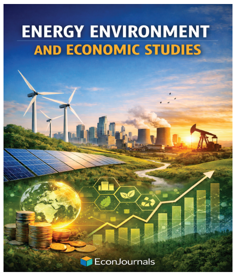

Energy Environment and Economic Studies

available at http: www.econjournals.com

Energy Environment and Economic Studies, 2025, 1(2), 8-14.

Carbon Productivity from Clean Power Portfolios: Variable Renewables, Dispatchable Low-Carbon Electricity, and Economic Value Creation in a Global Panel

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Received: 18 August 2025 **Accepted:** 18 December 2025 **DOI:** https://doi.org/10.32479/eees.23970

ABSTRACT

This paper looks at the question of whether low-carbon electricity portfolios composition is relevant to the carbon-efficient economic performance. Instead of considering the energy transition as one renewable aggregate, the analysis breaks these dispatchable clean electricity (hydro and nuclear shares) in to variable renewables (solar and wind shares), and analyzes their relationship to carbon productivity and carbon intensity in the electricity sector. The empirical design is a public country- year panel based on Our World in Data energy repository and approximates two-way fixed-effects models using country-clustered standard errors. The sample size in which the estimation is done is 3602 observations in 163 countries in the period between 2000 and 2022. The baseline performance indicates that the two portfolio components are linked with the higher carbon productivity and the reduced electricity carbon intensity. Increasing dispatchable clean share by ten percentage points is linked to 0.269 log points more carbon productivity and 0.253 log points less carbon intensity of electricity and the analogous values with variable renewables are approximately 0.307 and 0.236 log points. The substantive conclusion is maintained by robustness tests using lagged shares, a balanced panel, winsorization and an alternative greenhouse-gas-intensity outcome. The results indicate that, the business value of decarbonization lies not only in the extent to which an economy uses clean electricity, but also in the structure of the electricity portfolio.

Keywords: Carbon Productivity, Low-carbon Electricity, Variable Renewables, Dispatchable Clean Power, Energy Transition, Environmental Economics

JEL Classifications: Q43, Q56

1. INTRODUCTION

The decarbonization business case is no longer a compliance or corporate reputation issue anymore. The electricity systems determine operating costs, the carbon regulation exposure, supply resilience, and environmental efficiency in which firms convert inputs into market value. That is why, a cleaner power mix can be relevant not only to reduce emissions, but also to enhance the quality of economic development. Recent research is more and more relating renewable electricity to improved environmental performance, but they also reveal that the results of transition are different in all technologies, financial, and institutional environments (Gao and Chen, 2023; Peng et al., 2023).

The second lesson of the existing literature is that the transition should not be considered an even-handed renewable-energy aggregate. The studies that focus on productivity indicate that the development of greeners relies on the relationship among the implementation of clean energy, technological advances, and the quality of the systems used in the system (Zhang et al., 2024; Jiang et al., 2024). Electricity exchange and disaggregated renewable generation Work has also shown that transition effects vary across portfolio structures, and not increasing mechanically with a single clean-energy share in the portfolio (Liu and Han, 2024; Kartal et al., 2024). This poses a strategic question that has not been sufficiently explored in business-oriented empirical literature: Do various clean-power portfolios have different payoffs in carbon-efficiency?

The answer to that question is provided in this paper, which divides low-carbon electricity into two different portfolio elements. The former is dispatchable clean electricity, a proxy of which is the shares in hydro and nuclear. The second is the variable renewables which is proxied by solar and wind shares. The difference is economically significant. System stability, reduced balancing reliance on fossil generation, and predictable low-carbon supply are often linked with the use of dispatchable clean power. Variable renewables, on the other hand, are generally associated with quick incremental decarbonization, falling technology prices and emerging investment possibilities in energy-transition markets. A business-economics viewpoint must thus evaluate the possibility that these components of the portfolio are linked to increased carbon productivity - economic output at a given level of greenhouse-gas emissions.

The paper makes three contributions. First, it brings in a portfolio-composition approach to the carbon-productivity debate. Second, it employs a completely public and replicable country- year panel based on the Our World in Data energy repository. Third, it assesses the same strategic statement in two complementary ways, carbon productivity as an outcome of economic performance and electricity carbon intensity as an outcome of power-system decarbonization. The rest of the paper is structured in the following way. In part 2, the study is placed in the context of the recent literature and the hypotheses are formulated. Section 3 shows the data architecture, the design of variables, and the empirical model. Main results and robustness tests are reported in Section 4. The managerial and policy meaning of the findings is discussed in section 5. Section 6 concludes.

2. LITERATURE REVIEW AND HYPOTHESIS DEVELOPMENT

Post-2022 work has further diversified the energy-transition debate into a more comprehensive question that these issues are not tied to just one aspect, namely the question of emissions (Table 1). One of the streams is that renewable electricity and the wider implementation of green energies lower emissions and help to take a cleaner transition path. The other stream is concerned with productivity and sustainable-development mechanisms; it states that green total factor productivity and technological capability are key to sustainable transition results (Li et al., 2023; Zhang et al., 2024). The third stream demonstrates that transition benefits are mediated by policy structure, financing, and quality of infrastructure (Raza and Lin, 2024; Yang et al., 2025).

Despite these developments, there are two gaps in the literature that are practical. First, numerous studies analyze clean energy as a whole, whereas business strategy tends to rely on the electricity portfolio mix. Second, the literature addressing directly the concept of green productivity or sustainable development does not always provide the analysis of whether the design of low-carbon power is linked to greater economic value creation per unit of emission. The relevance of this distinction is supported by recent findings in China, Europe, and the MENA region indicating that the results of low-carbon transition hinge on the policy focus, regional cost conditions, energy management capacity, and technology mixes (Wu et al., 2025; Bamisile et al., 2025). These arguments indicate that transition quality can be dependent on portfolio quality, rather than just the size of a portfolio.

This paper develops four hypotheses. The first two concern carbon productivity. Dispatchable clean electricity can lower structural emissions while supporting reliable power supply, which should improve the amount of economic value created per unit of emissions. Variable renewables can also improve carbon productivity by displacing carbon-intensive generation and lowering the emissions burden associated with output growth. The remaining two hypotheses concern electricity carbon intensity. If cleaner portfolios substitute for fossil-based generation, both components should be associated with a less carbon-intensive electricity system.

- H_1. A higher share of dispatchable clean electricity is positively associated with carbon pro- ductivity.
- H_2. A higher share of variable renewables is positively associated with carbon productivity.
- H_3. A higher share of dispatchable clean electricity is negatively associated with electricity carbon intensity.
- H_4. A higher share of variable renewables is negatively associated with electricity carbon intensity.

3. DATA ARCHITECTURE AND EMPIRICAL DESIGN

3.1. Public Dataset and Sample Construction

The empirical analysis uses the public Our World in Data energy repository, which consolidates internationally recognized country-year indicators on electricity generation, energy use, emissions, population, and macroeconomic activity. The raw data file and codebook are included in the package for full reproducibility. The sample excludes aggregate regional entries and retains sovereign-country observations with complete information for the baseline variables. The estimation sample contains 3602 observations from 163 countries over 2000-2022.

3.2. Variable Design

The main dependent variable is carbon productivity:

$$CP_{it} = \frac{GDP_{it}}{GHG_{it}} \qquad (1)$$

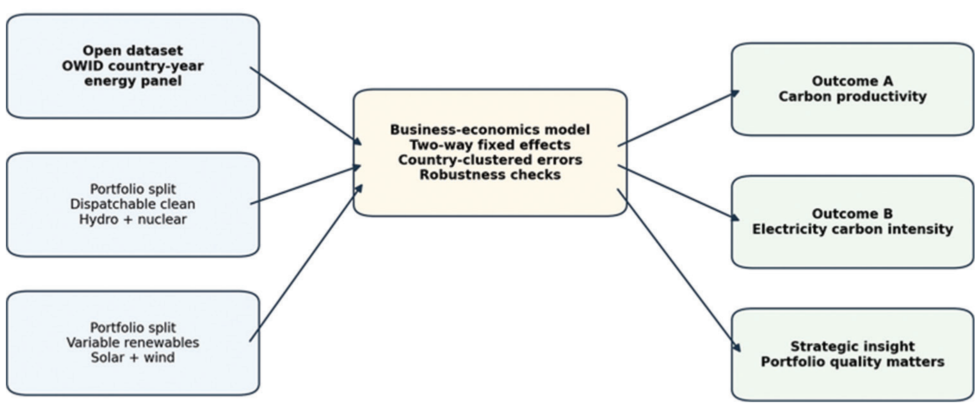
where GDP_{it} denotes real output and GHG_{it} denotes greenhouse-gas emissions in tonnes of CO_2-equivalent. The regressions use $\ln(CP_{it})$.

The second dependent variable is electricity carbon intensity, denoted CI_{it}^{elec}, measured as grams of CO_2-equivalent per kilowatt-hour of electricity generation. The regressions use .

Table 1: Recent post-2022 studies used to position the paper

Study	Outlet	Data context	Main message
Gao and Chen (2023)	Utilities Policy	21 developed economies, 1990-2020	Renewable electricity is associated with more sustainable energy transition and lower emissions
Wang et al. (2023)	Renewable Energy China, electricity sector	China, electricity sector	Renewable deployment lowers electricity sector emissions, with nonlinear patterns.
Li et al. (2023)	Energy Economics	33 countries, 1990-2021	Green energy is positively linked to sustainable development outcomes
Peng et al. (2023)	Nature communications	49 economies, scenario-based assessment	Low-carbon power transition can improve SDG progress overall, with regional disparities
Jiang et al. (2024)	Journal of Environmental Management	30 Chinese provinces, 2005-2020	Renewable energy and green innovation improve green total factor productivity.
Zhang et al. (2024)	Journal of Environmental Management	171 economies, 1990-2019	Green total factor productivity has a stronger role than conventional productivity in clean-energy transition
Liu and Han (2024)	Journal of Cleaner Production	Cross-country electricity-exchange perspective	Electricity exchange conditions shape the carbon effect of renewable development.
Kartal et al. (2024)	Energy Strategy Reviews	10 leading EU emitters, daily data 2019-2023	Hydro, solar, and wind reduce emissions with strong country heterogeneity.
Raza and Lin (2024)	Applied Energy	Pakistan, 1992-2021	Energy transition and carbon-trade conditions matter for sustainable electricity generation.
Yang et al. (2025)	Energy Strategy Reviews	China, 2009-2023	Cost of capital materially shapes renewable-energy productivity and efficiency.
Ai et al. (2025)	Energy Economics	281 Chinese prefectures, 2012-2022	Policy-induced renewable transition can improve structure but impose short-run sustainability costs.
Wu et al. (2025)	Energy	278 Chinese cities	FinTech accelerates low-carbon transition through policy-attention and innovation channels.
Bogdzinski et al. (2025)	Economic Analysis and Policy	221 European NUTS2 regions, 2009-2021	Green energy production improves green productivity, including hydrogen complementarities.
Sohaib et al. (2025)	Energy strategy reviews	China, 1990-2022	Renewable energy mitigates carbon emissions while fossil use and urbanization intensify them.
Bamisile et al. (2025)	Energy Strategy Reviews	MENA region	Cost and technical potential jointly shape low-carbon electricity transition feasibility.
Yu et al. (2025)	China economic review	China, regression discontinuity design	Corporate energy management improves firm-level carbon productivity.

Figure 1: Conceptual and empirical framework. The paper links clean-power portfolio composition to two outcomes: carbon productivity and electricity carbon intensity



The portfolio variables are defined as:

$$DCS_{it} = HydroShare_{it} + NuclearShare_{it}, \quad (2)$$

$$VRS_{it} = SolarShare_{it} + WindShare_{it}. \quad (3)$$

DCS_{it} is the dispatchable-clean share, while VRS_{it} is the variable-renewables share. Both are measured as percentage points of electricity generation.

Three controls are included. First, $\ln(GDPpc_{it})$ captures income level and development stage. Second, $\ln(EnergyIntensity_{it})$ captures how much energy is required to generate output. Third, $\ln(ElectricityDemandpc_{it})$ captures scale effects in electricity use.

3.3. Econometric Model

The baseline specification is a two-way fixed-effects model:

Table 2: Descriptive statistics

Variable	Mean	Standard deviation	Min	Median	Max
Log carbon productivity	9.950	1.249	6.780	9.699	14.165
Log electricity carbon intensity	5.791	0.974	2.847	6.183	7.175
Dispatchable clean share	33.726	32.835	0.000	25.000	100.000
Variable renewables share	2.750	6.395	0.000	0.067	61.267
Log GDP per capita	9.047	1.210	6.044	9.189	12.005
Log energy intensity	0.068	0.640	-2.551	0.093	2.317
Log electricity demand per capita	7.210	1.707	2.185	7.553	10.934

$$\ln(Y_{it}) = \beta_1 DCS_{it} + \beta_2 VRS_{it} + \beta_3 \ln(GDPp_{cit}) + \beta_4 \ln(EnergyIntensity_{it}) + \beta_5 \ln(ElectricityDemandpc_{it}) + \mu_i + \quad (4)$$

where μ_i denotes country fixed effects and τ_t denotes year fixed effects. Country-clustered standard errors are used throughout. Because the dependent variables are in logs while the portfolio variables are in percentage points, β_1 and β_2 are semi-elasticities. A one-point increase in a portfolio share changes the expected dependent variable by approximately 100 × β percent, holding the fixed effects and controls constant.

The analysis estimates two main models. The first uses $\ln(CP_{it})$ to evaluate carbon-efficient economic value creation. The second uses $\ln(CI_{it}^{elec})$ to evaluate power-system decarbonization. Robustness checks include a 1-year lag for the portfolio variables, a balanced-panel estimation, a winsorized sample, and an alternative dependent variable based on greenhouse-gas intensity of GDP. The paper links clean-power portfolio composition to two outcomes: carbon productivity and electricity carbon intensity Figure 1).

4. EMPIRICAL EVIDENCE

4.1. Descriptive Patterns

Table 2 reports the descriptive statistics. The mean of log carbon productivity is 9.950, while the mean of log electricity carbon intensity is 5.791. Dispatchable clean electricity averages 33.726% points of generation, whereas variable renewables average 2.750% points over the estimation period. The difference reflects the historical weight of hydro and nuclear in the early years of the panel and the later acceleration of wind and solar deployment.

Figure 2 presents four descriptive panels by income quartile. Two patterns are notable. First, variable renewables rise sharply in the upper part of the income distribution after the mid-2010s. Second, electricity carbon intensity trends downward across income groups, although the pace differs substantially. These patterns suggest that clean-power portfolios and carbon-efficient growth are linked, but not in identical ways across the global income distribution.

4.2. Baseline Regressions

Table 3 reports the baseline fixed-effects results. In Column (1), both portfolio variables are positively associated with carbon productivity. The coefficient on dispatchable clean share is 0.0269 ($P < 0.01$), and the coefficient on variable renewables share is 0.0307 ($P < 0.01$). In semi- elasticity terms, a ten-percentage-point increase in dispatchable clean electricity is associated with roughly 0.269 log points more carbon productivity, while the same increase in variable renewables is associated with roughly 0.307 log points more carbon productivity. This supports H_1 and H_2.

Table 3: Baseline fixed-effects regressions

Variable	Carbon productivity	Electricity carbon intensity
	(1)	(2)
Dispatchable clean share	0.0269***	−0.0253***
	(0.0028)	(0.0018)
Variable renewables share	0.0307***	−0.0236***
	(0.0032)	(0.0022)
Log GDP per capita	0.9023***	0.0740
	(0.1196)	(0.0724)
Log energy intensity	−0.1955	0.1515*
	(0.1461)	(0.0810)
Log electricity demand per capita	−0.8801***	−0.0060
	(0.0825)	(0.0609)
Observations	3602	3602
Countries	163	163
Years	2000-2022	2000-2022
Country fixed effects	Yes	Yes
Year fixed effects	Yes	Yes
Clustered SEs	Country	Country

The controls sharpen the business interpretation. Higher GDP per capita is strongly positively associated with carbon productivity, indicating that more advanced economies generate more value per unit of emissions. By contrast, electricity demand per capita is strongly negative, suggesting that scale effects can offset part of the carbon-efficiency gains from cleaner portfolios when electricity use expands faster than value creation.

Column (2) uses electricity carbon intensity as the dependent variable. The portfolio variables turn negative and remain highly significant. The coefficient on dispatchable clean share is −0.0253, and the coefficient on variable renewables share is −0.0236. This is the expected mirror image of the carbon-productivity model: cleaner portfolios are associated with a less carbon- intensive electricity system. The result supports H_3 and H_4.

Figure 3 visualizes the baseline coefficients and 95% confidence intervals. Variable renewables are more strongly associated with carbon-productivity gains, whereas dispatchable clean electricity is more strongly associated with lower electricity carbon intensity. That asymmetry is economically plausible. Wind and solar can generate strong marginal gains in carbon-efficient value creation once integrated into the system, while hydro and nuclear can anchor a low-carbon base load and reduce dependence on fossil balancing.

Figure 2: Four-panel descriptive trends by income quartile. The figure highlights how carbon productivity, dispatchable clean power, variable renewables, and electricity carbon intensity evolved across the income distribution

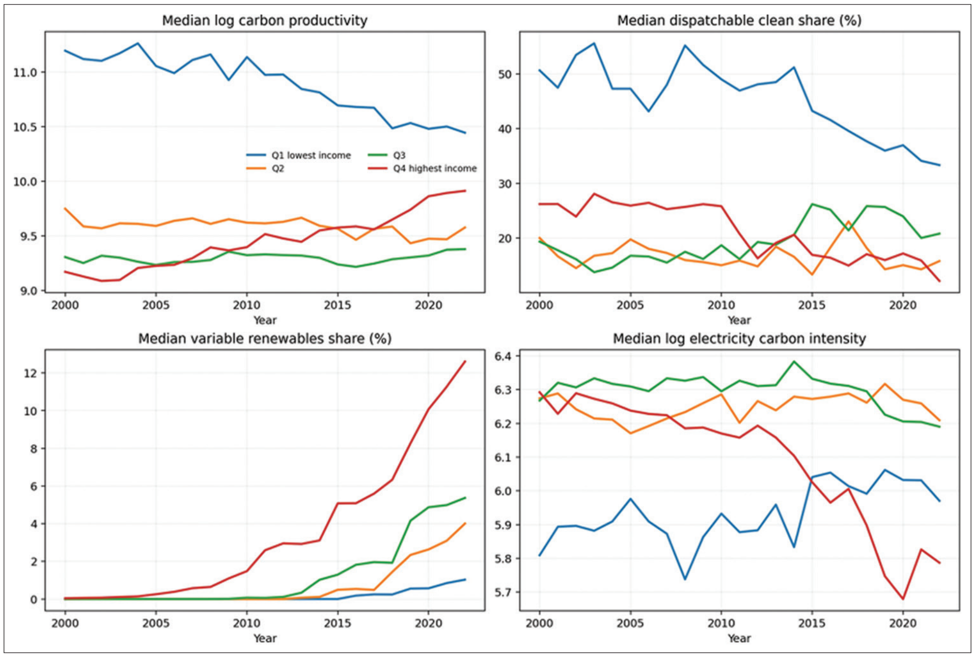
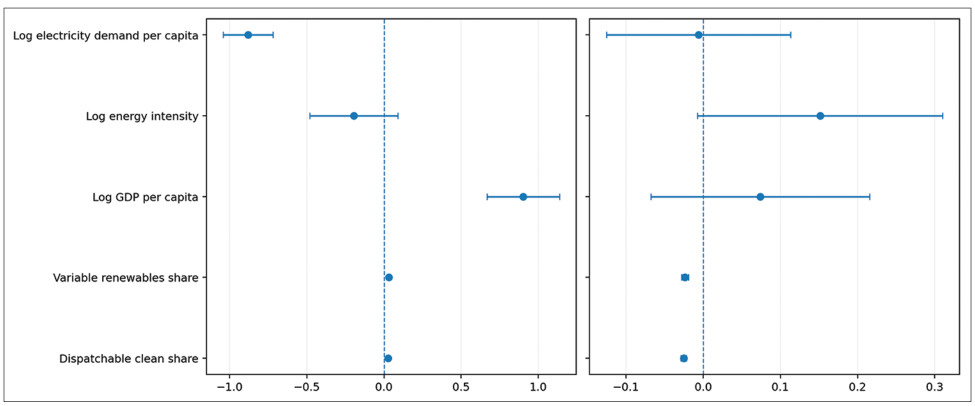


Figure 3: Two-panel coefficient plot for the baseline models. Panel A reports the carbon-productivity model; Panel B reports the electricity-carbon-intensity model. Horizontal bars indicate 95% confidence intervals



4.3. Robustness Tests

Table 4 reports four robustness checks. First, lagged portfolio shares preserve the positive association with carbon productivity. The coefficient on lagged dispatchable clean share is 0.0216, and the coefficient on lagged variable renewables is 0.0298. Second, the balanced-panel specification yields nearly identical signs and closely comparable magnitudes. Third, winsorizing the key variables leaves the main results intact. Fourth, replacing carbon productivity with greenhouse-gas intensity of GDP again produces negative coefficients for both portfolio variables. The message is therefore stable across timing, sample structure, and outcome definition.

Figures 4 and 5 offer two additional visual checks. The first compares 2022 cross-sectional associations. The second shows coefficient stability across the robustness exercises. The graphical evidence reinforces the regression findings rather than contradicting them.

Table 4: Robustness checks

Variable	Lagged shares	Balanced panel	Winsorized	Alt. dep. var.
	(1)	(2)	(3)	(4)
Lagged dispatchable share	0.0216***	–	–	–
	(0.0027)	–	–	–
Lagged variable renewables share	0.0298***	–	–	–
	(0.0032)	–	–	–
Dispatchable clean share	–	0.0287***	0.0254***	-0.0269***
	–	(0.0026)	(0.0027)	(0.0028)
Variable renewables share	–	0.0285***	0.0320***	-0.0307***
	–	(0.0028)	(0.0038)	(0.0032)
Observations	3440	3312	3602	3602
Country fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes

Figure 4: Two-panel association plots for the latest sample year. Panel A links variable-renewables share to carbon productivity. Panel B compares electricity carbon intensity across dispatchable-clean terciles

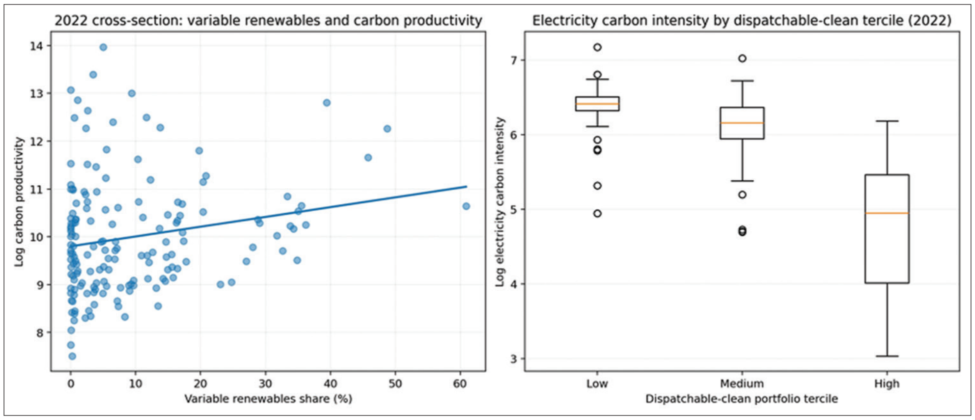
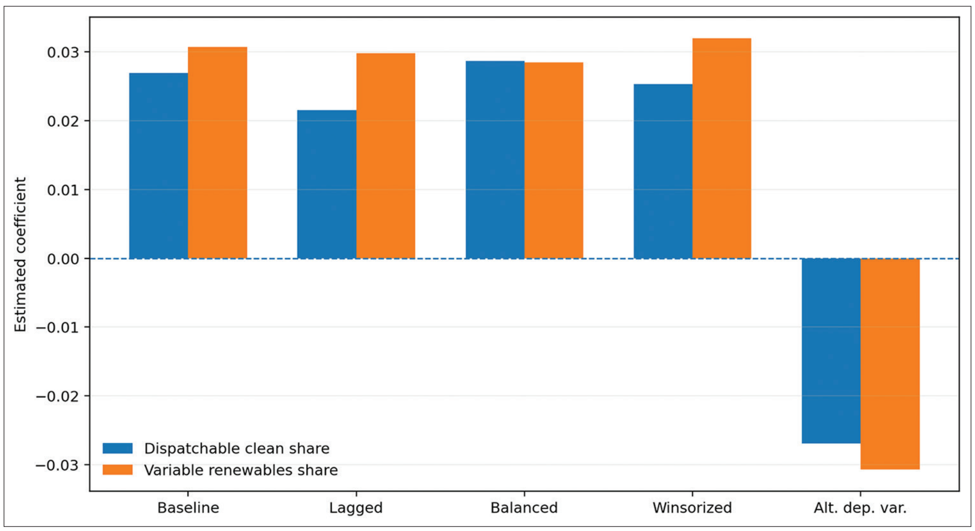


Figure 5: Coefficient stability across robustness checks. Positive bars in the baseline, lagged, balanced, and winsorized models indicate stronger carbon productivity. Negative bars in the alternative dependent- variable model indicate lower greenhouse-gas intensity



5. DISCUSSION

The key result is that portfolio composition is important in the quality of transition. This is a more discriminating finding than the general assertion that an increase in the renewable shares are advantageous. These estimates suggest that dispatchable clean electricity and variable renewables are both related to higher levels of carbon productivity, but not to the same extent. Variable renewables exhibit the greater relationship to carbon-productivity gains, and dispatch- able clean electricity exhibit the greater relationship to the lower electricity carbon intensity. This trend indicates a separation of strategic functions in the low-carbon transition. Variable renewables seem to be of particular interest in incremental creation of carbon-efficient value, whereas dispatchable clean resources seem to be of particular interest in reducing the structural carbon intensity of the power system.

The outcome is meaningful to business as companies are becoming more vulnerable to electricity- market realities by paying more for energy, disclosing carbon, subjecting their supply chains to scrutiny and evaluating their climate risks. A more diversified power portfolio and a cleaner power portfolio provides an operating environment where firms are able to produce output with a reduced emissions load. It does not imply that the performance of the firm is solely dependent on the portfolio of electricity. Instead, it implies that the quality of systems to some extent incorporates carbon-efficient growth. Combined with a stable low-carbon supply and growing variable renewable supply, these economies provide a more favorable environment in which to run efficiency and transition resilience.

The findings also warn against the one-dimensional transition measures. An aggregate clean- energy share can hide significant disparities between systems that are dominated by dispatchable clean, and those which are powered by quickly increasing but intermittent renewable sources. The quality of portfolio is an issue since investment timing, flexibility of systems, balancing arrangements and capital structure varies with different technologies. Whether the transition should be led by dispatchable clean power or by variable renewables, is not a strategic issue. What is more helpful in the analysis is whether investment and policy structures can be used to complement each other in a way that enhances not only the environmental outcomes but also the creation of economic value.

Another implication is related to transition sequencing. Other recent literature claims that renewable transitions implemented through policies can result in short-term adjustment costs or a substitution effect on other productive investments (Ai et al., 2025; Yang et al., 2025). The present results do not contradict that possibility. Rather, they imply that those short- run frictions must be offset by the carbon-efficiency dividend in the long run that comes with cleaner power portfolios. In this respect, a transition can remain a strategic benefit despite the short-term adjustment costs.

Lastly, the research adds to the broader literature on green productivity by demonstrating that electricity structure itself is a part of the productivity debate. More recent studies associate green energy generation with corporate energy management and financial status with produc- tivity and transition outcomes (Bogdzinski et al., 2025; Yu et al., 2025). The current evidence adds to those studies with a wide cross-country finding: the more the electricity portfolio is clean and well-constructed, the higher the correlation with the carbon-efficient value production.

6. CONCLUSION

The paper has created a portfolio perspective of the electricity transition. Instead of determining whether cleaner electricity lowers emissions in a generic sense, it determined whether specific low-carbon power portfolios are linked with a greater carbon-efficient value creation. The evidence using a global panel which is publicly accessible and two-way fixed-effects models provides both a positive relationship between dispatchable clean electricity and carbon productivity and a negative relationship between dispatchable clean electricity and electricity carbon intensity. These results are strong to lagged-share estimation, balanced-panel sampling, winsorization, and another outcome of greenhouse-gas-intensity.

The contribution is both practical and empirical. The quality of transition should be evaluated on the basis of portfolio composition, rather than on the basis of headline clean-energy shares. That observation applies to governments when determining the order in which to make generation investments, to infrastructure investors when considering the quality of transition across markets and to companies where the competitiveness of its operations increasingly becomes a matter of how carbon efficient the systems in which it conducts its operations are. The framework can be expanded in future research adding to the same portfolio perspective storage, grid flexibility, electricity prices and firm-level outcomes.

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