



Are renewable energy sources advancing towards a sustainable society?

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Abstract

While renewable electricity is widely recognized as key to achieving climate goals, its broader contribution to a sustainable and just energy transition remains underexplored. Several studies assess the effect of renewables on individual outcomes, but few adopt an integrated approach that captures the multiple dimensions of environmental sustainability, social well-being, and economic development. This study addresses this gap by exploring the effects of renewable electricity expansion in five key indicators, serving as proxies of environmental, economic and social justice, within the EU-27 and UK from 2007–2022. The analysis employs panel data models with fixed effects, incorporating lagged values of renewable electricity generation by technology type to assess cross-country and temporal dynamics. Findings indicate renewable electricity reduces greenhouse gas emissions, confirming its climate mitigation potential, and contributes positively to economic growth and employment, with solar technologies showing the largest association with job creation, followed by wind. The analysis, however, finds no significant effect on income inequality (measured by Gini Index), and only marginal impacts on household electricity prices. These results suggest that while renewable deployment may advance environmental and economic goals, its contribution to greater social equity is less evident, underscoring the importance of policies that explicitly integrate decarbonization with distributive justice and affordability. Future research should further explore the differentiated social impacts of renewable deployment across income groups, and household types, providing a stronger empirical basis for designing energy transitions that are not only sustainable but also just.

Keywords Just Transition · Renewables · Econometric models · EU 27+UK

1 Introduction

Limiting the global temperature increase to 1.5° C above pre-industrial levels, as outlined in the Paris Agreement (UNFCCC, 2015) requires a transition to climate-neutral economy, driven by the rapid and deep decarbonization of the energy system, with renewable energy sources (RES) playing a pivotal role (IEA, 2022). This transformation, commonly referred

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to as energy transition, involves a shift towards low-carbon and RES-based technologies, such as solar photovoltaics (PV) and wind turbines, accompanied by improvements in energy efficiency (Widuto, 2023). However, beyond the technological and environmental dimensions, energy transition may also pose some social and economic challenges (Arias et al., 2023; Chipangamate & Nwaila, 2024) potentially leading to job displacement, and income losses, which may contribute to diminished social well-being and the worsening energy affordability, particularly affecting the most vulnerable populations (Garcia-Casals et al., 2019; Johansson, 2023).

More recently, energy transition has been raising pressing questions about fairness and equity, ensuring that the social impacts of decarbonization are explicitly addressed alongside environmental and economic objectives, views that central in the Just Transition (JT) concept (Wang & Lo, 2021) (Delina & Sovacool, 2018).

JT concept first emerged in the late 1970s, from demands by US labor union demands for compensation for job losses in polluting industries affected by environmental regulations (Wang & Lo, 2021). Since then, JT has evolved into a globally recognized principle, incorporated into the UN International Labor Organization (ILO)'s 2015 Guidelines (ILO, 2015) and embedded in key climate governance, including the Paris Agreement, Conferences of the Parties (COPs) and the Intergovernmental Panel on Climate Change (IPCC) reports (IPCC, 2014; UNFCCC, 2015).

Currently, JT emphasizes that energy transition must not only deliver deep reductions in GHG emissions but also ensure social and equity, justice, and promote inclusive development. It aims to guarantee that the opportunities of energy transition are shared fairly among all agents, including workers, communities, and vulnerable populations, and no one is left behind, i.e., a Just Energy Transition (JET) (European Commission, 2019).

Within this context, the EU has emerged as a global leader in operationalizing Just Energy Transition through its policy landscape, particularly under the European Green Deal (European Commission, 2019). The EU goal is to reach its climate neutrality by 2050 while offering support to those most affected by climate change (McCauley et al., 2023; Pianta & Lucchese, 2020). EU member states are actively engaged in advancing energy transition, aiming to integrate RES in a way that strengthens both economic resilience and social cohesion (EIB, 2023).

However, while environmental benefits of RES deployment are well established (IEA, 2023), their social and economic impacts remain debated. Some studies suggest the potential of renewable deployment to drive inclusive growth, job creation, and enhanced welfare (Dincer, 2000; Silva et al., 2024; Villavicencio Calzadilla & Mauger, 2018). Others raise concerns about rising electricity costs, regional disparities and the risk of increase inequality, especially among vulnerable communities (Garcia-Casals et al., 2019; Kashour, 2023).

To ensure a Just Energy Transition, it is essential to monitor to understand the impacts of RES on key indicators like employment ratios, energy affordability, and emission reductions, which may assist policymakers in mitigating negative impacts and maximizing social and environmental benefits (Filipović et al., 2022; WRI World Resources Institute, 2025).

Although renewable electricity is widely acknowledged as crucial for reducing greenhouse gas emissions, its broader implications for economic development and social equity remain less clear. Much of the existing research has examined these dimensions separately, namely focus on the effects of renewable energy on economic growth (Atems & Hotaling, 2018; Ntanos et al., 2018; Sharma et al., 2021), or on the volatility of wholesale electricity

prices (Cevik & Ninomiya, 2023), on employment (Arvanitopoulos & Agnolucci, 2020; Proença & Fortes, 2020), or income and inequality (García-García et al., 2020; Topcu & Tugcu, 2020). This fragmented evidence that makes it difficult to assess the overall contribution of renewables to a sustainable energy transition. Additionally, many studies rely on aggregated measures of renewable energy, often dominated by traditional sources such as biomass and hydropower. This masks the potential different effects of specific technologies such as wind, or solar, which are expected to play a central role in future climate mitigation (Huenteler et al., 2016; IEA, 2022).

As a result, there is still no comprehensive empirical assessment of whether renewable electricity deployment advances environmental, economic, and social goals simultaneously, nor of how these outcomes vary across technologies.

In this context, this study investigates to which extent the expansion various renewable electricity technologies have influenced GHG emissions and key-socio-economic outcomes in the EU-27 and the UK, from 2007 to 2022. We apply a panel data econometric approach to analyze five indicators Gross Domestic Product per capita (GDPpc), Gini Index, employment ratio, GHG emissions per capita, and household electricity prices. These variables are selected to capture a macro-level perspective framed under the broader concept of “Sustainable and Just Energy Transition”, which aims to integrate environmental sustainability, social justice and well-being, and economic development in a common framework for evaluating energy transition outcomes (Abram et al., 2022; Boyle, 2023). By adopting an integrated and cross-national and technology-differentiated approach, this study addresses the existing research gaps and provides new empirical evidence of renewable electricity deployment contribution to broader sustainability outcomes. The findings aim to inform the design of energy policies that are more aligned with the principles of justice and sustainability.

The remainder of this paper is organized as follows: Sect. 2 presents literature review of relevant literature; Sect. 3 describes the methodology employed, including the econometric model, and data used; Sect. 4 presents the results and discuss them in the light of existing literature; Sect. 5 describes the policy implications of our findings, and finally Sect. 6 concludes.

2 Literature review

The energy transition, including a shift toward RES, is widely recognized as crucial for climate mitigation objectives (IEA, 2023; IPCC, 2022). However, analyzing renewable technologies as a homogenous category can mask important differences, for instance, wind has fewer environmental impacts than solar, while hydropower presents greater ecological risks [Gilson et al., 2017].

Additionally, recent studies emphasize the importance of evaluating renewables through a broader perspective that also incorporates social justice (Carley & Konisky, 2020) and economic issues (Garcia-Casals et al., 2019). This wider perspective has fostered the growing relevance of the Just Energy Transition (JET) framework, which emphasizes that decarbonization must also be economic benefits and socially just promoting equity (UNCC, 2018; Wang & Lo, 2021). Nonetheless, critiques persist, as economic dimension is often overlooked in discussions of Just Energy Transition, despite ILO (ILO, 2015) guideline explicitly emphasizing the importance of aligning economic growth with social and envi-

ronmental goals (Berthe & Turquet, 2023). These gaps underscore the need for an integrated assessment of renewable deployment that explicitly captures the three core pillars of sustainable development: environmental, economic, and social sustainability (Filipović et al., 2022).

To address this, this literature review aims to critically assess empirical evidence on how renewable electricity expansion affects environmental indicators, economic performance and social well-being, including equity and affordability, identifying also research advances and gaps.

2.1 Review strategy and scope

The purpose of this literature review is to provide a critical synthesis of existing studies on empirical evidence of the effects of renewable electricity deployment on economic, social well-being and environmental indicators. The review was performed using Scopus, and Web of Science databases, considering final peer-reviewed articles in English that were published from 2000 onwards. To ensure that the focus remained on empirical contributions and not just conceptual or descriptive studies, the search strings combined the core terms “renewable electricity” with methodological fillers such as “empirical”, “econometric”, and with outcome-specific terms capturing social, economic, environmental dimensions, and just dimensions, query research: word in TITLE_ABS_KEY (“Renewable Electricity” and (Empirical” or “Econometric”) and TITLE-ABS-KEY (“Economic Growth” or “GDP”) or TITLE-ABS-KEY (“Employment”) or TITLE-ABS-KEY (“Inequality” or “Gini Index”) or TITLE-ABS-KEY (“Household electricity prices”) and TITLE-ABS-KEY (“Just Transition” or “Just Energy Transition”).

After removing duplicates, titles and abstracts were examined to assess whether the studies met the minimum relevance criteria. Studies were retained only if they investigated at least one of the outcome variables central to this paper: GDP per capita or economic growth, employment, income inequality, Gini index, household electricity prices or affordability, greenhouse gas emissions. Research focusing solely on non-electricity energy sources, such as transport fuels or biofuels, was excluded. Likewise, studies concerned only with technologies or system modelling without reference to socio-economic or environmental outcomes, were excluded. Table A.1 in the Appendix synthesis the main studies reviewed, organized by region, time period, methodology, indicators, and key findings.

2.2 Environmental effects

The provided literature underscores the significant role of renewable electricity in mitigating GHG emissions (Mac Domhnaill & Ryan, 2020; Relich, 2024), a topic of considerable relevance in scholars’ discussions on environment policy and energy transition. Large-scale panel econometric studies the potential of renewable electricity to mitigate climate is well analyzed, environmental outcomes have often been studied. (Mecu et al., 2023) confirmed that renewable energy production effectively reduces GHG emissions in EU member states employing panel data regression models. Similarly, (Paramati et al., 2021) establish a robust causal relationship between increases in renewable shares and reductions in CO₂ emissions. (Busu, 2019) further corroborates these findings, noting that RES positively impact CO₂ emissions in the EU, despite technological disparities among member-states (Gajdzik et al.,

2024). Additionally, (Ortega-Izquierdo & Río, 2020) emphasize wind energy deployment's role in displacing fossil fuels and contributing to emission abatement. While others authors found a limited effect on reducing CO₂ emissions (Charfeddine & Kahia, 2019). Collectively, most of these studies highlight renewable energy's environmental benefits, reinforcing its importance in strategies aimed at climate change mitigation.

2.3 Economic effects

The relationship between renewable electricity and economic growth has been widely studied, although findings are not fully uniform. Several panel analyses identify positive effects. (García-Casals et al., 2019), for instance, show that investment in renewables correlate with GDP expansion and job creation.

(Atems & Hotaling, 2018; Bayraktutan et al., 2011; Mazzanti, 2021) and (Chou et al., 2023) report that renewable but also non-renewable electricity significantly influence growth dynamic. However, (Mazzanti, 2021) emphasizes conditionality. By using econometric panel data from OECD countries to analyze the long-run relationship between electricity consumption and economic performance the authors find that electricity consumption and GDP are positively related but that causality runs mainly from economic growth to energy demand, suggesting that renewable deployment may follow rather than drive economic expansion.

By contrast some studies evidence weak or negative effects. (Li & Leung, 2021) find no causal link between renewable consumption and GDP in Europe, while (Sharma et al., 2021) report a two-way negative relationship between renewable energy consumption and economic growth European Union, concluding that while the shift towards renewables may not appear economically viable in the short run, it is expected to yield positive impacts on growth in the longer term.

2.4 Employment effects

Labor effects are central to the JT debate, since the expansion of renewable electricity coincides with decline of carbon-intensive sectors. A broad strand of empirical research confirms that renewables are more labor-intensive than fossil fuels and tend to generate net employment gains. For the European Union, (Proença & Fortes, 2020) estimate that a one per cent increase in renewable capacity results in a 0.48 per cent rise in employment. Complementary evidence also reinforces this conclusion with (Del Rio & Burguillo, 2008) reporting positive, but modest, local employment effects in Spanish regions, and (Hatlelid & Aass, 2016) showing that solar deployment in Rwanda generated new jobs and local value creation. Studies highlight RES expansion can create new jobs, especially in consumption, installation, and maintenance, which may offset associated job losses in the fossil fuels sectors (Cha, 2020).

Despite this generally positive picture, the literature also identifies import caveats. (García-García et al., 2020) find that net employment gains in renewables may be modest once fossil fuel displacement is considered, and that job quality and regional disparities remain significant concerns. (Gambhir et al., 2018) warn that the decline of coal mining can lead to structural unemployment and highlight the need for reskilling policies. Computable general equilibrium models, such as those developed by (Böhringer et al., 2013), similarly suggest

that the magnitude of employment and welfare benefits depends heavily on subsidy design, financing mechanisms, and macroeconomic conditions.

Overall, the evidence indicates that renewable deployment has the potential to generate employment and mitigate inequality, but the magnitude and distribution of these benefits are far from uniform. Outcomes vary across technologies, regions, and policy frameworks, and positive effects are often subjects to complementary measures such as reskilling, targeted subsidies, and infrastructure investments.

2.5 Inequality and affordability

The distributional implications of this labor market also shifts extend to inequality and affordability. However, the distributive effects of renewable electricity remain ambiguous, with the literature producing contrasting results. (Topcu & Tugcu, 2020) find that renewable energy consumption can decrease income inequality in developed economies, as cleaner energy systems enhance access and affordability. (Apergis, 2015) reaches the opposite conclusion for OECD countries, arguing that publicly financed renewable are associated with higher inequality, with solar showing the strongest effect compared to wind and biofuels: a 1 per cent increase in solar production raises inequality by 0.22 per cent. This may be justified by the fact that the fiscal costs of subsidies increase taxation and reduce public spending, thereby offsetting the distributive gains of lower electricity prices.

Similarly, concerns are raised by (Duan & Chen, 2018), applying a Lorenz curve and found greater inequality in renewable energy than fossil fuels, due to a huge technological gap among countries. These findings suggest that renewable deployment can alleviate inequality if embedded in redistributive policy frameworks, but may also reinforce disparities when technological and income gaps remain unaddressed.

Affordability outcomes, typically measures through electricity prices, are equally heterogeneous. Evidence from European wholesale markets shows that increasing the share of renewables has a dampening effect on average prices, particularly at higher penetration levels (Cevik & Ninomiya, 2023). However, the intermittent and variable nature of renewables introduces uncertainty and may increase volatility, particularly in the absence of supporting infrastructure such as grid interconnections and storage. The econometric analysis of (Liebensteiner et al., 2025) for German wholesale electricity market, also demonstrated that the downward pressure of renewables on electricity prices can be offset by other pressures, including higher carbon and gas prices, growing electricity demand and the nuclear phaseout, with forecasts pointing to persistently high prices despite continued renewable deployment. Similar concerns are found in Japan, where complementary evidence from EU context by (Kashour, 2023), focusing on EU member states, reveals that electricity prices explain more than 11 per cent of household energy inequality, underscoring that affordability outcomes depend not only on renewable penetration but also on broader market and socioeconomic conditions.

The literature indicates that renewables can thus reduce inequality, but these effects are highly heterogeneous and conditional on the broader policy and market environment. The inequality effects vary depending on financing arrangements and economic structures, and affordability gains are often undermined by volatility and external price pressures.

2.6 Research gaps and paper contribution

Although existing literature offers valuable insights, important gaps remain. Most studies focus on single or a few dimensions of renewables outcomes, whether economic outcomes such as economic growth (Li & Leung, 2021; Sharma et al., 2021; Yang et al., 2020) socio-economic indicators such as employment (Böhringer et al., 2013; Del Rio & Burguillo, 2008; Proença & Fortes, 2020), inequality (Apergis, 2015; Duan & Chen, 2018; Topcu & Tugcu, 2020), social distributional effects or electricity prices (Cevik & Ninomiya, 2023; Kashour, 2023; Liebensteiner et al., 2025) or environmental impacts such as emissions (Mac Domhnaill & Ryan, 2020; Mecu et al., 2023; Paramati et al., 2021). Moreover, quantitative studies frequently rely on aggregated renewable consumption, which neglects the heterogeneous effects of specific technologies and overlooking newer sources like solar and wind, which may be the principal contributors of GHG reduction (Gibson et al., 2017; IPCC, 2018).

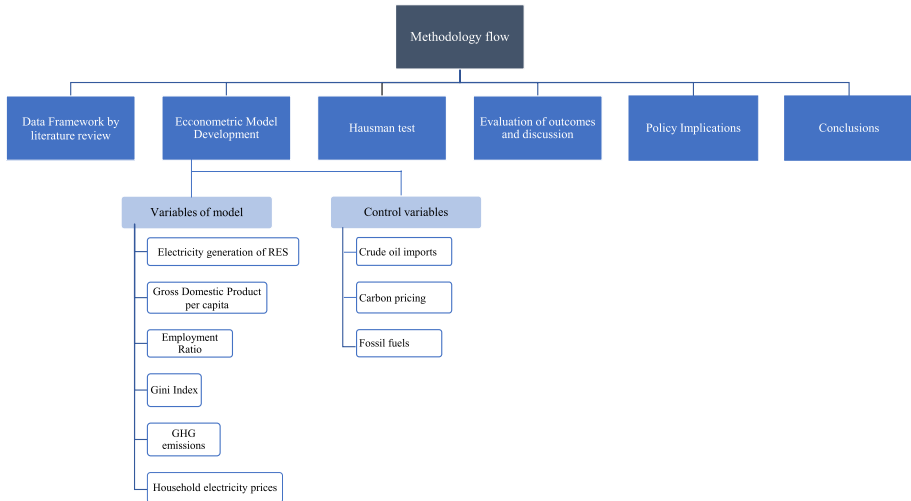
This study addresses these gaps in two-ways. First, adopts an integrated frameworks that jointly evaluates five key-indicators: GHG emissions per capita, GDP per capita, employment ratio, Gini index, and household electricity prices, across the EU-27 and the UK from the period 2007 to 2022, capturing environmental, economic, social, and justice dimensions of energy transition. Second, it disaggregates renewable electricity by technology, allowing for the identification of the heterogeneous effects across solar, wind, hydro and all renewable sources. The novelty on this study lies in its comprehensive, cross-national, and technology-differentiated econometric analysis, thereby advancing the empirical basis for understanding whether renewable electricity in Europe supports a transition that is environmentally effective, economically positive, and socially just promoting a Sustainable and Just Energy Transition.

3 Methods and data

This study assesses the relationship between renewable electricity deployment and key indicators reflecting the environmental, economic, and social dimensions of a “Sustainable and Just Energy Transition”, spanning the 27 EU Member States and UK. Methodology flow applied is summarized in Fig. 1.

3.1 Data and statistics framework

The methodology has been applied to investigate how the expansion of RES electricity generation, as an independent variable, influences social well-being and equity represented by Gini Index, employment ratio and household electricity prices; economic development considering Gross Domestic Product per capita (GDPpc), and environmental aspects only reflected in GHG emission per capita as dependent variables. These indicators serve as measurable proxies of macroeconomic perspective framed under the concept of sustainable and Just Energy Transition, towards sustainable electricity production. Table A.2 provides a list of the variables used and respective sources. Annual data cover de period from 2007 to 2022.



Source: The workflow of the study by the authors

Fig. 1 Methodology flow of the study

Dependent variables are based on (Silva et al., 2024), adding household electricity price for this research. Independent variable is RES total electricity generation, especially, Solar PV, wind energy, and hydropower, due to their significant contribution in recent years, alongside the noteworthy input of hydropower (IEA, 2024; Omri & Nguyen, 2014). (Cialani & Mortazavi, 2018) and (Kashour, 2023) assumed taxes and levies, focused on electricity prices for medium-sized households in consumption Band DC, with annual usage of 2,500 to 4,999 kWh, highlighting potential bias from their limited scope. In contrast, our study examined semesterly average electricity prices across all consumption bands from Eurostat data and reported in Purchasing Power Standard (PPS), beginning with those consuming less than 1,000 kWh. This aspect is relevant given that many households in the lowest decile face severe material deprivation. We also analyzed data for households consuming 15,000 kWh or more, indicating that higher energy usage is crucial for maintaining a satisfactory standard of living (Eurostat, 2024c). Bulgaria, Croatia, Cyprus, Romania, and Malta have employment data gaps due to comparability issues with other databases. Fossil fuel electricity production, Carbon pricing, and crude oil import price as controlling variables from Eurostat and World Bank, emphasizing countries rather than sub-regions.

3.2 Econometric models

We employ a panel data econometric method utilizing fixed effects (FE) models. The work aims to simulate the simple linear regressions represented as:

$$Y_{it} = \alpha + \beta RE_{it-1} + X_{it}'\gamma + \mu_i + \lambda_t + u_{it}. \tag{1}$$

Several models were estimated for different dependent variables: GHG Emissions, Household Electricity Prices (DA, DB, DC, DD, DE), Employment Ratio; log (GDPpc), and Gini Index. Among the independent variables (RE_{it-1}) is expressed annually by total RES lag-log electricity generation in Gigawatt-hour. For RES generation assessment, we employed

five regression models for each one of the nine dependent variables Y_{it} , considering aggregate measures within specific groupings of technologies. We differentiated groups of RES electricity generation based on varying levels of maturity of technologies, ranging from the most to the least mature, which encompassed: i) All RES, ii) just Hydro and Bioenergy (aggregated), iii) Wind and PV (aggregated), iv) Wind, v) PV. X'_{it} is a vector of control variables that includes fossil fuel electricity production, crude oil import prices and the binary environmental policy variable carbon pricing. u_{it} is the idiosyncratic random disturbance, μ_i and λ_t are a country fixed effect and the year fixed effect, respectively.

Our models also use a one-year logarithmic lag of renewable electricity generation as the independent variable to capture its delayed effects on economic performance, emissions, and distributional outcomes. However, alternative lag lengths were tested, but the one-year lag was found to provide the best balance of explanatory power, data coverage, and interpretability.

Utilizing a panel-data econometric approach with FE models, the study effectively captures unobserved, time-invariant heterogeneity across countries. The validity of the FE estimator is supported by Hausman tests, as shown in Table A.3, which generally reject the null hypothesis of no correlation between regressors and unobserved effects, affirming its robustness of the results and validate the use of the FE estimator rather than random effects model) (Nogueira & Madaleno, 2021). A p-value less than 0.05 favors the fixed effects model, indicating inconsistency in random effects (Greene, 2003), as presented in Table A.3. Robust standard errors (White2, HC3), we employed in all specifications to account for heteroskedasticity and within-panel serial correlation. All models include country and fixed effects, which control respectively for time-variant unobserved heterogeneity across country. We examined the potential for multicollinearity, particularly among energy source variables, and used both grouped and disaggregated specifications such as Solar PV vs. wind alone, to check consistency. In addition, while endogeneity cannot be ruled out entirely, particularly for price-related outcomes, the lag structure, extensive controls, and fixed effects help to mitigate its effects. Future research may explore instrumental variable approaches to address this limitation more directly.

Meanwhile, we use grounded control variables to isolate the net effect of RES and reduce omitted variable bias. These include: (i) electricity generation from oil, gas, coal, and nuclear sources, to account for the overall energy mix; (ii) the average crude oil import price, to capture external energy price shocks; and (iii) a binary indicator for carbon pricing. These variables are standard energy economics to control for factors influencing energy prices, emissions, and macroeconomic indicators.

4 Results and discussion

4.1 Statistical analysis of sustainable and just energy transition

Table A.4 summarizes the main outcomes of the panel data econometric analysis. Further details, including Gini Index, employment ratio, household electricity prices, economic development and environmental factors, are presented in Appendix (Tables A.5 to A.13).

Results for fixed effects models indicate that, RES expansion does not provide clear evidence of a significant impact on reducing the inequality between the EU-27 Members States and the UK, during the period spanning this research, as the statistical difference stays below

1%. Considering the variables Gini Index and household electricity prices, as proxies of Just Energy Transition this may demonstrate a weak role of RES technologies to foster social equity.

Table A.4 reports a positive, but limited, correlation among RES deployment and the Gini Index, suggesting a potential link between RES expansion and social well-being. The fixed effects specification controls for country-specific factors, e.g., carbon pricing that may influence inequality (Al-Abdulqader et al., 2025), allowing for a more precise estimation of the RES effects on reducing income inequality (Nguyen & Song, 2021). However, the magnitude of the estimated coefficients remains limited, and the results do not provide strong evidence of a significant redistributive effect. This may reflect a limitation of our analysis, as the benefits of RES policies and carbon pricing mechanisms are not necessarily evenly distributed across social groups, as seen in Table A.4 in Appendix.

Our results differ from the ones achieved by (Topcu & Tugcu, 2020), who investigated the impact of RES consumption on income inequality in 23 developed economies, showing reduction in income inequality. These divergencies may result from differences in geographic scope, specially, their inclusion of non-EU and UK nations and the focus on RES consumption rather than RES power production. Despite progress by the European Commission and the UK, challenges like unequal RES deployment and inadequate policies for low-income families remain (Nora & Klaus, 2022). Meanwhile, these issues present an opportunity for policymakers and stakeholders concentrate on more targeted investments in RES energy, promoting greater social inclusion and sustainable future.

In the light of the theoretical and empirical literature, the outcomes indicate that RES electricity generation positively influence economic growth (Atems & Hotaling, 2018; Bayraktutan et al., 2011). According to model for GDPpc, all RES, except for mature technologies, show a statistically significant positive impact on GDPpc. Based on the estimation results, a 1% increase in power production from the combined group of wind and solar PV technologies demonstrated the most pronounced effect at 0.027 increase in GDPpc, while a 1% increase in total renewable electricity generation corresponds to a 0.026 increase in GDPpc. Individual wind and solar PV technologies also exhibited a positive effect on economic growth with coefficients of 0.020 and 0.018, respectively. In contrast, mature renewable technologies such as hydropower and bioenergy are statistically insignificant. These results may be attributed to Europe energy diversification strategy, which has prioritized the rapid growth and investment in wind and solar energy in the period of analysis. These investments stimulated economic activity in various sectors, thereby contributing to GDPpc growth. Conversely, hydropower's reliance on water resources and climatic conditions, as well as the economic impacts of such projects, limits its scalability compared to compared to solar and wind energy (Ntanos et al., 2018; Yildirim et al., 2012).

Regarding employment, an increase of RES electricity shows a positive and statistically significant effect for the aggregate of all renewables. An increase of 1% of total RES production results in 0.504. Similarly, the combined group of wind and solar PV technologies and individual solar PV, also contribute to employment growth, with estimated impacts of 0.344 and 0.279, respectively. Other renewables show statistically insignificant effects, as depicted in Table A.4. Again, these results may reflect Europe prioritization of wind and solar energy, which has attracted investment, generated employment and stimulated economic activity (Arvanitopoulos & Agnolucci, 2020; Proença & Fortes, 2020).

Moreover, the significant reduction in GHG emissions associated with RES expansion, reinforces the crucial role of RES in climate change mitigation. Our findings, indicate that all

renewable sources, except for mature technologies, are associated with a statistically significant decrease in GHG emissions. This supports the empirical evidence of (Adebayo & Kirikkaleli, 2021), who also identified a negative correlation between RES and CO₂ emissions for Japan. The largest GHG emissions decrease is observed in the aggregate of all renewables and the combined group of wind and solar PV, demonstrating a decline in the emissions around -0.399 and -0.244 , respectively. Individually, solar PV and wind technologies are also associated with decrease in emissions at -0.169 and -0.145 , respectively. In contrast, mature renewable technologies such as hydropower and bioenergy show statistically insignificant relation.

Our findings indicate that, even after the expansion of electricity generation by RES, especially in wind and solar PV, household electricity prices tend to increase, albeit with low statistical significance in all consumption bands DA, DB, DC, DD and DE. However, the fixed effects model underscores the significance of wind energy in relation to the variability of electricity prices. Although, the lower R-square value suggests that even after considering country-specific effects, a portion of the variability in electricity prices remains unexplained, suggesting that additional unobserved factors may be influencing electricity prices, as outlined Tables A.5—A.13 in Appendix. These findings underscore a limitation of the study, the exclusion of variables such as urbanization rate, health, age, gender, marriage, family composition, demographic, household size and type (Cialani & Mortazavi, 2018; Kashour, 2023), which shapes household energy consumption across different consumption bands.

As states by Kanzig (Känzig, 2023) severe carbon pricing policies, can lead to higher energy prices, which burden lower-income households who then lower their consumption significantly.

These raises concerns that carbon neutrality policy in EU may conflict with certain sustainable development goals, as high energy price adversely affects well-being, particularly for low-income households.

Our findings highlight both the strengths and the limits of renewable electricity deployment in advancing a sustainable and just energy transition. The positive effects on growth and employment, along with significant reductions in GHG emissions, reinforce the conclusions of earlier studies such as (Adebayo & Kirikkaleli, 2021; Atems & Hotaling, 2018; Proença & Fortes, 2020), which underline the macroeconomic and environmental benefits of renewables. However, the weak and statistically insignificant impact on inequality diverges from (Topcu & Tugcu, 2020), who find that renewable energy consumption reduces inequality in developed economies. The modest and inconsistent effects on electricity prices also echo (Cevik & Ninomiya, 2023) and (Liebensteiner et al., 2025), who point to structural and market factors in shaping affordability outcomes. Our outcomes may reflect Europe's emphasis on large-scale deployment and market-based instruments, which stimulate aggregate economic activity but do not necessarily improve distributional results.

Overall, results confirm that while the environmental and economic pillars of sustainability have been supported by renewable deployment, the social dimension remains less conclusive, reflecting one of the policy concerns inherent in the just energy transition.

5 Policy implications

This study provides insights that can offer valuable guidance for the design of policies aimed at ensuring a sustainable and Just Energy Transition. Our results show that renewable electricity expansion, particularly in wind and solar PV, has played an effective role in

driving economic growth, employment growth, and GHG emissions reduction. However, the analysis also reveals important limitations in distributional outcomes and affordability, underscoring the need for integrated and responsive policy frameworks that go beyond environmental targets and integrate social objectives.

The robust positive association between wind and solar PV deployment on GHG emissions decline and GDPpc growth, presented in our results, suggest continued public and private investment in these technologies. However, greater grid flexibility and infrastructure investment will be necessary to integrate the high share of variable renewables (IEA, 2023). At the same time, policymakers should also consider how renewables can be expanded in ways that generate wider social benefits. The modest and not always statistically significant relation between renewables and household electricity prices may raise additional concerns about energy affordability, which is especially relevant for low-income households. Prior research suggests that redistributive policy instruments, such as energy vouchers, social electricity tariffs, or target funding to promote more energy efficient buildings, can help mitigate the risks for vulnerable households (Streimikiene et al., 2020), to ensure the economic benefits generated by deployment of renewable energy are shared with consumers (Pereira et al., 2019).

The literature also points to decentralized solar generation through community energy schemes and residential PV programs as one promising strategy for improving affordability and resilience (Lee & Shepley, 2020). However, evidence from German energy communities indicates that without enabling regulation and targeted subsidies, most initiatives struggle to reach low-income households (Hanke & Guyet, 2023). Local financing mechanisms, such as municipality-backed subsidies or targeted support for low-income households (Parreño-Rodríguez et al., 2023), could therefore play a key role in ensuring that decentralization complements the broader economic and environmental gains from renewable deployment.

Employment gains further reinforce the need to align renewable deployment with labor market policies. While their expansion contributes to a general employment growth, as seen in our results, the benefits may not be equitably distributed without targeted policy measures. As (Letta, 2024) argues, reskilling programs and policies that support workforce mobility are crucial to offset losses in carbon-intensive industries.

In fact, the absence of a statistically significant effect on income inequality, sustained by the Gini index model, suggests that renewable deployment alone cannot guarantee social equity objectives, aligning with (Cludius et al., 2014), who emphasize the importance of integrating distributive mechanisms into energy policy. Options such as social tariffs, targeted subsidies, or the recycling of carbon revenues to vulnerable households (Borge-Diez et al., 2024), can ensure that the aggregate economic benefits of renewables are more equitably distributed.

Such policies can help ensure that the benefits of renewables deployment extend beyond growth and decarbonization, translating into concrete improvements in social equity and thereby reinforcing the foundations of a sustainable and just energy transition in Europe.

6 Conclusion

This study empirically assesses the relationship between renewable electricity deployment and key environmental, economic and social indicators across the EU-27 Member States and UK between 2007 to 2022. Framed within sustainable and Just Energy Transition concept. The analysis employed a panel data econometric approach to quantify how the expansion

of renewable electricity has influenced GHG emissions, economic growth, employment, income inequality, a household electricity prices, identifying both the potential benefits and limitations of RES deployment.

The results indicate that RES expansion, particularly wind and solar PV, has significantly contributed to increases in GDP per capita and employment. However, it has not shown a consistent or statistically significant effect on reducing income inequality, as measured by the Gini Index. This highlights a key limitation, while RES can generate aggregate economic benefits, their distributional impacts remain uneven, despite policy efforts at the EU and national levels to enhance equity in the transition, structural barriers persist that prevent all social groups from equally benefiting.

In terms of environmental outcomes, the study confirms that RES expansion is crucial in reducing GHG emissions, reinforcing its value as a cornerstone of climate policy. However, the relationship between RES deployment and household electricity prices remains more ambiguous. Although, some association is observed, particularly with wind energy, the effects are modest and not statistically significant across all consumption bands. Moreover, the low explanatory power of the models suggests that other unobserved factors influence price variability and merit further investigation.

The current study has limitations, including the exclusion of variables such as households size, family composition, gender, and age, which could improve insights into household electricity prices. Additionally, the social dimension is proxied by broad measures like Gini Index and electricity prices by consumption bands, which do not fully capture the complexity of Just Energy Transition or the impacts on different income groups. This highlights the need warrants further in-depth investigation in future studies.

Building of these results, the study contributes to the policy debate by suggesting that renewable deployment must be complemented with measures that enhance equity and affordability. In particular, redistributive measures, such as social tariffs or targeted subsidies are needed to protect vulnerable households from price volatility and promote greater equality, while labor market measures, including training and reskilling programs may ensure that consolidate climate mitigations and economic growth. Together, these strategies can help EU and UK align environmental effectiveness with economic prosperity and social fairness.

Future research should expand on these findings by further exploring the distributive consequences of decarbonization policies, particularly through disaggregated analysis across income groups, regions, and household types. A deeper understanding of these dynamics will be essential to guide evidence-based policymakers for a truly sustainable and Just Energy Transition.

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Data availability The data presented in this study are available on request from the corresponding author.

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