extended probit regression since the endogenous is bivariate and does not fit the typical IV regressions

fact that firm-level GVC embedding is encouraged by the average GVC participation practices of surrounding firms within same locality and sectoral operation. The exclusion of the focal firm helps avoid the contamination of the instrument by the firm's own GVC participation and individual capacities. It ensures that the instrument captures only the GVC exposure of comparable firms within the same reference group (Agostino et al., 2023; Lee & Wen, 2025). Thus, the instrument is more expected to be correlated with the probability of the focal observation's integration within GVCs and is unlikely to directly impact energy innovation conditional on the included firm-level controls and fixed effects.

The baseline analysis is extended in three ways. First, we examine the change in the baseline effect while adopting a tighter criterion of identifying firms' integration into GVCs. We follow Dovis and Zaki (2020) and estimate separate regressions with three other stricter GVC definitions: firms that simultaneously export and import and also have a positive share of foreign-owned capital (GVC 2), or an internationally recognized quality certification (GVC 3) or that combine two-way trading with foreign ownership and international certified status (GVC 4)[8]. Second, a mechanism analysis is conducted to uncover the mediator factors that explain the baseline effect. Third, sub-sampling regressions are conducted to unveil heterogeneous effects and draw inferences on moderator factors at firm, industry, country, and global region levels.

4. Main results

4.1. Baseline results

Table 5 presents the baseline probit results of estimating equation (1). Column (1) includes GVC estimates while controlling only for country and year fixed effects, whereas the specification in column (2) further includes industry-fixed effects. In both cases, the coefficient of GVC is significant at 5% level with a 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 an even higher magnitude of impact[9]. More specifically, the multivariate probit results show that GVC participation induces businesses to innovate in lighting system improvements, machinery and equipment upgrades, vehicle upgrades, and the use of renewable energy resources[10] (See Appendix B). Across other restrictive definitions of the likelihood of a firm's integration within the global chains, columns (4 - 6) show that GVC participation is associated with a

[8] Descriptive data on the distribution of GVC participation across energy innovation practices shows that the share of GVC participants innovating in energy efficiency is increasing across the whole sample as the GVC identification criteria get stricter (80% for GVC 2, 82% for GVC 3 and 90% for GVC 4,) (See Appendix A)

[9] To a certain extent, these results verify that unobserved heterogeneity at the country-sector level underestimates the true effect of GVC parameter.

[10] Likelihood ratio test strongly rejects the null hypothesis, supporting the appropriateness of applying multivariate probit and confirming the interdependence between energy innovation outcomes

positive energy innovation effect only in the GVC 2 category[11]. These findings support our first hypothesis, that is, GVC participation can drive firm-level adoption of innovative measures for reducing energy intensity. They are also concurrent with prior evidence that GVC participation is effectively conducive to reducing a firm's energy intensity (Meng et al., 2022; Jin et al., 2022; Siewers et al., 2024; Lee & Wen, 2025; Huan et al., 2026). Business integration within the international production chains supports the adoption of innovative production practices that enhance energy productivity and reduce reliance on fossil fuels. GVCs channel sustainable management experience, green action plans, and modern technologies throughout the trading networks. Such novel practices encourage participants to adapt to emerging green production and technological trends and environmental preferences of consumers and leading suppliers (Li et al., 2019; Pahl & Timmer, 2020; Ha & Thanh, 2022; Meng et al., 2022; Bai & Yu, 2024).

Concerning the covariates' impact, they coincide, in most cases, with the theoretical expectation and the reasonability of our model setting. Most of the control variables across all specifications are positively significant at the 1% level. Older firms are more likely to adopt energy innovation (Horbach et al., 2012; Dekker & Hasso, 2016). Knowledge development activities reinforce a firm's absorptive and adaptable capacity, encouraging its energy innovation propensities (Solnørdal & Thyholdt, 2019; Arranz et al., 2021). Installing energy management systems is proactive for resource efficiency, including energy innovation (Rehfeld et al., 2007; Wagner, 2008; 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 financially constrained are highly unlikely to approach any clean investment opportunities (Cruz et al., 2014; Moreno-Mondéjar & Cuerva, 2020), but lucrative firms with high revenues are financially robust to cover the high upfront costs of energy innovation (Berrone et al., 2010; Dekker & Hasso, 2016). As the share of foreign-owned capital increases, firms are more likely to have the productive capacity for green innovation (Kong et al., 2020; Wu, 2023). Finally, businesses are more inclined to alter their energy consumption structure under increased pressure from environmentally-conscious customers (He et al., 2016; He et al., 2018; Andries & Stephan, 2019; Capozza et al., 2021). Surprisingly, firm size, energy regulation and employee training variables reveal no significant effect on energy innovation.

Before delving into further nuanced analyses of the baseline effect, we test for the validity of the main findings to self-selection and endogeneity biases, and extended model specifications. Across all robustness checks, our main conclusions hold regardless of the instrumented GVC variable, re-estimation on matched observations and variations in model specifications (See the results of robustness checks in Appendix C).

[11] The insignificant effect of more strictly defined GVC on energy innovation suggest 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 technologically competent. Yet, we find a substantial effect of GVC 3 and GVC 4 on energy innovation, that is even higher than that reported in the baseline analysis, only among large firms, indicating that energy innovative impact of GVC integration is more reliant on firm-level internal resources and capacities than on specific definition.

Table 5. Baseline results

Variables	(1)	(2)	(3)	(4)	(5)	(6)
GVC	0.0904**	0.0941**	0.139***			
	(-0.0456)	(-0.0421)	(-0.0482)			
GVC 2				0.393*		
				(0.205)		
GVC 3					-0.206	
					(0.130)	
GVC 4						0.277
						(0.294)
Small firm	0.102	0.115	0.129	0.140	0.119	0.139
	(-0.0959)	(-0.101)	(-0.106)	(0.113)	(0.101)	(0.113)
Large firm	-0.062	-0.0903	-0.0982	-0.0642	-0.0938	-0.0607
	(-0.0739)	(-0.0848)	(-0.0936)	(0.0822)	(0.0900)	(0.0815)
Ln age	0.206***	0.217**	0.243***	0.243***	0.244***	0.242**
	(-0.0672)	(-0.0852)	(-0.0911)	(0.0938)	(0.0929)	(0.0941)
Financial constraint	-0.269***	-0.280***	-0.291***	-0.287***	-0.293***	-0.286***
	(-0.0639)	(-0.0519)	(-0.0483)	(0.0482)	(0.0479)	(0.0479)
Ln annual sales	0.0751**	0.0824**	0.0834**	0.0850**	0.0880**	0.0854**
	(-0.0333)	(-0.0391)	(-0.0396)	(0.0401)	(0.0400)	(0.0401)
Knowledge development	0.485***	0.486***	0.465***	0.494***	0.497***	0.495***
	(-0.154)	(-0.161)	(-0.161)	(0.159)	(0.160)	(0.159)
National institutional quality	0.594***	0.578***	0.571***	0.561***	0.595***	0.558***
	(-0.17)	(-0.174)	(-0.175)	(0.186)	(0.187)	(0.184)
Employee training	0.0437	0.061	0.058	0.0474	0.0600	0.0482
	(-0.0727)	(-0.0739)	(-0.0751)	(0.0738)	(0.0750)	(0.0739)
Energy management	2.229***	2.221***	2.194***	2.192***	2.199***	2.192***
	(-0.3)	(-0.306)	(-0.294)	(0.298)	(0.302)	(0.298)
Energy regulation	0.084	0.0674	0.107	0.110	0.106	0.111
	(-0.229)	(-0.232)	(-0.251)	(0.247)	(0.251)	(0.246)
Environmental demand	0.488*	0.513*	0.546*	0.596*	0.552*	0.595*
	(-0.275)	(-0.307)	(-0.313)	(0.326)	(0.307)	(0.326)
Foreign ownership	0.377***	0.379***	0.360***		0.394***	
	(-0.125)	(-0.127)	(-0.127)		(0.138)	
Industry Fixed effect	No	Yes	Yes	Yes	Yes	Yes
Year Fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Country Fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Industry Country Fixed effect	No	No	Yes	Yes	Yes	Yes
Constant	-2.200***	-2.274***	-2.185**	-2.098**	-2.111**	-2.094**
	(-0.683)	(-0.778)	(-0.866)	(0.867)	(0.868)	(0.866)
Observations	22,888	22,888	22,888	23,037	22,888	23,037

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

4.2. Mechanism analysis

Firm-level capacity of energy innovation is determined by its resource use (Lopez et al., 2015), and knowledge and technological absorptive potentialities (Solnørdal & Thyholdt, 2019). Involvement in GVCs can stimulate these drivers through generating market scale and learning effects. GVC firms have lower trade costs to access global factors and end-product markets, broadening their market scale and scope (Shu & Steinwender, 2019; Li et al., 2023). This not only upscales their production and increases their productivity but also facilitates their outreach to upstream and downstream producers

with a lower cost of information sharing per output unit (Gereffi & Lee, 2012). The spillover effect of the overseas transmission of knowledge, production technology and management standards induces them to acquire energy-saving measures and consume less energy-intensive resources. We thereupon uncover the potential mechanisms driving our main estimates by running separate regressions to assess the association between GVCs and mediation outcomes. Since both market scale and learning effects are, at their core, broad in definition, we follow Lee and Wen (2025) in measuring them through stimulated revenue streams, enhanced productivity and technological capabilities. To verify whether the baseline impact takes place through exposure to wider market scale, we consider the natural logarithm of total annual sales and annual sales per employee (Costa-Campi et al., 2015; Wu, 2023) as alternative dependent variables. For proxying the absorption of foreign technologies and technical knowledge, we use a dummy variable coded 1 if the firm has reported any intangible knowledge development and the tangible innovation experience and 0 if it has no relevant experience. That is, if the firm conducts any type of R&D activities, acquires external knowledge, innovates in a new product or new process, or uses a licensed technology from a foreign-owned company (Capozza et al., 2021; Šūmakaris et al., 2021; Eissa & Zaki, 2023).

As shown in columns (1- 3) of Table 6, 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. The magnitude of GVC impact on energy efficiency innovation declined compared to that reported in Table 5, suggesting the partial mediating role of market scale and learning effects, particularly in terms of the induced technological advancements. These outcomes thus imply that GVCs stimulate the key enablers (technological capacity and productivity) of firm-level energy efficiency innovation (Reddy, 1991; Jalo et al., 2021).

Table 6. 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

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

4.3. Heterogeneity analysis

While it has been established that GVC can encourage firms' innovation in energy efficiency, its impact may hinge on enterprise-level resources and capabilities (Šumakaris et al., 2021) and sector- and country-specific patterns of resource integration and production fragmentation (Ayadi et al., 2020; Rigo, 2021). We accordingly run sub-sample estimations across firm-, industry-, country-, and regional levels to examine how GVC participation may differently prompt energy innovation.

4.3.1. Firm heterogeneity

The first source of heterogeneity is firm-level internal aspects and external pressures, such as size, capacity to easily access finance, and subjection to environmental policy instruments. Subsample regressions of financially constrained versus non-constrained firms are presented in columns (1) and (2) of Table 7. GVC significantly infers energy innovation only among non-financially constrained businesses. Conversely, financing constraints hinder energy innovation by limiting firms' resource allocative capacity to leverage overseas knowledge and technology transfer (Elshaarawy & Ezzat, 2022; Moreno-Mondéjar & Cuerva, 2020). Looking at estimates in columns (3) and (4), we observe

that the baseline impact is pronounced among SMEs and turns insignificant for larger enterprises[12]. This can add to the findings of Lee and Wen (2025) that GVC embedding promotes SMEs' energy efficiency. Penetrating international markets exposes SMEs to higher production scales and multinational peers, making it convenient to offset their R&D fixed costs, avert their technology trap (Eissa & Zaki, 2025), and adopt clean energy (Ranasinghe et al., 2024). Columns (5) and (6) depict the heterogeneity in the GVC-energy innovation relationship by environmental regulatory exposure, like performance standards and taxation. GVC significantly encourages energy innovation among both subject and non-subject firms in energy regulations. Yet, 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 GVC integration and mandatory compliance with national environmental regulations can motivate investments in innovative energy savings (Hille et al., 2020; Du et al, 2022).

Table 7. Heterogeneity analysis - firm-level characteristics

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

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

[12] 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 conducted a heterogeneous analysis for the large 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 accordingly seems that large firms solely leverage their economies of scale and their structural network effect as long as they are backed by a resilient doing-business environment and internal sustainable managerial experience.

4.3.2. Industry heterogeneity

The following heterogeneity analysis gauges sectoral differences across types of industry, and the intensity level 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 8, GVCs incur its significant effect for both types of industries, but with a larger effect for manufacturing firms than for other retail and service firms[13]. According to Siewers et al. (2024), the manufacturing sector is arguably more relevant when it comes to exploring the relation between GVC and decarbonizing energy consumption. That is due to the high exposure and vulnerability of the multi-phased nature of the industry, including procurement, production, logistics, sales, and after-sales, to climate transitional and physical risks (Guo et al., 2024). 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[14]. The propensity for innovation in sustainable energy is significant among both technologically heterogeneous groups. Compared to lower technologically intensive industries, high-tech and medium-high manufacturers have a higher GVC coefficient. Our findings extend those reported by Bai and Yu (2024) on the predominant GVC impact on firms' carbon emission reduction among technologically intensive industries by providing further evidence on energy innovation. Higher-tech industries have intensive R&D engagement (Liu et al., 2018a, 2018b), an innovation pipeline and technology absorption capacity (Baldwin & Lopez-Gonzalez, 2014) that enable them to capitalize on GVC spillovers and adopt clean energy technologies. We then run separate regressions on two subsamples of energy-intensive and less energy-intensive industries[15] and display the probit results in columns (5) and (6). While regressing energy efficiency innovation on GVC participation of less energy-intensive businesses generates a positive and significant estimate, 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 capital. However, higher energy-intensive sectors are ultimately pollution-intensive, with substantial dependence on complex technological innovation processes for their green transition, such as green technology R&D and conversion of innovative inputs into green output. These processes differ among firms within energy-intensive sectors based on their green technological capacity (Zhu et al., 2021) and their GVC embedding method, direction and position (Yang et al., 2022) to access and channel the needed cutting-edge know-how for energy transition (Garrone & Mrkajic, 2018).

[13] Notably, the effect is mostly significant among retail sectors.

[14] We use the Eurostat high-tech classification of manufacturing industries based on NACE Rev. 2 3-digit level.

[15] 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).

Table 8. Heterogeneity analysis - industry-level classifications

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

*Notes: 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.*

4.3.3. Income group heterogeneity

We then delve into the heterogeneous baseline estimates across different country-level developmental statuses and present the results in Table 9. The sample is divided into high- and low-income economies using the UN income classification, and separate regressions are tested for subsampled firms from low- and high-income countries. In columns (1) and (2), the positive and significant GVC impact holds 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. This aligns with existing evidence on how exposure to learning-by-doing and technological spillovers can allow developing countries to upgrade their industries and enhance their GVC position, away from backward chain levels (Ivarsson & Alvstam, 2010; De Marchi et al., 2018; Amendolagine et al., 2019). Approaching higher-value segments of GVCs, firms from lower-income countries secure cooperative alliances with master business partners and are induced to match sustainable production modes (Ghisetti & Quatraro, 2017). Environmental management and technological spillovers are thus stimulated via the establishment of local subsidiaries, engagement with expatriates, and compliance with environmental standards. Such an international realm may exert greater pressure on firms in low-

income countries to mitigate their environmental footprint and pursue eco-friendly process upgrades (Ha & Thanh, 2022). It is then possible that they are more likely to shift to more innovative measures to minimize their energy consumption and meet the cross-border environmental requirements (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 examine the differential impact in energy-intensive and less energy-intensive countries across both income groups. Columns (3-6) show that GVC can increase the propensity of firms' energy innovation among higher-income firms, regardless of the intensity of their operational industry energy consumption. On the contrary, firms from lower-income countries innovate in their energy intensity only if they are classified as part of a relatively energy-efficient industry. In other terms, firms operating in energy-intensive sectors don't exhibit any green innovation gains from their GVC participation. This is consistent with the pollution haven hypothesis and its firm-level adaptation of the pollution offshoring hypothesis (Cherniwchan et al., 2017; Forslid et al., 2018). 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 is likely to trap energy-intensive enterprises from low-income countries on the periphery of the GVC, where they heavily rely on the comparative advantages of abundant energy factors (Huang et al., 2022; Yang et al., 2022). So, the gap between peripheral and core countries' technologies can be enlarged, inhibiting the energy-saving technology and knowledge overflow (Yang et al., 2022). Putting it differently, the technological progress of low-income businesses can be biased towards more energy-intensive production through the path dependency effect (Huang et al., 2022; Yang et al., 2022). On the opposite side of the chain, more developed industries master their upward position with forward production segments (Koopman et al., 2010; Wang et al., 2013), and enabling scope for higher energy efficiency (Jin et al., 2022; Yang et al., 2022). Our results, therefore, indicate that the locked-in effect of production in high energy consumption and low value-added links can catalyze energy security inequality and unequal sharing of energy costs in GVCs (Li et al., 2021; Huang et al., 2022; Ji et al., 2022) through unequal energy innovation opportunities.

According to Bartley (2010) and Tsoi (2010), a lack of robust sanctions and regulations further demotivates technology adoption by less competitive GVC firms. Enterprises essentially need to be compelled by the domestic environmental regulatory policies to alter the direction of their technology application. Upon this, we extend the country-level heterogeneity analysis to explore whether the adverse GVC effect on energy-intensive low-income firms can be mitigated conditional on the existence of local energy regulations (Noailly & Smeets, 2015; Wu et al., 2024). Interestingly, columns (7) and (8) support the view that firms from lower-income countries that participate in GVC and are simultaneously required to pay energy taxes and adhere to energy performance standards are encouraged to innovate in their energy consumption reduction.

Table 9. Heterogenous analysis – country-level developmental status and sectoral structure

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

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

4.3.4. Region heterogeneity

Our last differential analysis focuses on untangling the effect of GVC participation on energy innovation within global regions. In Table 10, we split firms according to whether they are based in Europe, MENA, or 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 context-specific dynamics that warrant further moderation examination.

Table 10. Heterogeneous analysis- regional classifications

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

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

4.3.5 MENA region heterogeneity

MENA countries are known for their unsatisfactory 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 and 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., 2017; Ayadi et al., 2020). Broadening GVC linkages of MENA firms enhances 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 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 (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

enabler of improving environmental competitive advantage and 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 decarbonization (Yu et al., 2016; Elkebti & Khalifa, 2025). This is due to the region's grappling with structural and economic challenges of 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 (Usman & Hammar, 2021; Ghanem & Alamri, 2023; Baffour Gyau et al., 2024; Elkebti & Khalifa, 2025). Amid this setting, we extend the existing firm-level GVC participation evidence to gauge the extent to which it can help cushion the regional impediments to green energy transition.

In Table 11, we probe into the dynamics between GVCs and energy innovation in MENA by decomposing the effect across firm-level attributes. The significant positive impact of GVC participation is more apparent among SMEs, non-financially constrained firms and businesses operating under energy regulatory pressure. This pattern suggests the tandem relevance of internal capacities and external pressures in enabling firms to capitalize on their GVC exposure for energy innovation gains. Restraints to accessing 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 GVCs. They can have the needed 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 can guide firms to structure their proactive environmental management systems, nurture their technological innovation capacity (investment in R&D), and strengthen their productive and adaptive capacity (Ayouni & Zouiri, 2024; Hazem & Zaki, 2025). Exposure to domestic and global environmental standards may make 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.

Table 11. 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

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

Table 12 is dedicated to sectoral-level segregation across MENA firms. The positive impact is mostly evident among enterprises in retail, energy-efficient, and low-technological-intensity sectors. This is consistent with the region's structural realities from three perspectives. 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). Their technological gap may trigger their catch-up in environmental upgrading to meet foreign partners' sustainability requirements through know-how transfers, high-quality inputs, and machinery importing. Second, activities that are intensively reliant on sophisticated technologies are relatively 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).

Third, energy-intensive sectors may encounter diminishing returns to efficiency, where they need substantial technological and financial spillovers to invest in less energy-intensive processes. As long as their GVC positioning lacks meaningful engagement with environmental know-how and innovation peer practices, they are pressured to scale up their production with higher net emissions (Del Prete et al., 2017). As such, our results indicate that MENA firms operating in high-emission-intensive sectors are structurally locked into peripheral segments of GVCs, limiting their chances of accessing cleaner technologies.

Table 12. 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

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

5. 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 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 firm-level energy innovation. Using the latest firm-level WB-EBRD BEEPS dataset from 41 global countries, our findings depict that GVC embedding draws a positive and 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 heterogeneous, 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, firms operating in medium-high and high-tech industries, energy-efficient sectors, and in low-income countries are the most benefited from GVC integration in terms of deploying innovative energy-saving measures. On the 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.

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 salient regulatory frameworks with readiness mechanisms to facilitate firms' GVC embedding, specifically in the context of lower-income countries. First, public agencies need to improve their trading policies and reduce trade barriers (tariffs and non-tariff ones) to support firms' embeddedness in GVCs. 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. Enforceable environmental regulations compel process-level decarbonization transition, specifically among carbon-intensive industries. Regulatory scheme could also embrace the development of voluntary carbon markets to reallocate the use of proceeds of sold carbon credits towards the development of energy-saving technologies and the replacement of decarbonisation costs. Third, governments need to provide incentives for firms to replace obsolete and energy-intensive capital with cleaner machinery and energy-efficient production systems. Policy instruments and industrial-support programs may include targeted tax incentives, accelerated depreciation for green capital investments, and subsidies for technology upgrading and retrofitting. Fourth, regulators need to support firms' GVC embedding by providing private sector players with technical and financial incentives for adopting green technologies and environmental management systems. Fifth, governmental entities in developing countries should work on enhancing businesses' competitiveness by mandating the alignment of their environmental management with international quality standards to ensure compliance for accessing foreign markets. For instance, a firm-level measure, report and verification (MRV) system is highly imperative and globally required for green procurement screenings. Sixth, it is imperative to encourage SMEs' access to different financing services with low cost of capital. This could also be coupled with the provision of crafted public financial incentives (i.e. tax credits, exemptions, etc.) to encourage SMEs' green R&D investments in energy-related fields. Finally, governments at the global and regional levels must collaborate for the

development of green partnerships, like the ongoing cooperation between the European Union and Southern Mediterranean countries and the established platforms for green dialogue and knowledge exchange.

Based on our prominent regional results among MENA economies, MENA need to cushion the structural barriers to trade and foreign direct investment (FDI) by streamlining administrative anti-corruption and anti-discriminatory mechanisms, enforcing property rights, and enhancing transport and logistics. Since GVC firms that are liable to energy regulation are more likely to improve their energy efficiency, it is also crucial for governments to strengthen and harmonize the stringency of environmental regulations and energy-efficiency standards. The regulatory alignment helps mitigate the lock-in effect that constrains firms' environmental upgrading, especially those operating in energy-intensive and low-technological-intensity sectors. It is also crucial to facilitate businesses' access to finance, especially green financing for SMEs and energy-intensive industries. These can embed guidelines and manuals for expanding dedicated green credit lines, partial credit-guarantee and risk-sharing schemes, and concessional and blended-finance facilities to address the high upfront costs associated with energy-efficiency investments and the adoption of low-carbon technologies. Public agencies may also need to develop environmental absorptive capacity across businesses to assimilate and adapt to imported and more advanced green technologies. In this context, investment in green human capital through on-the-job training focused on green technologies and energy management practices may also be a required enabler for extracting the positive environmental externalities of businesses' GVC participation. At the regional level, the governments should collaborate on establishing regional innovation hubs and promote industrial cluster-based knowledge diffusion. These hubs would serve as platforms for knowledge sharing and collective learning on energy-saving practices that are compatible with the regional context. Additionally, establishing regional voluntary carbon markets could facilitate the trading of carbon credits, generate stable revenues, and support firms' adoption of green practices and energy-efficient technologies. Finally, MENA governments should leverage their neighborhood with EU countries and their environmental programs. Aligning MENA green practices with those of the EU would help them unlock greater potential to deepen their GVC integration and upgrade their positioning towards higher-value and more environmentally sustainable 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 alternatively focus on physical energy consumption units, rather than energy expenditure for measurement. Other measures of energy efficiency can be evaluated, such as the total factor energy efficiency that accounts not only for energy sources but also all production inputs.

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Appendix

Appendix A: Descriptive statistics

Table 13. Cross frequencies share of firm-level GVC participation and energy efficiency

Energy	GVC Strict1			GVC Strict2			GVC Strictest		
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
Notes: 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: Multivariate probit results

Table 14. Multivariate probit estimation of GVC impact on individual energy innovation types

Variables	(1) Lightening system improvement	(2) Heating and cooling system improvement	(3) Machinery upgrades	(4) Vehicle upgrades	(5) Energy saving onsite generation	(6) 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

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

Appendix C: Robustness checks

1. Addressing endogeneity concerns

We verify the exogeneity of the baseline results by using an instrumental variable approach where GVC is instrumented by leaving- one-out average measure. Instrumentation results show that GVC still retains its significant positive effect on businesses' propensity to innovate in their energy efficiency at the 1% level. In Table 15, GVC coefficients exhibit a higher impact compared to baseline results, indicating the underestimated GVC effect due to endogeneity bias. Thus, the robustness of the paper's main story is reinforced.

Table 15. Instrumental variable estimates

Variables	(1)
GVC	0.113**
	(0.0510)
Small firm	0.108
	(0.0956)
Large firm	-0.0777
	(0.0788)
Ln age	0.248***
	(0.0934)
Financial constraint	-0.317***
	(0.0478)
Ln annual sales	0.0871**
	(0.0431)
Knowledge development	0.477***
	(0.128)
National institutional quality	0.529***
	(0.176)
Employee training	0.0526
	(0.0680)
Foreign ownership	0.398***
	(0.142)
Energy management	2.201***
	(0.299)
Energy regulation	0.0556
	(0.256)
Environmental demand	0.630*
	(0.359)
Constant	-2.079**
	(0.901)
Year Fixed Effect	Yes
Industry Country Fixed Effect	Yes
Observations	22,572

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

2. Addressing selection bias

We correct for the potential selection bias and run PSM using the specified vector of selection variables to eliminate the GVC confounding effect by firm pre-existing disparities. We conduct 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. To ensure the results' robustness to matching methods, 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 eliminates confounding bias (see Tables 16-19). As such, the established estimates are robust to self-selection biasedness.

Table 16. 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 17. 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 18. PSM results- 5 nearest neighboring 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 19. 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

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

3. Adding more Covariates

For more reliable estimates, 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[16] (Stephenson et al., 2015; Arranz et al., 2019), natural logarithm of country-level fossil fuel subsidy in USD[17] (Yang et al., 2022), percentage of a firm's shares owned by the same family[18] (Agostino et al., 2023), informal competition (Wu, 2023), and good management practices (Delera et al., 2022). Table 20 presents the outcome of expanding the baseline model specification. Across all specifications, GVC still reveals a positive and significant impact with similar coefficients to what was previously elucidated in the baseline analysis. Hence, the main conclusions hold regardless of variations in either model or variable specifications.

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

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

[18] 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).

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

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

Appendix D: 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 E: 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

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