PROBLEMY EKOROZWOJU/ PROBLEMS OF SUSTAINABLE DEVELOPMENT

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Green Jobs in the Energy Transition among the Eight Largest Economies: Assessing Employment Quality in Renewable Energy Supply Chains

Zielone miejsca pracy w transformacji energetycznej wśród ośmiu największych gospodarek: ocena jakości zatrudnienia w łańcuchach dostaw energii odnawialnej

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Abstract

The global transition toward renewable energy has intensified not only efforts to mitigate climate change and enhance energy security but also expectations regarding the creation of decent and high-quality green jobs. While existing studies largely focus on the quantity of green employment, limited attention has been paid to job quality and how major global shocks reshape green labour markets. This study examines the determinants of green job penetration and green job quality across the eight largest global economies, Brazil, China, France, Germany, India, Japan, Spain, and the United States, over the period 2013–2023. Drawing on structural transformation, energy security, and regulatory theories, the analysis evaluates the roles of renewable energy investment, regulatory quality, energy import dependence, and global supply chain pressure, while explicitly accounting for the COVID-19 pandemic and the Russia–Ukraine conflict. Using a combination of Panel-Corrected Standard Errors, Driscoll–Kraay fixed effects, and bias-corrected dynamic panel estimators, the study further decomposes outcomes into pre-COVID (2013–2019), COVID shock (2020–2021), and post-COVID recovery (2022–2023) periods. The findings reveal a clear trade-off between green job penetration and green job quality. Renewable energy investment generally increases green job intensity but, in the post-COVID period, is associated with weaker job quality, suggesting that recovery programmes prioritised speed and scale over employment conditions. Regulatory quality and energy import dependence enhance green job quality but tend to constrain job penetration. Global supply chain pressure stimulates green job creation before COVID-19 but weakens both penetration and quality after the pandemic. Overall, the results underscore the need for integrated energy, labour, and industrial policies that balance employment expansion with decent work standards, thereby advancing SDGs 7, 8, 9, and 13 in the post-pandemic green transition.

Key words: green jobs, job quality, renewable investment, energy imports, sustainable development

Streszczenie

Globalna transformacja w kierunku energii odnawialnej zintensyfikowała nie tylko działania na rzecz łagodzenia zmian klimatu i poprawy bezpieczeństwa energetycznego, ale także zwiększyła oczekiwania dotyczące tworzenia godziwych i wysokiej jakości zielonych miejsc pracy. Istniejące badania koncentrują się głównie na liczbie miejsc pracy w sektorze zielonej energii, niewiele uwagi poświęcono jednak jakości miejsc pracy i temu, jak poważne globalne wstrząsy wpływają na kształt rynków zielonej pracy. W niniejszym artykule przeanalizowano czynniki determinujące zielone miejsca pracy i ich jakość w ośmiu największych gospodarkach świata: Brazylii, Chinach, Francji, Niemczech, Indiach, Japonii, Hiszpanii i Stanach Zjednoczonych, w latach 2013–2023. Opierając się na teoriach transformacji strukturalnej, bezpieczeństwa energetycznego i regulacji, oceniono rolę inwestycji w energię odnawialną, jakości regulacji, zależności od importu energii oraz presji globalnego łańcucha dostaw, jednocześnie wyraźnie uwzględniając pandemię COVID-19 i konflikt rosyjsko-ukraiński. Wykorzystując kombinację błędów standardowych skorygowanych metodą panelową, efektów stałych Driscolla-Kraaya oraz dynamicznych estymatorów panelowych skorygowanych o błędy, badanie dodatkowo rozkłada wyniki na okresy sprzed pandemii COVID-19 (2013–2019), szoku COVID-19 (2020–2021) i odbudowy po pandemii COVID-19 (2022–2023). Wyniki ujawniają wyraźny kompromis między penetracją zielonych miejsc pracy a ich jakością. Inwestycje w energię odnawialną generalnie zwiększają intensywność zielonych miejsc pracy, ale w okresie po pandemii COVID-19 wiążą się z niższą jakością miejsc pracy, co sugeruje, że programy odbudowy priorytetowo traktowały szybkość i skalę ponad warunkami zatrudnienia. Jakość regulacji i zależność od importu energii poprawiają jakość zielonych miejsc pracy, ale zazwyczaj ograniczają penetrację rynku pracy. Presja globalnego łańcucha dostaw stymuluje tworzenie zielonych miejsc pracy przed pandemią COVID-19, ale osłabia zarówno penetrację rynku pracy, jak i jakość po pandemii. Ogólnie rzecz biorąc, wyniki podkreślają potrzebę zintegrowanej polityki energetycznej, pracowniczej i przemysłowej, która zrównoważy wzrost zatrudnienia z godnymi standardami pracy, przyczyniając się tym samym do realizacji Celów Zrównoważonego Rozwoju nr 7, 8, 9 i 13 w ramach zielonej transformacji po pandemii.

Słowa kluczowe: zielone miejsca pracy, jakość pracy, inwestycje w odnawialne źródła energii, import energii, rozwój zrównoważony

1. Introduction

In a quest to mitigate climate change, enhance energy security, promote economic resilience and decarbonize energy sectors, the world is rapidly transitioning away from fossil fuel-based energy systems to renewables such as solar, wind, hydro and biofuels. The over-reliance on traditional energy sources, particularly fossil fuels for households and industrial uses, has overwhelmed the global greenhouse, leading to catastrophic climate change and global warming necessitating global efforts to combat the problem.

Renewable energy transition remains one the important strategies adopted by the Intergovernmental Panel on Climate Change (IPCC) to limit global warming to 1.5°C, a target set by the Paris Agreement (IPCC, 2022). Sustainable Development Goals (SDGs) remain the current and most comprehensive global framework designed to harmonize and fast-track countries' efforts to decarbonize energy sector and transition to renewables. For instance, SDG 13-Climate Action enjoins countries to urgently combat climate change and its attendant consequences. SDG-7 Affordable and Clean Energy urges countries increase the share of renewable energy in their energy mix. The global commitment to renewable energy transition has reached an unprecedented level of 582 GW capacity in 2024 (International Renewable Energy Agency (IRENA), 2025).

Renewable energy transition is also observed to be creating huge job opportunities, better known as green jobs, for people across the world. The direct green job opportunities can be created from building, installing, and maintaining renewable energy facilities including solar farms, wind turbines, and bioenergy plants, for they require a large workforce to man them. The transition can also create green job opportunities indirectly as a result of labor demand arising from the complex supply chains for components of renewable energy technologies. Expansion in the green manufacturing activities creates additional jobs in factories and logistics.

The transition also spurs demand for research, development, and innovation in new energy technologies, storage, and smart grids. This leads to employment in high-skill sectors such as engineering, software development, and environmental consulting. IRENA (2024) estimates green jobs at 16.2 million in 2023, up from 8.5 million in 2013 with solar photovoltaic contributing largely to the jobs. China has the largest number of green jobs (7.4 million), followed by the European Union (EU) (1.8 million), Brazil 1.6 million, and the United States and India each having slightly above 1 million jobs in 2023.

In view of the global commitment to the energy transition and the subsequent employment creation potentials of renewable energy, this current study seeks to explore how investments in renewables, regulatory quality, energy import dependence and global supply chain pressure to drive the penetration of green jobs across top eight green employers. Given that SDG 8-Decent Work and Economic Growth seek to create adequate decent jobs, better compensation, and protection of labor rights, and promote safe and secure working environments for all workers, this current study takes a step further to examine how the above factors determine green job quality.

United Nations Economic Commission for Europe (UNECE) (2015) contends that employment is central to most people's lives, and job quality is a key factor in their overall well-being. Thus, securing and maintaining employment is essential for sustaining one's livelihood; however, the quality of that employment is equally important. This means job quality is about having a good balance of fair pay, safe and reasonable work conditions, job stability, social benefits, meaningful tasks, and respect for worker rights (International Labor Organization (ILO), 2020).

Finally, the study decomposes the analysis of green job penetration and green job quality into pre-COVID, COVID shock and COVID recovery periods. This study focuses on the eight largest global economies, Brazil, China, France, Germany, India, Japan, Spain, and the United States, because they collectively account for the highest concentration of renewable-energy–related employment and represent the world's dominant economic blocs. This modification aligns with the reviewer's recommendation to explicitly emphasize the role of large economies rather than *top green-employing countries*, ensuring both economic relevance and international comparability.

2. Literature review

The main theoretical channel through which investments in renewables create job opportunities is structural transformation as hypothesized by Lewis (1954). Reallocation of resources to renewable industries promotes green industrialization by transforming the economy from low-productivity sectors (fossil fuels) to high-productivity sectors (renewables). This transformation leads to the creation of new employment opportunities while demanding higher skills and better working conditions. Thus, the investment does not only create green job opportunities but also fosters quality of the jobs. Energy-security theory is deployed to connect energy-import dependence to green job penetration and green job quality.

Recent studies have broadened sustainability and employment debates by linking energy transition, digitalisation, institutional quality, green finance, behavioural change, and labour-market outcomes. Ma and Bennett (2024) examine perceived graduate employability from sufficiency and necessity perspectives, showing that employment outcomes depend on the presence of key enabling conditions. This is relevant to green jobs because renewable-energy employment requires not only investment but also skills, institutional support, and labour-market readiness. Duan (2025) further emphasises the need to balance energy, environment, and sustainable development, supporting the argument that the energy transition should generate both environmental gains and decent employment outcomes.

In energy systems research, Meng et al. (2024) analyse benefit allocation in regional integrated energy systems with multiple stakeholders, showing that fairness and coordination are central to sustainable energy outcomes. This supports the present study's focus on how regulatory quality and energy governance shape green job penetration and quality. Similarly, Ji et al. (2026) show that technology, organisation, environment, and human factors influence autonomous driving adoption for new energy vehicles, suggesting that green transitions are not purely technological but also depend on organisational capacity and human readiness.

Labour-market and industrial transformation studies also provide useful insights. Liang and Zhang (2024) find a two-way employment-driving effect between manufacturing and producer services in China, indicating that industrial restructuring can generate employment spillovers across related sectors. This supports the argument that renewable energy supply chains can create both direct and indirect green jobs. Zhang, Boonsub, and Shen (2025) show that green human resource management and green supply chain management improve sustainable organisational performance, reinforcing the importance of organisational practices in improving the quality of green jobs.

Behavioural and decision-making studies further enrich the discussion. Sun et al. (2025) demonstrate that changing users' attachment to the status quo is important for encouraging new decision-making patterns. This is relevant because the adoption of green technologies, renewable energy systems, and sustainable work practices often requires behavioural change from firms, workers, and consumers. Wu, Zhang, and Fang (2025) also show that shareholder activism affects firms' innovation focus, implying that governance pressure can redirect firms toward sustainability-oriented innovation.

Recent work on digital transformation and green finance also supports the present study. Hu et al. (2026) examine urban green technology transfer networks and green finance development in China, showing that technology diffusion and green finance are mutually reinforcing. Gao, Yuan, and Liu (2026) find that digital transformation supports value co-creation in state-owned manufacturing enterprises, while Hu, Ai, and Wang (2026) show that supply chain digitalisation promotes technological innovation among new energy vehicle enterprises. These studies suggest that digitalisation can strengthen renewable energy value chains, improve innovation capacity, and indirectly support green employment.

Other studies highlight broader socio-economic and welfare dimensions of sustainability. Ma, Utaberta, and Zainordin (2025) examine online-to-offline attractiveness in urban tourism areas and show that emotional fulfilment influences place-based development outcomes. Jiang and Yuan (2026) find that China's e-CNY pilot promotes consumption upgrading, suggesting that digital financial innovation can reshape consumption and development patterns. Lu and Yoon (2026) show that cultural–tourism integration improves livelihood and well-being in China's Yellow River Basin, reinforcing the point that sustainable development must be evaluated not only through economic or environmental indicators but also through welfare outcomes.

Metcalf (2014) posits that energy security is about ensuring the continuous, reliable, and affordable availability of energy to meet the needs of all economic agents. The vulnerability of energy-import dependent countries to external shocks motivates them to build a resilient and high-value renewable industry. The efforts may not stop at just establishing the industry but also creating decent, stable, attractive compensations and good standards for the green jobs. The motive for quality enhancement is to attract highly talented workforce to the industry.

Regulation can promote the creation of green jobs especially the process of business registration and licensing is made easier for the prospective green firms. However, strict environmental and labour market standards can deter the prospective firms from entering renewable industry. This could be due regulatory capture as propounded by Laffont and Tirole (1993). Regulatory capture arises when the regulatory agencies that are intended to control and regulate business firms end up being controlled by them. This means regulatory quality could foster or deter green job creation but it can principally spur green job quality improvement through formulation and implementation of environmental and labour market regulations that are friendly to the workforce. Following global value chain theory, this study any disruptions in green technology supply chain can cause delays and cost increment, which may reduce green job penetration. Another perspective is that if the disruption is on the fossil fuel supply chain, then the disruptions may motivate countries to also build their resilient renewable industry.

From empirical point of view, there is burgeoning studies on green job creation. For example, Yi (2012) utilized two-stage probit regression to analyse the effect of state and local clean energy and climate policies on green employment in U.S. metropolitan areas (MSAs) in 2006. The study established that the clean energy policy led to 1% increase in the green jobs. Similarly, Woods, Kang and Lowder (2023) apply meta-regression to examine the effect of clean policies on green job growth among the American states. It was established that renewable portfolio standards and public benefit fund raises green jobs.

In Germany, Lehr, Lutz and Edler (2012) assessed the effects of investments in renewable technologies and found that all the investments have positive net employment effect. Focusing on BRICS, Ma and Wang (2025), while employing ARDL and dynamic ARDL, discovered that renewable energy significantly caused green job creation across the economies in both short and long runs. Based on data of more than 3,900 Spanish municipalities over 13 years, Fabra et al. (2023) also established that investments in renewables, especially solar technology, foster green jobs. Aldieri et al. (2021), using 1985-2011 data for OECD countries, found that higher supply of green energies increased employment and the effect is mediated by the quality of institutions.

In terms of green job quality, Huang and Cheng (2023) explored the impact of environmental regulations on rural migrants' job quality based on 2016–2018 China Migrants Dynamic Survey. Findings from the study indicated that environmental regulation significantly improves the job quality of rural migrant workers. Wu et al. (2022) also found that China's Clean Air Action significantly spurred the job quality of migrant workers in China. Antonucci, Seo and Strobl (2024) also investigated the impact of welfare state interventions job quality in Europe from the mid-1990s to the last 2021 COVID crisis. The study found that both active and passive labour market policies significantly improved most of the dimensions of job quality.

Recent studies emphasize the multidimensional drivers of sustainable development, energy transition, and environmental performance. Evidence shows that renewable energy, innovation, and human capital significantly advance decarbonization and green growth (Amin et al., 2025).

Digital infrastructure, entrepreneurship, and climate finance enhance sustainable energy systems and address the energy trilemma (Du et al., 2025; Imandojemu et al., 2026). While GHRM and climate risk mitigation strengthen environmental performance (Sahan et al., 2025; Wei et al., 2025; Mohamed et al., 2024; Osabohien et al., 2026a).

Evident from the empirical reviews, there are many studies on determinants of green job creation and the number of studies is rising rapidly. The studies established the key determinants of green job creation include investments in renewables, policies and regulation. Thus, the studies fell short of examining the effects of energy-import dependence or energy security and global supply chain pressure despite the importance of the factors in motivating the countries to transition to renewable energy. Another serious gap is the absence or paucity of studies on green job quality. The available studies focused on general job quality without being specific to green jobs. This current study fills the gaps by examining all these factors and constructing job quality index. Another contribution of the current study is the decomposition of the analysis into pre-COVID, COVID shock and COVID recovery periods.

3. Data and methodology

3.1. Theoretical underpinnings and empirical model

This study is underpinned within structural transformation, regulatory and energy security frameworks. While structural transformation posits that renewable investments and global supply chain disruption transforms an economy from traditional energy (fossil) economy to modern energy (renewables) economy, thereby creating green jobs and improve the job quality. Regulatory theory postulates how friendly or complicated regulations improve or lower green job creation and green job quality. Energy security framework highlights how vulnerability to external shocks motivate countries to build a strong and resilient renewable industry. Equations (1) and (2) are the baseline models for equitable energy access and energy justice respectively:

$$GJP_{it} = \beta_0 + \beta_1 REI_{it} + \beta_2 REQ_{it} + \beta_3 EID_{it} + \beta_4 GSC_{it} + \beta_m CONV_{it} + \mu_{it} \quad (1)$$

$$GJQ_{it} = \delta_0 + \delta_1 REI_{it} + \delta_2 REQ_{it} + \delta_3 EID_{it} + \delta_3 GSC_{it} + \delta_m CONV_{it} + \varepsilon_{it} \quad (2)$$

Where t denotes the time (year), i represents cross-sectional unit (country) and μ_{it} and ε_{it} stand for the error terms in the equations. The dependent variable, GJP_{it} signifies green job penetration, representing number of green jobs relative countries' population. GJQ_{it} is the green job quality index. REG_{it} is a score of regulatory quality; EID_{it} represents energy import dependence; GSC_{it} is an index of global supply chain pressure. CON_{it} is a vector of control variables (real GDP per capita, trade openness, foreign direct investments, mean years of schooling, financial development). Many country-level factors are included as control variables to account for their potential influence on the green job creation and green job quality. For example, real GDP per capita indicates the available resources for investment in energy infrastructures.

3.2. Data, measurements and estimation techniques

This study explores a panel of top 8 green employers: Brazil, China, France, Germany, India, Japan, Spain and the US., using data from International Renewable Energy Agency (IRENA), World Development Indicators (WDI), Worldwide Governance Indicators (WGI), International labor organization (ILO), Heritage Foundation's Economic Freedom Index Database (HFE), New York Federal Reserve (NFR) and database for the Sustainable Development Report (SDR) compiled and constructed by Sachs, Lafortune and Fuller (2024). And the dataset covers the period from 2013 to 2023. The countries included in this study were selected due to their relatively large number of green jobs and availability of data for the years to be analysed.

The selection of the study period (2013–2023) is motivated by the outbreak of the COVID-19 pandemic, which permits a structured decomposition of the analysis into pre-COVID-19 (2013–2018), COVID-19 shock (2019–2021), and post-COVID-19 recovery (2022–2023) phases. This temporal disaggregation allows the study to capture heterogeneous labour-market and energy-transition dynamics associated with the pandemic and subsequent recovery.

To empirically examine the determinants of green job penetration and green job quality across countries, the study adopts multiple econometric strategies tailored to the data structure of each period. For the full sample (2013–2023) and the pre-COVID-19 period (2013–2018), Panel-Corrected Standard Errors (PCSE) estimators are employed to address heteroskedasticity, contemporaneous correlation, and serial correlation in panels with a relatively long time dimension.

Table 1. Variables, Measurement, Data Sources, and SDG Linkages, source: World Bank's WDI and WGI, SDR, NFR, ILO and HFE

Variable	Measurement	Source	Related SDG(s)
Green Job Penetration	Jobs in renewable sectors per 10,000 population	IRENA, WDI	SDG 8, SDG 9, SDG 13
Green Job Quality Index	PCA[1] of wages, labor rights, labor freedom, job stability	IRENA, ILO, HFE, SDR	SDG 8
Renewable Energy Investment	Renewable electricity output (% of total)	WDI	SDG 7, SDG 13
Regulatory Quality	Governance effectiveness (rescaled 0–10)	WGI	SDG 16
Energy Import Dependence	Energy imports (% of GDP)	WDI	SDG 7, SDG 9
Global Supply Chain Pressure	GSCPI	NFR	SDG 9, SDG 12
Trade Openness	Trade (% of GDP)	WDI	SDG 17
Domestic Credit	Credit to private sector (% GDP)	WDI	SDG 8, SDG 9
FDI	Net inflows (% GDP)	WDI	SDG 8, SDG 17
Mean Years of Schooling	Average years of education	SDR	SDG 4

Given the short time span of the pandemic and recovery phases, fixed-effects regressions with Driscoll–Kraay standard errors are applied to the COVID-19 shock (2019–2021) and post-COVID-19 recovery (2022–2023) periods for the green job penetration models, allowing for cross-sectional dependence and autocorrelation. For green job quality, which exhibits strong persistence over time, the linear dynamic panel bias-corrected (LDPBC) estimator is employed for the COVID-19 shock and post-COVID-19 recovery periods, ensuring consistent estimation in short panels with dynamic effects.

Beck and Katz's (1995) PCSE is designed for panel data, in which there are more time periods than units (T>N), which fits the structure of our dataset (8 countries observed annually over 10 years). The PCSE approach addresses

[1] We used principal component analysis (PCA) to construct green job quality index. Four variables (green job penetration, annual weekly labor earnings per hour, labor freedom index, and protection of labor rights and safety) are used in constructing the index. These variables are used to reflect job security (labor rights and safety), fair pay (annual weekly labor earnings), greenness of the job (green job penetration) and stability of the jobs (labor freedom index

three key econometric challenges often encountered in comparative political economy and international development studies: Panel heteroscedasticity, contemporaneous correlation and autocorrelation.
The COVID-19 shock period (2019–2021) and the post-COVID-19 recovery period (2022–2023) together form a relatively short panel, rendering the Panel-Corrected Standard Errors (PCSE) estimator less suitable due to the limited time dimension. Accordingly, this study employs a Fixed Effects (FE) estimator with Driscoll–Kraay standard errors for the green job penetration models during the shock and recovery phases. This approach controls for unobserved, time-invariant country heterogeneity while accounting for heteroskedasticity, serial correlation, and cross-sectional dependence across countries.
Given that the green job quality index exhibits stronger persistence and dynamic adjustment than green job penetration (see Figures 4 and 5), the analysis of green job quality during the COVID-19 shock (2019–2021) and post-COVID-19 recovery (2022–2023) periods relies on a Linear Dynamic Panel Bias-Corrected (LDPBC) estimator, following Kiviet (1995) and Bruno (2005). This estimator corrects for incidental parameter bias in short dynamic panels, enabling consistent estimation of within-country institutional and economic effects in periods characterised by heightened uncertainty and structural disruption. Inference is based on country-clustered standard errors to further account for serial correlation and heteroskedasticity.

4. Results and discussions

This section presents and discusses the empirical findings on the determinants of green job penetration and green job quality across the eight largest economies over the period 2013–2023. The analysis is structured to reflect the heterogeneous impacts of the COVID-19 pandemic by explicitly distinguishing between the pre-COVID-19 period (2013–2019), the COVID-19 shock period (2019–2021), and the post-COVID-19 recovery period (2022–2023).
The section begins with descriptive statistics and stylized facts to highlight cross-country patterns and temporal changes in green employment, job quality, institutional conditions, energy dependence, and global supply chain pressures. This is followed by regression results examining the effects of renewable energy investment, regulatory quality, energy import dependence, and global supply chain disruptions on green job outcomes. The discussion interprets the estimated coefficients in light of structural transformation, energy security, and regulatory theories, while emphasizing differences across pandemic phases. Particular attention is paid to the trade-offs between green job quantity and quality and to the extent to which external shocks reshaped labour-market outcomes during and after the pandemic.

4.1. Summary statistics

Table 2 presents the summary statistics on key variables incorporated in the regression models and the variables used in the construction of green job quality index. On average, green jobs amount to about 1.1 million, but with a large disparity of about 1.5 million jobs. This suggests high inequality in green jobs among countries, which ranges from as low as 81 thousand to nearly 7.4 million. This pattern reflects a significant heterogeneity in renewable industry size and labor absorption capacity. When normalized by population, green job intensity averages 0.03 jobs per 10,000 persons, with a relatively small spread (0.02). This signifies a reasonable penetration of green employment opportunities across economies. The minimum and maximum values (0.003–0.074) reveals that while some countries have begun to scale up green labor markets, others remain at a nascent stage of transition.
In Table 2, renewable energy investments average 19.6%, with substantial cross-country disparity as some countries have as low as 5% while others have as high as 50% as the proportion of renewable energy consumption to total energy consumption. This means diverse commitments to clean energy transitions. Energy imports are estimated at 43.4% of GDP on average while the extreme values range from -13.7% (indicating net exporters) to 95.7%, suggesting divergent levels of energy dependence and vulnerability to global energy price shocks. Table 2 indicates that regulatory quality index has a relatively high mean value of 6.42 (on a 0–10 scale), with medium disparity. This suggests that most sampled countries maintain relatively strong institutional environments conducive to clean energy investment and green job creation. However, the variation (minimum 4.04, maximum 8.61) also points to governance gaps between advanced and emerging economies.The table reveals that the global supply chain pressure index averages slightly positive, which means continuous but manageable disturbances during the study period. This shows substantial temporal and spatial fluctuations in global production disruptions, which might have been triggered by COVID-19 and the Russia–Ukraine conflict. These shocks could affect renewable energy investments and employment stability in green sectors. Foreign direct investment is reasonable (2.04% of GDP) while human capital development shows reasonable attainment (mean of 10.5 years of schooling), though with significant educational disparities across countries. Countries in the sample are generally upper-middle to high income (average per-capita GDP of $28,000). Given that the range values of $1,400-$65,500 highlight wide income disparity among the countries. Trade openness is significant (mean 48.3%) with healthy financial development (domestic credit averaging 119% of GDP).

Table 2a. Summary statistics, source: Authors' computation

	Mean	Standard Dev	Minimum	Maximum
Green Jobs (in thousands)	1084.51	1492.09	81.3	7388
Green Job Intensity (jobs per 10,000)	0.027	0.016	0.003	0.074
Labor Rights Protection	60.007	31.920	0	100
Labor Freedom Index	61.061	15.361	41.2	98.5
Labor Earnings per hour (US$)	18.114	12.607	0.918	39.9
RGDP Per-Capita (US$)	27858.88	18736.32	1399.454	65505.26
Trade Openness	48.26	18.691	23.080	89.064
Domestic Credit (% of GDP)	119.038	51.262	48.794	220.381
Mean Years of Schooling	10.489	2.794	5.495	14.296
FDI (% of GDP)	2.041	1.152	.118162	4.527
Renewable Energy Investments (%)	19.596	12.509	5	50
Energy Imports (% of GDP)	43.398	32.642	-13.681	95.673
Regulatory Quality	6.425	1.548	4.044	8.613
Global Supply Chain Pressure Index	0.456	1.235	-0.674	3.084

Table 2b. Summary statistics- three-period decomposition

Variable	COVID Shock (2019–2021)	post-COVID-19 recovery period (2022–2023)	Pre-COVID (2013–2018)
Green Jobs (in thousands)	1207.3	1607.615	914.124
Green Job Intensity (jobs per 10,000)	0.026	0.033	0.026
Labor Rights Protection	58.375	58.818	60.643
Labor Freedom Index	59.825	60.881	61.466
Labor Earnings per hour (US$)	18.153	18.246	18.071
RGDP Per-Capita (US$)	27980.497	29550.506	27340.815
Trade Openness	46.363	53.368	47.342
Domestic Credit (% of GDP)	127.644	131.462	113.473
Mean Years of Schooling	10.731	10.825	10.324
FDI (% of GDP)	2.26	1.898	2.02
Renewable Energy Investments (%)	21.512	nan	19.048
Energy Imports (% of GDP)	40.208	41.346	44.895
Regulatory Quality	0.724	0.691	0.715
Global Supply Chain Pressure Index	2.37	0.802	-0.189

The summary statistics reported in Table 2b illustrate how green employment outcomes, labour institutions, and key macroeconomic indicators evolved across the pre-COVID period (2013–2018), the COVID shock period (2020–2021), and the post-COVID recovery period (2022–2023). This decomposition provides insight into the resilience of green labour markets and the broader dynamics of the energy transition during a period of unprecedented global disruption.

Green jobs expanded steadily across all three phases, increasing from an average of 914 thousand jobs before COVID-19 to 1,207 thousand during the shock period, and further to 1,608 thousand in the recovery phase. This consistent growth suggests that green sectors were relatively resilient to the pandemic-induced economic downturn and benefited from sustained policy support for renewable energy deployment. The pattern underscores the role of green industries in advancing SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) while supporting employment generation under SDG 8 (Decent Work and Economic Growth).

A similar trend is observed for green job intensity, which rose from 0.026 jobs per 10,000 population pre-COVID to 0.033 in the post-COVID period, indicating gradual structural reallocation toward greener industries. Although modest in magnitude, this upward movement reflects incremental progress toward sustainable industrial transformation, consistent with SDG 9 and SDG 12. In contrast, green job quality, proxied by labour earnings per hour, remained broadly stable across periods, with only a slight improvement during recovery. Labour rights protection and labour freedom declined during the COVID shock and recovered only partially thereafter, reflecting temporary institutional weakening associated with emergency measures and labour market disruptions.

Macroeconomic indicators reveal mild growth in real GDP per capita and expanded trade and credit during the pandemic, reflecting recovery-oriented fiscal and financial responses. Renewable energy investment increased over time, while energy import dependence declined post-COVID, signalling renewed emphasis on domestic energy security. Finally, the Global Supply Chain Pressure Index peaked sharply during COVID before easing, highlighting the importance of resilient and diversified supply chains for sustaining green employment growth.

4.2. Stylized facts

The cross-country comparison of green jobs across the pre-COVID (2013–2019), during-COVID (2020–2021), and post-COVID (2022–2023) periods (Presented in figure 1) reveals significant structural changes in renewable-energy employment among the eight largest economies. The most striking pattern is the dominant role of China, which consistently outperforms all other economies in absolute green job numbers. Green jobs in China rise sharply from the pre-pandemic period to the post-COVID years, reflecting accelerated renewable energy deployment, large-scale manufacturing capacity, and strong industrial policies designed to reinforce domestic energy security. This upward trend supports the study's finding that renewable investments, especially in large emerging economies, expand green job penetration despite supply chain disruptions.

Among the remaining economies, Brazil, India, and the United States display moderate but notable growth in green jobs across the three periods. Brazil's rise aligns with its bioenergy-driven renewable mix, while India's post-COVID increase reflects its solar sector expansion. In the United States, the post-pandemic rebound corresponds with clean-energy stimulus spending and renewed policy commitments. These patterns reinforce the empirical results showing that global shocks such as COVID-19 and the Russia–Ukraine war triggered policy responses that boosted green job creation, even amid broader labor market instability.

For Germany, Japan, France, and Spain, green job levels remain relatively stable with only marginal post-COVID improvements. These advanced economies tend to prioritize job quality and technological sophistication over large-scale labor absorption, which is consistent with the study's evidence that regulatory quality enhances job quality but may constrain job quantity.

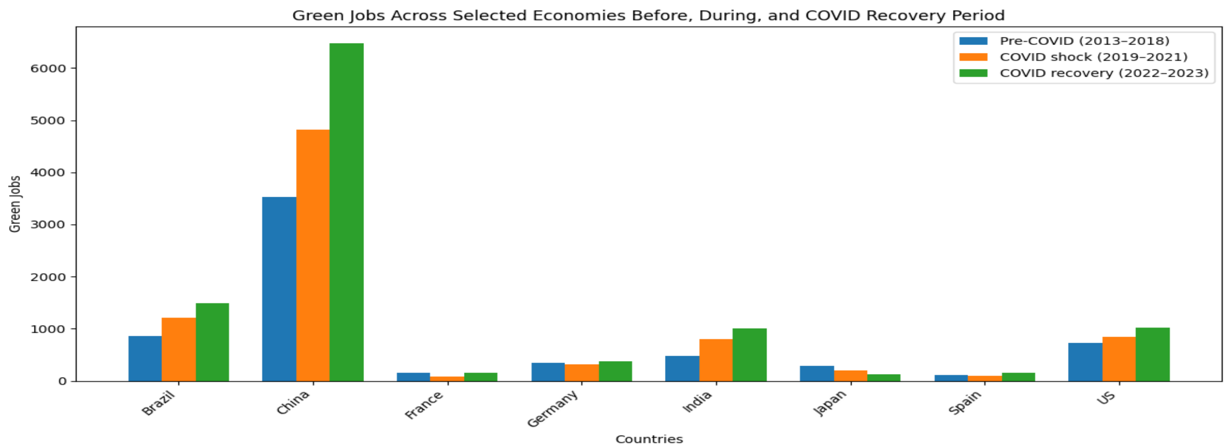

Figure 1. Green jobs across the eight largest economies: pre-COVID, Ddring COVID, and COVID recovery periods

In contrast to Figure 1, which reports absolute green job numbers and therefore reflects country side effects, Figure 2 presents green job intensity, measured as green jobs per million population, to capture the relative penetration of green employment across countries. This population-adjusted measure reveals important differences in how green jobs are distributed across the eight largest economies.

The figure shows that Brazil consistently records the highest green job intensity across all three periods, with a pronounced increase during the COVID shock and a further expansion in the COVID recovery phase. This pattern reflects Brazil's strong labor absorption in bioenergy, hydropower, and biomass-related activities, which are relatively labor intensive. Germany also exhibits persistently high green job intensity, indicating that its ambitious energy transition and industrial decarbonization policies have translated into substantial per-capita green employment gains.

Although China dominates in absolute green job numbers, it ranks at a mid-level in terms of green job intensity due to its large population base. Nevertheless, China shows a clear upward trajectory, particularly during the COVID recovery period, consistent with accelerated renewable energy deployment following supply-chain normalization. France, Spain, and the United States display moderate green job intensity levels, with noticeable improvements during the COVID recovery phase. Spain's steady post-COVID increase aligns with rapid solar photovoltaic expansion, while the U.S. recovery reflects clean-energy stimulus measures and renewed policy support. Japan shows a temporary decline during the COVID shock period and only a partial recovery thereafter, suggesting that technological efficiency gains and automation may have limited labor-intensive green job expansion. By contrast, India consistently records the lowest green job intensity across all periods. While India's renewable energy sector has expanded rapidly, its large population dampens per-capita green employment, highlighting the need for stronger policy coordination to enhance labor absorption alongside clean energy growth.

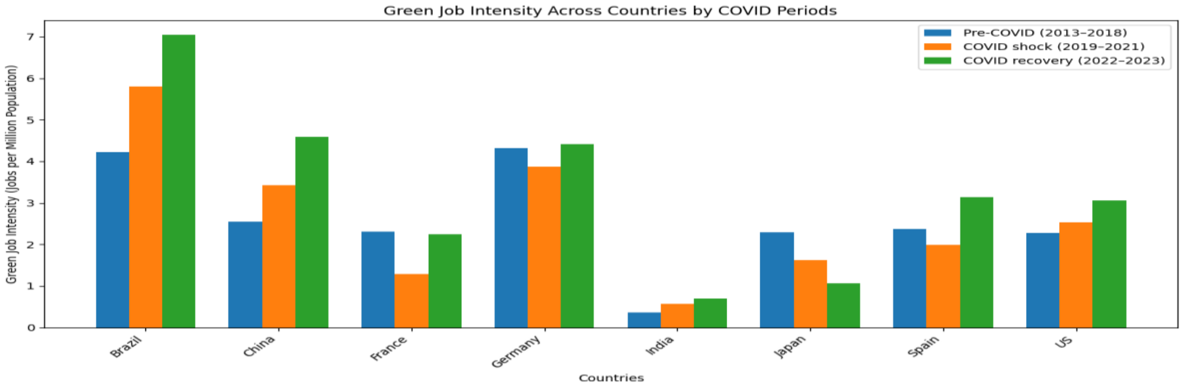

Figure 2. Distribution of green job intensity across the countries

China, despite having the largest absolute number of green jobs, ranks third in intensity, showing that while its total employment base is vast, green jobs still make up a relatively a modest share of the overall labor market. The U.S., Spain, Japan, and France cluster in the middle range, reflecting moderate progress in green workforce development tied to renewable energy, waste management, and clean technology innovation. India ranks the lowest, highlighting the challenge of scaling green employment relative to its very large population base and the persistence of informal and non-green sectors.

Figure 3 compares green job quality across the eight largest economies over the pre-COVID, COVID shock, and post-COVID recovery periods, using labour earnings per hour as a proxy. The figure reveals pronounced cross-country disparities in job quality, reflecting structural differences in labour market institutions, technological intensity, and the maturity of renewable energy value chains. Advanced economies, particularly Germany, the United States, and Japan – consistently exhibit the highest levels of green job quality across all three periods, with average hourly earnings ranging between approximately US$24 and US$39. Notably, job quality in these countries remains relatively stable despite the pandemic-induced shock, suggesting that strong labour regulations, high skill requirements, and well-established worker protection frameworks helped cushion green-sector wages against economic disruptions.

By contrast, other economies display markedly lower earnings, underscoring persistent global inequalities in the quality dimension of green employment. Overall, the observed stability and wage premium in leading economies highlight the role of institutional strength and technological sophistication in sustaining decent work outcomes within green industries. These patterns are consistent with SDG 8 (Decent Work and Economic Growth), particularly Target 8.5, which advocates productive employment and fair remuneration, and they reinforce the importance of embedding labour standards within green transition strategies.

Figure 3 presents the evolution of average labour earnings per hour, used as a proxy for green job quality, across the eight largest economies from 2013 to 2023. The figure indicates relatively stable job quality before the pandemic, a noticeable decline during the COVID shock period (2020–2021), and a gradual but incomplete recovery in the post-COVID phase (2022–2023), highlighting the asymmetric impact of the pandemic on employment quality compared to job creation.

In contrast, China, Brazil, and particularly India exhibits substantially lower levels of green job quality, with India recording average labour earnings of around US$1 per hour across all three periods. These disparities reflect structural characteristics of labour markets in developing economies, including higher informality, lower industrial wage levels, and the dominance of labour-intensive renewable energy segments. Such patterns underscore persistent global inequalities in green transition outcomes and are closely linked to SDG 10 (Reduced Inequalities) and SDG 1 (No Poverty). Addressing these gaps will require targeted policy interventions aimed at improving wage standards in green sectors, strengthening skills development, and enhancing labour protections.

The COVID-19 pandemic appears to have had limited adverse effects on green job quality in most countries, particularly in advanced economies, suggesting that green employment offered a degree of wage resilience during the crisis. This stability supports SDG 9 (Industry, Innovation, and Infrastructure), as sustained job quality reflects robust technological capabilities and institutional frameworks underpinning green industries. Notably, post-COVID improvements in green job quality in countries such as the United States and Germany point to the effectiveness of green stimulus packages, clean-energy investments, and workforce upskilling initiatives implemented during the recovery phase, thereby advancing SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action).

By contrast, developing economies show little or no improvement in green job quality during the COVID recovery period, highlighting a widening global divide in the quality dimension of green employment. These findings reinforce the need for inclusive, skills-oriented, and labour-rights-focused green transition policies, including gender-responsive measures, to ensure that progress toward the Sustainable Development Goals remains equitable and socially sustainable.

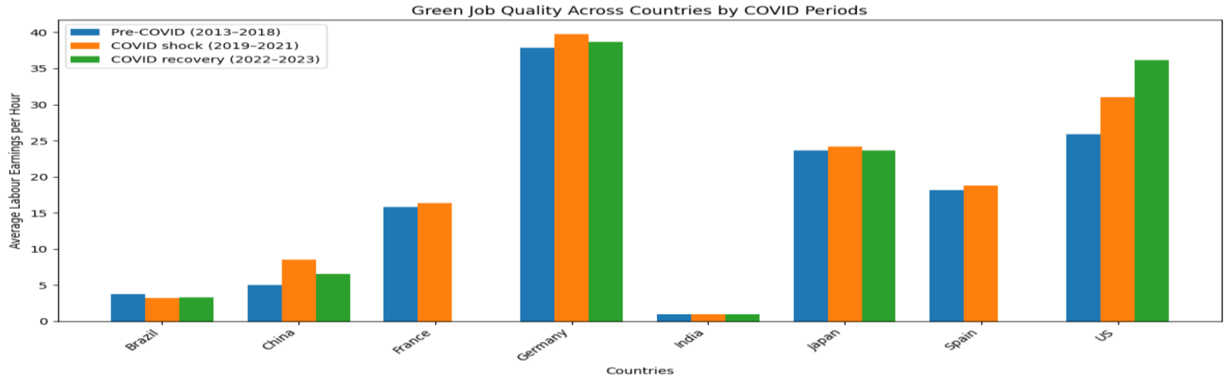

Figure 3. Green job quality by COVID periods

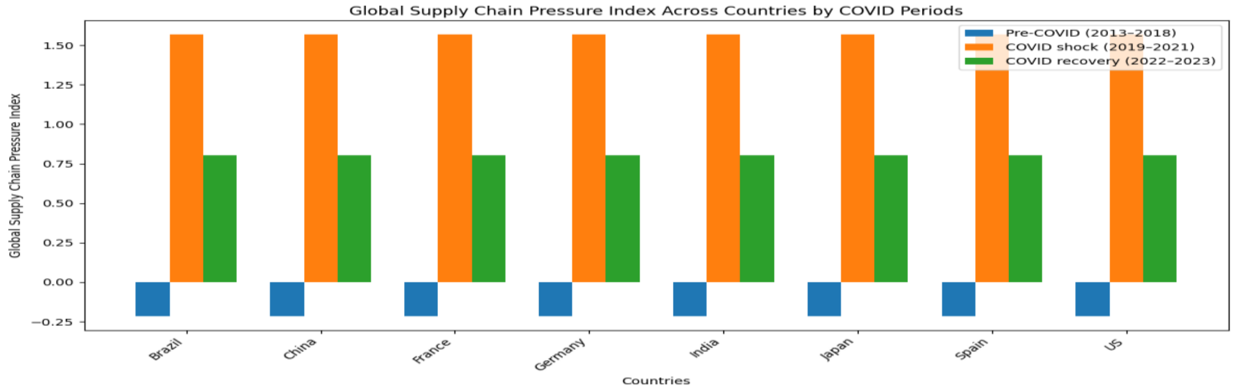

Figure 4. Global Supply Chain Pressure Index

Figure 4 presents the Global Supply Chain Pressure Index (GSCPI) across the eight largest economies during the pre-COVID period (2013–2018), the COVID shock period (2019–2021), and the COVID recovery period (2022–2023). The cross-country comparison reveals a highly synchronized pattern of global supply-chain dynamics, reflecting the systemic and globalised nature of modern production networks.

During the pre-COVID period, all countries exhibit low and slightly negative values of the GSCPI, indicating a global environment characterised by efficient logistics, stable production networks, and relatively low transportation and inventory costs. This phase reflects well-functioning industrial ecosystems and reliable international trade channels, consistent with progress toward SDG 9 (Industry, Innovation and Infrastructure). Stable global supply flows during this period also supported SDG 8 (Decent Work and Economic Growth) by ensuring uninterrupted access to intermediate inputs for labour-intensive and technology-driven sectors, including renewable energy manufacturing.

The onset of the COVID-19 pandemic is associated with a sharp and uniform spike in the GSCPI across all countries, with index values rising to historically high levels during the COVID shock period. This pronounced increase reflects unprecedented global disruptions to industrial production, shipping capacity, port operations, and supply logistics. The near-identical surge across economies confirms that the pandemic constituted a systemic global shock rather than a country-specific disturbance.

Elevated supply-chain pressure during this period disrupted green technology value chains, contributing to delays in the production and deployment of solar panels, wind turbines, and electric-vehicle components. These disruptions temporarily slowed progress toward SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) by constraining access to critical inputs. At the same time, heightened supply bottlenecks increased uncertainty for firms and workers, posing challenges to SDG 8, particularly in sectors dependent on globally integrated supply networks.

During the COVID recovery period, the GSCPI declines substantially across all countries, indicating partial normalization of global supply chains. However, index values remain above pre-COVID levels, suggesting that supply-chain pressures have not fully dissipated. This incomplete recovery reflects ongoing structural adjustments, geopolitical tensions, and energy-market disruptions. The persistence of elevated pressure underscores the importance of building resilient and diversified supply chains, a core requirement of SDG 9, and a necessary condition for sustaining long-term progress toward SDGs 7 and 13 in the global green transition.

4.3 Green job intensity models: pre- and post-COVID analyses

Table 3 reports the Panel-Corrected Standard Errors (PCSE) estimates examining the effects of renewable energy investment, regulatory quality, energy import dependence, global supply chain pressure, and major external shocks, namely the COVID-19 pandemic and the Russia–Ukraine conflict, on green job penetration (green job intensity) across the world's leading green-employing economies. The PCSE framework accounts for heteroskedasticity, contemporaneous correlation, and serial dependence inherent in cross-country panel data, thereby providing robust inference on the structural drivers of green employment intensity.

Table 3. Panel Corrected Standard Errors (PCSE) for green job intensity

Green Job Intensity	**1**	**2**	**3**	**4**	**5**
RGDP Per-cap (ln)	0.014***	0.014***	0.015***	0.014***	0.013***
	(0.003)	(0.002)	(0.003)	(0.002)	(0.003)
Trade Openness	-0.0002*	-0.0003***	-0.0005***	-0.0002***	7.95e-06
	(0.0001)	(6.56e-05)	(9.51e-05)	(6.51e-05)	(8.31e-05)
Domestic credit	-0.0001	-0.0002***	-0.0002***	-0.0002***	-0.0001***
	(7.08e-05)	(2.98e-05)	(3.89e-05)	(2.80e-05)	(3.97e-05)
Mean years of sch.	-0.002*	-0.002**	-0.002**	0.010***	0.012***
	(0.001)	(0.001)	(0.001)	(0.002)	(0.002)
FDI	0.0004	0.0002	0.001	1.97e-05	-0.0002
	(0.001)	(0.001)	(0.002)	(0.001)	(0.001)
Renewable Investment	0.001*				0.0005***
	(0.0003)				(0.0002)
COVID-19 Shocks	0.001	0.004**	0.007***	0.0002	-0.002
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Ukraine-Russia war	0.006**	0.007***	0.006***	0.003**	0.001
	(0.003)	(0.002)	(0.002)	(0.002)	(0.002)
Energy imports		-0.0001***			1.34e-05
		(3.38e-05)			(3.76e-05)
Global Supply Chain Pres.			-0.001		-0.0004
			(0.001)		(0.0008)
Regulatory quality				-0.024***	-0.024***
				(0.002)	(0.003)
Constant	-0.088***	-0.053***	-0.055***	-0.031**	-0.058***
	(0.022)	(0.009)	(0.011)	(0.012)	(0.015)
Year Effect	Yes	Yes	Yes	Yes	Yes
Observations	88	88	88	88	88
R-squared	0.405	0.417	0.369	0.712	0.741
Number of Countries	8	8	8	8	8

Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

The results reported in Table 3 indicate that renewable energy investment exerts a positive and statistically significant effect on green job penetration, at least at the 10% level (columns 1 and 5). This finding suggests that countries with higher investment in renewable energy sectors tend to record greater green job intensity per 10,000 people, reinforcing the employment-generating potential of the energy transition. By contrast, energy import dependence is negative and highly significant at the 1% level (column 2), implying that greater reliance on imported energy constrains domestic green job creation by reducing incentives to develop local renewable industries.

Regulatory quality exhibits a negative and statistically significant association with green job penetration. Although counterintuitive, this result suggests that stricter or more complex regulatory frameworks may raise compliance costs and slow the pace of green-sector expansion, thereby limiting short-term employment growth. With respect to external shocks, global supply chain pressure carries a negative but statistically insignificant coefficient, indicating a limited direct effect on green job intensity within the full sample. In contrast, both the COVID-19 pandemic and the Russia–Ukraine conflict displays positive and statistically significant effects in most specifications (columns 2–3), suggesting that these shocks triggered policy responses—such as green recovery programmes and accelerated energy diversification—that stimulated green employment expansion.

Among the control variables, trade openness is predominantly negative and significant, indicating that economies more deeply integrated into global trade may rely more heavily on imported green technologies rather than domestically generated green employment. Domestic credit also shows a small but negative effect, implying that financial deepening did not systematically translate into support for green sectors, possibly due to the dominance of conventional rather than sustainable financing channels. Mean years of schooling switches from negative to positive and statistically significant in Models (4)–(5), consistent with the view that higher human capital facilitates the development of more advanced and skill-intensive green industries. Economic growth remains positive and significant across specifications, underscoring the role of overall development in supporting green job penetration.

Table 4. Determinants of green job penetration across pre-COVID, COVID shock, and post-COVID recovery periods

	Panel-Corrected Standard Errors: Pre-COVID (2013–2018)				**Driscoll-Kraay Standard Errors: COVID + COVID recovery (2019–2023)**			
Green Job Intensity	1	2	3	4	5	6	7	8
RGDP Per-cap (ln)	0.007**	0.009***	0.013***	0.009***	0.116**	0.128**	0.106**	0.102**
	(0.003)	(0.003)	(0.003)	(0.003)	(0.030)	(0.027)	(0.028)	(0.023)
Trade Openness	0.0001	-0.0002***	-8.58e-05	-0.0003***	-0.0004**	-0.001**	-0.0003**	-0.0003**
	(0.0003)	(7.98e-05)	(6.15e-05)	(9.63e-05)	(0.0001)	(0.0001)	(9.36e-05)	(9.75e-05)
Domestic credit	9.23e-05	-0.0002***	-0.0002***	-0.0002***	-0.0002**	-0.0001*	-0.0001*	-0.0001**
	(0.0002)	(3.13e-05)	(3.90e-05)	(3.33e-05)	(4.70e-05)	(5.10e-05)	(3.93e-05)	(3.52e-05)
Mean years of sch.	0.001	0.0004	0.010***	0.0004	-0.022	-0.020	-0.018	-0.020
	(0.001)	(0.001)	(0.002)	(0.001)	(0.014)	(0.014)	(0.013)	(0.013)
FDI	0.001	0.003*	0.002	0.003**	-0.002**	-0.001*	-0.0005	-0.0003
	(0.002)	(0.002)	(0.001)	(0.001)	(0.0004)	(0.0004)	(0.0002)	(0.001)
Renewable Investment	0.001*				-0.0003**			
	(0.0006)				(5.50e-05)			
Energy imports		-6.53e-05				0.0005		
		(4.02e-05)				(0.0003)		
Regulatory Quality			-0.021***				-0.010*	
			(0.003)				(0.004)	
Global Supply Chain				0.008***				-0.001**
				(0.0003)				(0.0002)
Constant	-0.093***	-0.041***	-0.049***	-0.037***	-0.825***	-0.986***	-0.720**	-0.735***
	(0.034)	(0.013)	(0.012)	(0.013)	(0.139)	(0.116)	(0.133)	(0.082)
Year Effect	Yes	Yes	Yes	Yes	No	No	No	No
Observations	56	56	56	56	32	32	32	32
R-squared	0.463	0.432	0.714	0.419	0.684	0.653	0.675	0.652
Number of Countries	8	8	8	8	8	8	8	8

Note: Due to the short time dimension of the COVID (2020–2021) and post-COVID (2022–2023) periods, these years are jointly estimated using Driscoll–Kraay standard errors to ensure econometric reliability, while interpretation distinguishes shock and recovery dynamics.
Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Table 4 compares how the drivers of green job intensity differ between the pre- and post-COVID-19 periods. The results reveal a structural shift in the factors determining of green employment following the pandemic. Before COVID-19, renewable investment is positive and significant (at 10%), asserting that higher renewable investments spur green job penetration. However, in the peak and recovery models, the investment turns negative and significant at 5%. Across both periods, regulatory quality significantly reduces green job penetration, though the effect is stronger pre-COVID-19 than after the COVID-19. While global supply chain pressure significantly fosters green job penetration before the pandemic; it reduces the penetration after the pandemic. Overall, Before COVID-19, green job intensity was primarily influenced by renewable investments, regulatory quality and global supply chain pressure. After COVID-19, green job penetration is also determined by the same variables but with weaker impact.

4.4. Quality of green jobs models and COVID-19 impact

This subsection examines the determinants of green job quality across the sampled economies, extending the analysis beyond employment quantity to the conditions, stability, and remuneration associated with green jobs. By distinguishing between the pre-COVID-19 period and the pandemic and post-pandemic phases, the section highlights how structural factors, institutional quality, energy market conditions, and external shocks shaped the quality dimension of green employment over time.

Table 5 presents the regression results on the determinants of green job quality index, which is the availability of high-paid, skill-intensive, decent and flexible green jobs.

The analysis presents interesting findings. In columns 4-5 of Table 5, regulatory quality is observed to a positive and significant (at 1%) impact on the job quality index, accentuating that good regulations and enforcement of environmental standards are important in driving green jobs that are decent, stable, and fairly compensated. Similarly, Energy imports wield a positive and significant (at 1%) impact on the quality index, highlighting that dependence on energy importations may motivate economies to diversify towards greener and more efficient domestic energy sources, thereby improving the quality of green jobs. Conversely, COVID-19 pandemic is negative and weakly significant (at 10%) in determining green job quality index. Among the control variables, economic growth and mean years of schooling are positive and significant.

Table 5. Panel Corrected Standard Errors (PCSE) for green job quality

Green Job Quality	**1**	**2**	**3**	**4**	**5**
RGDP Per-cap (ln)	0.504**	0.544**	0.441*	0.520*	0.532*
	(0.253)	(0.263)	(0.262)	(0.291)	(0.299)
Trade Openness	-0.003	-0.007	0.004	-0.005	-0.0131*
	(0.006)	(0.005)	(0.003)	(0.004)	(0.007)
Domestic credit	-0.002	-0.0005	0.002	0.001	-0.002
	(0.003)	(0.001)	(0.002)	(0.002)	(0.003)
Mean years of sch.	0.272***	0.265***	0.298***	-0.090	-0.055
	(0.095)	(0.094)	(0.096)	(0.155)	(0.150)
FDI	-0.120*	-0.092	-0.110	-0.106*	-0.054
	(0.070)	(0.068)	(0.078)	(0.0627)	(0.073)
Renewable Investment	-0.017				-0.012
	(0.014)				(0.011)
COVID-19	-0.250	-0.290*	-0.149	-0.209	0.104
	(0.164)	(0.149)	(0.221)	(0.162)	(0.245)
Ukraine-Russia war	-0.013	0.005	-0.199	0.0716	-0.013
	(0.165)	(0.170)	(0.196)	(0.181)	(0.199)
Energy imports		0.008***			0.004
		(0.002)			(0.003)
Global Supply Chain			-0.079		-0.102
			(0.077)		(0.077)
Regulatory quality				0.719***	0.629***
				(0.175)	(0.175)
Constant	-6.663***	-7.712***	-7.442***	-8.297***	-7.585***
	(1.527)	(1.503)	(1.480)	(1.730)	(1.649)
Year Effect	Yes	Yes	Yes	Yes	Yes
Observations	88	88	88	88	88
R-squared	0.825	0.838	0.823	0.853	0.861
Number of Countries	8	8	8	8	8

Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Table 6. Determinants of green job quality: pre versus post-COVID-19

Panel-Corrected Standard Errors for Pre-COVID					**LSDV Bias-corrected Estimator- During and COVID Recovery Periods**			
Variables	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Quality of Green Job$_{t-1}$					-0.736***	-0.722***	-0.729***	-0.722***
					(0.096)	(0.142)	(0.129)	(0.135)
RGDP Per-cap (ln)	0.114	0.211	0.026	0.219	2.070***	2.266*	1.844*	2.084
	(0.315)	(0.300)	(0.340)	(0.306)	(0.778)	(1.186)	(0.996)	(1.445)
Trade Openness	0.024*	-0.006	-0.006	0.002	-0.007	-0.014	-0.009	-0.011
	(0.014)	(0.005)	(0.005)	(0.003)	(0.011)	(0.018)	(0.013)	(0.018)
Domestic credit	0.013	-0.001	0.002	-0.0004	0.001	0.005**	0.005***	0.005***
	(0.008)	(0.001)	(0.001)	(0.001)	(0.002)	(0.002)	(0.001)	(0.002)
Mean years of sch.	0.429***	0.386***	-0.002	0.388***	0.338	0.648	0.680*	0.662
	(0.116)	(0.107)	(0.170)	(0.111)	(0.399)	(0.411)	(0.407)	(0.440)
FDI	-0.255**	-0.048	-0.068	-0.124*	-0.014*	0.040	0.054**	0.042
	(0.119)	(0.072)	(0.066)	(0.068)	(0.007)	(0.027)	(0.026)	(0.037)
Renewable Investment	0.056*				-0.027***			
	(0.034)				(0.010)			
Energy imports		0.008***				0.007		
		(0.003)				(0.027)		
Regulatory Quality			0.876***				-0.241	
			(0.219)				(0.475)	
Global Supply Chain				-0.980***				0.001
				(0.036)				(0.071)
Constant	-8.314***	-5.556***	-5.259***	-6.085***	-23.41***	-29.74***	-24.44***	-28.00**
	(2.314)	(1.691)	(1.867)	(1.723)	(5.498)	(9.405)	(8.459)	(14.04)
Year effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	56	56	56	56	32	32	32	32
R-squared	0.856	0.861	0.885	0.847				

Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Table 6 decomposes the analysis into pre, shock and recovery periods to observe the pandemic changed the pattern of the relationships. Prior to the pandemic, renewable energy investments significantly enhance green job quality. During and the recovery periods of the pandemic, the investments curtail the quality.
The impact is stronger during and after the pandemic. Similarly, energy imports and regulatory quality are significant in promoting the green job quality before the pandemic. However, the variables turn either not significant or at worse negative during, and pandemic recovery periods. Lastly, global supply shock pressure negatively affects the green job quality pre-COVID but it turns to positive and insignificant recovery period. Thus, renewable investments, energy imports, regulatory quality and global supply shock pressure are the significant determinants of pre-COVID whereas only renewable investments matter for the green job quality during and shock/recovery periods.

4.5. Discussion of the findings and linkages to the Sustainable Development Goals (SDGs)
This section discusses the empirical findings on green job penetration and green job quality across the pre-COVID-19 period (2013–2018), the COVID-19 shock period (2019–2021), and the post-COVID-19 recovery phase (2022–2023), with explicit reference to the Sustainable Development Goals (SDGs). The results reveal strong temporal heterogeneity in the drivers of green employment and highlight important trade-offs between clean energy expansion, industrial resilience, and decent work outcomes.

4.5.1. Pre-COVID period (2013–2018): synergies and trade-offs across SDGs
In the pre-COVID period, renewable energy investment plays a decisive role in expanding green job penetration and improving job quality. Higher investment in renewable technologies stimulates labour demand through direct channels – such as manufacturing, installation, operation, and maintenance – as well as indirect channels along renewable energy value chains. These outcomes support SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), while simultaneously advancing SDG 8 (Decent Work and Economic Growth) through employment creation. The findings are consistent with structural transformation theory (Lewis, 1954) and corroborate empirical evidence from Germany, Spain, and BRICS economies, which documents positive net employment effects of renewable energy investments (Lehr et al., 2012; Fabra et al., 2023; Ma & Wang, 2025).
Global supply chain pressure significantly fosters green job penetration during this period, reflecting strong global demand for renewable energy technologies and the rapid scaling of green manufacturing and logistics. This expansion aligns with SDG 9 (Industry, Innovation and Infrastructure) and SDG 12 (Responsible Consumption and Production). However, the negative association between supply chain pressure and green job quality suggests that rapid industrial expansion may have occurred at the expense of wage growth, employment stability, and labour protections. Similar concerns about quantity–quality trade-offs in green employment have been noted in OECD economies (Aldieri et al., 2021) and European labour markets (Antonucci et al., 2024).
Regulatory quality and energy import dependence display a dual effect before COVID-19. While both variables constrain green job penetration—likely due to compliance costs and regulatory stringency – they significantly enhance green job quality. Strong regulatory institutions facilitate the enforcement of labour standards, workplace safety, and contractual protections, directly advancing SDG 8 (UNECE, 2015; ILO, 2020). From an energy-security perspective, energy-import-dependent economies appear to prioritise the development of high-value domestic renewable industries to reduce vulnerability to external shocks, offering better wages and working conditions to attract skilled labour (Metcalf, 2014; Meckling et al., 2015). This pattern underscores the inherent trade-off between green job quantity and quality during periods of stable economic conditions.

4.5.2. COVID shock period (2019–2021): employment stabilisation amid institutional strain
The COVID-19 shock constitutes a major structural break in green labour-market dynamics. Although renewable energy investment continues during this period, its effectiveness in improving green job quality weakens markedly. Pandemic-related disruptions—such as lockdowns, labour mobility constraints, and supply chain breakdowns—delayed project implementation and reduced job security, particularly in construction- and manufacturing-intensive green sectors (ILO, 2021; IEA, 2023).
Despite these disruptions, green job penetration increases during the COVID shock period. This countercyclical outcome reflects the adoption of green recovery strategies, whereby governments deployed renewable energy investments as instruments for economic stabilisation and employment support (UNEP, 2021). These measures helped sustain progress toward SDG 7 and SDG 13, while partially cushioning labour markets in line with SDG 8. However, the emphasis on rapid deployment and cost efficiency appears to have prioritised employment quantity over quality, leading to stagnant wages and weaker labour protections – an outcome consistent with ILO (2022) warnings regarding post-crisis job precarity.
Global supply chain pressure during the pandemic significantly undermines both green job penetration and quality. Severe disruptions in the availability of critical renewable energy inputs – such as solar panels, wind components, and batteries – limited firms' capacity to expand employment and maintain favourable working conditions (IEA, 2023). These disruptions weakened progress toward SDG 9 and SDG 12, exposing vulnerabilities in globally integrated green production networks.

4.5.3. Post-COVID recovery period (2022–2023): accelerated transition with uneven labour outcomes

In the post-COVID recovery phase, renewable energy investment regains prominence as a driver of green job penetration, reinforcing SDG 7 and SDG 13, particularly as countries accelerated renewable deployment in response to energy security concerns following the Russia–Ukraine conflict (Bastos et al., 2024). However, the persistent negative effect of renewable investment on green job quality suggests that recovery programmes largely prioritised project scale, speed, and energy independence over employment conditions.

Regulatory quality and energy import dependence lose their pre-COVID significance in shaping green job quality during the recovery period. This weakening effect may reflect fiscal constraints, policy fatigue, and the reorientation of regulatory priorities toward stabilising energy markets rather than strengthening labour standards. Similar post-crisis institutional trade-offs have been observed in European labour markets, where employment recovery outpaced improvements in job quality (Antonucci et al., 2024).

Global supply chain pressure continues to exert a dampening effect on green job penetration in the recovery phase, indicating that lingering logistics bottlenecks and geopolitical uncertainty constrained labour-intensive expansion in renewable sectors. As a result, progress toward SDG 9 and SDG 12 remained incomplete, despite sustained momentum in clean energy deployment.

Taken together, the findings reveal a persistent tension between advancing clean energy and climate objectives (SDGs 7 and 13) and ensuring decent, high-quality employment (SDG 8). Before COVID-19, structural and institutional factors supported both green job quantity and quality, albeit unevenly. During the pandemic, emergency green recovery policies sustained employment but weakened job quality. In the post-COVID period, continued investment and energy-security concerns maintained green job growth, yet employment conditions remained fragile.

These dynamics underscore the importance of policy coherence across energy, labour, and industrial domains. Strengthening labour institutions, promoting skills development, and embedding employment standards into renewable energy strategies are essential to ensure that progress toward SDG 9 and SDG 12 complements, rather than undermines, decent work outcomes. Ultimately, achieving a socially inclusive green transition requires aligning climate action with labour-market resilience, thereby ensuring that the pursuit of net-zero pathways delivers both employment growth and high-quality jobs.

5. Conclusions and policy implications

Escalating carbon emissions and other greenhouse gases, together with their adverse consequences for climate stability and global warming, have intensified the shift toward renewable energy systems in both advanced and newly industrialising economies. While climate mitigation remains the primary motivation for this transition, the generation of green employment has increasingly emerged as a central co-benefit. Consistent with International Labour Organization (ILO) standards, green jobs are expected to be decent, stable, adequately remunerated, and flexible, thereby contributing directly to Sustainable Development Goal (SDG) 8 on decent work and economic growth.

Against this backdrop, the present study examines how renewable energy investment, energy import dependence, regulatory quality, and global supply chain pressures – alongside major external shocks such as the COVID-19 pandemic and the Russia–Ukraine conflict – shape green job penetration and green job quality across the eight largest green-employing economies (Brazil, China, France, Germany, India, Japan, Spain, and the United States) over the period 2013–2023. To capture temporal heterogeneity, the analysis is further decomposed into pre-COVID, COVID shock, and post-COVID recovery phases.

A key finding of the study is the dual and contrasting role of regulatory quality. While stronger regulatory frameworks tend to slow the expansion of green job penetration by increasing compliance costs and procedural complexity, they significantly enhance green job quality by promoting job stability, skill intensity, adequate compensation, and labour protections. This result highlights a fundamental policy trade-off between expanding the quantity of green jobs and safeguarding their quality. Equally important is the role of energy security. Higher energy import dependence is found to constrain green job penetration while simultaneously improving job quality, suggesting that exposure to external energy shocks encourages countries to develop high-value domestic renewable industries that offer superior employment conditions to attract skilled labour.

The study also finds that major external shocks have asymmetric effects on green labour markets. Both the COVID-19 pandemic and the Russia–Ukraine conflict is associated with increased green job penetration, reflecting policy responses that accelerated renewable deployment to support economic recovery and energy security. However, the COVID-19 pandemic significantly eroded green job quality, indicating that emergency recovery measures prioritised employment quantity and project scale over working conditions.

Further insights emerge from the temporal decomposition of the analysis. Prior to the pandemic, renewable investment, regulatory quality, and energy import dependence jointly supported both green job quantity and quality. In contrast, during the post-pandemic recovery, renewable investment remains a significant driver of green job penetration but exerts a negative effect on job quality, suggesting that rapid green recovery programmes emphasised speed and scale at the expense of employment standards. In addition, global supply chain pressure is found to stimulate green job creation before COVID-19, consistent with rising global demand for green technologies, but becomes detrimental in the post-COVID period as persistent bottlenecks and geopolitical tensions constrain labour-intensive expansion.

Overall, the findings indicate that the transition to a net-zero economy entails not only a transformation of energy systems but also a profound restructuring of labour markets. Policymakers therefore face a dual challenge: expanding green employment opportunities while ensuring that these jobs are decent, secure, and well compensated. Addressing this challenge requires coherent and integrated energy, trade, and labour-market policies that strengthen domestic renewable capacity, promote equitable labour standards, and enhance regulatory effectiveness without stifling innovation.

Such policy pathways are essential for advancing SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), SDG 9 (Industry, Innovation and Infrastructure), and SDG 13 (Climate Action) in the post-pandemic global economy. In particular, crisis-resilient employment standards should be embedded within green recovery frameworks to ensure that expansions in renewable energy projects do not undermine labour protection, wage adequacy, or skills development. More broadly, ongoing policy reforms in the sampled economies should recalibrate renewable investment strategies, energy security objectives, regulatory design, and global supply chain resilience to support a socially inclusive and sustainable green transition.

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References

1. ALDIERI L., BARRA C., RUGGIERO N., VINCI C.P., 2021, Green energies, employment, and institutional quality: Some evidence for the OECD, *Sustainability*, 13(6): 3252, https://doi.org/10.3390/su13063252.
2. AMIN A., YUSOFF N.Y.B.M., ISIK C., OSABOHIEN R., 2025, Decarbonizing the US economy: The roles of renewable energy, technology innovation, human capital, and green growth, *Clean Technologies and Environmental Policy*, 27(11): 7395–7415, https://doi.org/10.1007/s10098-025-03283-w.
3. ANTONUCCI L., SEO H., STROBL M., 2024, Quantity over quality? How economic factors and welfare state interventions affected job insecurity and job quality before, during and after the economic crises, *Social Policy & Administration*, 58(2): 277–298.
4. BASTOS P., GREENSPON J., STAPLETON K., TAGLIONI D., 2024, Did the 2022 global energy crisis accelerate the diffusion of low-carbon technologies? *World Bank*.
5. BRUNO G.S., 2005, Estimation and inference in dynamic unbalanced panel-data models with a small number of individuals, *The Stata Journal*, 5(4): 473–500.
6. DU Z.H., OSABOHIEN R., ARIYIBI M.E., ONYESOM M., 2025, Energy intensity, digital infrastructure and sustainable development in the OECD, *Applied Ecology & Environmental Research*, 23(4), https://doi.org/10.15666/aeer/2304_74577483.
7. DUAN N., 2025, The quest for balance: The journey of energy, environment and sustainable development, *Energy & Environmental Sustainability*, 1(1): 100001, https://doi.org/10.1016/j.eesus.2024.12.001.
8. FABRA N., GUTIÉRREZ E., LACUESTA A., RAMOS R., 2023, Do Working Papers 2307, *Banco de España*.
9. GAO K., YUAN Y., LIU T., 2026, Digital transformation and value co-creation in state-owned manufacturing enterprises: A hypernetwork perspective, *Business Process Management Journal*, 1–25, https://doi.org/10.1108/BPMJ-10-2025-1659.
10. HUANG Z., CHENG X., 2023, Environmental regulation and rural migrant workers' job quality: Evidence from China migrants dynamic surveys, *Economic Analysis and Policy*, 78: 845–858.
11. HU F., YANG H., WEI S., ZHOU H., CHEN Y., HU H., 2026, Urban green technology transfer networks and green finance development: Evidence from the Yangtze River Delta, China, *Pacific-Basin Finance Journal*, 96: 103055, https://doi.org/10.1016/j.pacfin.2026.103055.
12. HU J., AI X., WANG J., 2026, The impact of supply chain digitalization on the technological innovation of new energy vehicle enterprises: The moderated mediation effect, *Business Process Management Journal*, 1–24, https://doi.org/10.1108/BPMJ-10-2025-1657.
13. IMANDOJEMU K., SHOWUNMI O.L., OROLE F., ELUYELA F.D., MUSIBAU H., OSABOHIEN R., 2026, Probing the energy trilemma pillars: Do innovation pathways deliver cleaner and more equitable energy systems? *Sustainable Development*, https://doi.org/10.1002/sd.71116.
14. INTERNATIONAL ENERGY AGENCY (IEA), 2023, *Energy Employment Review 2023*, https://www.iea.org/reports/world-energy-employment-2023.
15. INTERNATIONAL LABOR ORGANIZATION (ILO), 2020, *Measuring Job Quality: Difficult but Necessary*, https://ilostat.ilo.org/measuring-job-quality-difficult-but-necessary/.

16. INTERNATIONAL LABOR ORGANIZATION (ILO), 2021, *World Employment and Social Outlook: Trends 2021*, https://www.ilo.org/sites/default/files/wcmsp5/groups/public/%40dgreports/%40dcomm/%40publ/documents/publication/wcms_795453.pdf.
17. INTERNATIONAL RENEWABLE ENERGY AGENCY (IRENA), 2025, World breaks renewable records but must move faster to hit 2030 tripling goal, https://www.irena.org/News/pressreleases/2025/Oct/World-Breaks-Renewable-Records-but-Must-Move-Faster-to-Hit-2030-Tripling-Goal.
18. JI T., WANG S., WANG J., ZHANG J., 2026, Beyond technology: Role of technology-organization-environment-human factors in autonomous driving adoption for new energy vehicles, *Journal of Retailing and Consumer Services*, 88: 104552, https://doi.org/10.1016/j.jretconser.2025.104552.
19. JIANG S., YUAN X., 2026, Does the e-CNY pilot boost consumption upgrading? Evidence from China's city-level quasi-experiment, *Applied Economics Letters*, 1–5, https://doi.org/10.1080/13504851.2026.2634858.
20. KIVIET J.F., 1995, On bias, inconsistency, and efficiency of various estimators in dynamic panel data models, *Journal of Econometrics*, 68(1): 53–78.
21. LAFFONT J.J., TIROLE J., 1993, *A Theory of Incentives in Procurement and Regulation*, MIT Press.
22. LEHR U., LUTZ C., EDLER D., 2012, Green jobs? Economic impacts of renewable energy in Germany, *Energy Policy*, 47: 358–364.
23. LEWIS W.A., 1954, Economic development with unlimited supplies of labour, *The Manchester School*, XXII(2): 139–191.
24. LIANG Y., ZHANG C., 2024, Two-way employment-driving effect of manufacturing and producer services: Evidence from China, *International Journal of Population Studies*, 10(2): 78–89, https://doi.org/10.36922/ijps.0316.
25. LU F., YOON S.J., 2026, Cultural–tourism integration and people's livelihood and well-being in China's Yellow River Basin: Dynamic panel evidence and spatial spillovers (2011–2023), *Sustainability*, 18(2): 1006, https://doi.org/10.3390/su18021006.
26. MA B., WANG A., 2025, Exploring the role of renewable energy in green job creation and sustainable economic development: An empirical approach, *Energy Strategy Reviews*, 58: 101642.
27. MA X., UTABERTA N., ZAINORDIN N., 2025, From online to offline attractiveness: Investigating urban tourist area appeal and tourist emotional fulfillment, *Current Issues in Tourism*, 1–21, https://doi.org/10.1080/13683500. 2025. 575930.
28. MA Y., BENNETT D., 2024, Analyzing predictors of perceived graduate employability from sufficiency and necessity perspectives, *Higher Education*, 88(6): 2375–2397, https://doi.org/10.1007/s10734-024-01221-1.
29. MENG Q., JIN X., LUO F., WANG Z., HUSSAIN S., 2024, Distributionally robust scheduling for benefit allocation in regional integrated energy systems with multiple stakeholders, *Journal of Modern Power Systems and Clean Energy*, 12(5): 1631–1642, https://doi.org/10.35833/MPCE.2023.000661.
30. MECKLING J., KELSEY N., BIBER E., ZYSMAN J., 2015, Winning the green revolution: Why climate politics is heating up, *Nature Climate Change*, 5(5): 440–442.
31. METCALF G.E., 2014, The economics of energy security, *Annual Review of Resource Economics*, 6(1): 155–174.
32. MOHAMED E.F., ABDULLAH A., JAAFFAR A.H., OSABOHIEN R., 2024, Reinvestigating the EKC hypothesis, *Energy Strategy Reviews*, 53: 101387, https://doi.org/10.1016/j.esr.2024.101387.
33. OSABOHIEN R., AKPA A.F., OLONADE O., JAAFFAR A.H., AL-FARYAN M.A.S., 2026, Advancing environmental management through renewable energy and carbon footprint reduction, *International Journal of Energy Research*, https://doi.org/10.1155/er/8136569.
34. SAHAN U.M.H., JAAFFAR A.H., OSABOHIEN R., 2025, Green human resource management and environmental performance, *International Journal of Energy Sector Management*, 19(1): 220–237, https://doi.org/10.1108/IJESM-01-2024-0013.
35. SUN X., GUO B., YANG Y., PAN Y., 2025, Time for a change! Uprooting users embedded in the status quo from habitual decision-making, *Decision Support Systems*, 189: 114371, https://doi.org/10.1016/j.dss.2024.114371.
36. UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE (UNECE), 2015, *Quality of Employment Framework*, https://unece.org/statistics/quality-employment-framework.
37. UNITED NATIONS ENVIRONMENT PROGRAMME (UNEP), 2021, *Green Recovery*, https://wedocs.unep.org/xmlui/bitstream/handle/20.500.11822/35358/GreenRecov.pdf.
38. YI H., 2013, Clean energy policies and green jobs: An evaluation of green jobs in US metropolitan areas, *Energy Policy*, 56: 644–652.
39. WEI R., ADELEKE O.K., OKOGOR K.C., OSABOHIEN R., 2025, Climate risks and clean cooking energy for sustainable futures, *Applied Ecology & Environmental Research*, 23(4), https://doi.org/10.15666/aeer/2304_82978316.
40. WU B., ZHANG Y., FANG C., 2025, Shifts in innovation focus in response to online and offline shareholder activism: Unpacking patterns in family and non-family firms, *Entrepreneurship Theory and Practice*, https://doi.org/10.1177/10422587251401182.
41. WOODS N.D., KANG J., LOWDER M.A., 2023, Do green policies produce green jobs? *Social Science Quarterly*, 104(2): 153–167.
42. WU W.P., YAN J.J., CHEN Y.H., WANG Z.J., LIN Y.R., 2022, Has environmental policy improved the job quality of migrant workers? A quasi-natural experiment on China's Clean Air Action, *Journal of Cleaner Production*, 347: 131231.

43. ZHANG M., BOONSUB P., SHEN S., 2025, Impact of green human resource management and green supply chain management practices on sustainable organizational performance: A case of China–Laos Railway, *Journal of Chinese Human Resources Management*, 16(2): 3–21, https://doi.org/10.47297/wspchrmWSP2040-800501.20251602.