

Towards the green transition in the European regions. Assessing eco-efficiency in greenhouse gases emissions

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The green transition represents one of the most profound economic, social, and environmental challenges facing the European Union (EU) today. Accelerating global warming and the increasing frequency of climate-related extreme events have reinforced the urgency of reducing greenhouse gas (GHG) emissions, which constitute the primary driver of climate change. In response, the Paris Agreement and, more specifically, the European Green Deal (EGD) set ambitious targets: a 55% reduction in GHG emissions by 2030 compared to 1990 levels and the achievement of climate neutrality by 2050. Achieving these objectives requires not only absolute reductions in emissions but also a transformation of economic systems in a way that preserves economic growth, social cohesion, and territorial balance across the EU.

The challenge of the green transition is inherently spatial. European regions differ widely in their economic structures, levels of development, institutional quality, and social norms. These differences imply that regions face very unequal capacities and constraints in decoupling economic activity from environmental pressure. Regions specialized in carbon-intensive industries, such as energy production, heavy manufacturing, and extractive activities, face higher transition costs than service-oriented regions characterized by knowledge-intensive activities. As a result, the green transition risks exacerbating existing territorial inequalities unless policies are carefully designed and grounded in accurate, region-specific evidence.

Against this background, the measurement of environmental performance becomes a critical prerequisite for effective policymaking. Traditional indicators focusing exclusively on environmental outcomes – such as air or water quality – provide valuable information but fail to account for the economic dimension of sustainability. From a policy perspective, the core objective of the green transition is not simply to reduce emissions, but to do so while sustaining economic activity and living standards. This calls for indicators capable of jointly assessing economic performance and environmental impact. Eco-efficiency indicators respond directly to this need by measuring the ability of territories to generate economic value while minimizing environmental damage.

This paper develops and applies a novel eco-efficiency indicator focused on greenhouse gas emissions at the regional level in the European Union. Eco-efficiency is defined as the capacity of a region to produce economic output while exerting the lowest possible pressure on the environment. By explicitly relating

GHG emissions to economic performance, the proposed indicator closely aligns with the fundamental objectives of the European Green Deal and provides policymakers with an intuitive and operational tool for guiding the green transition.

The empirical analysis covers 231 NUTS2 regions across the European Union and focuses on the year 2023, using three-year averages for the period 2021–2023 to mitigate the influence of short-term fluctuations and measurement errors. Economic performance is proxied by regional Gross Domestic Product (GDP) expressed in constant 2015 euros. Environmental performance is measured using aggregate greenhouse gas emissions, including fossil carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and fluorinated gases, all expressed in CO₂-equivalents based on the Global Warming Potentials from the IPCC Fifth Assessment Report. Emissions data are sourced from the Emissions Database for Global Atmospheric Research (EDGAR), which enables, for the first time, a comprehensive and harmonized assessment of GHG emissions at the regional level within the EU.

Methodologically, the paper employs Data Envelopment Analysis (DEA), a non-parametric frontier technique widely used to evaluate relative performance in the presence of multiple inputs and outputs. DEA constructs a best-practice frontier from the observed data and assesses each region relative to this benchmark. In the context of eco-efficiency, GDP is treated as a desirable output, while GHG emissions represent undesirable outputs to be minimized. A key advantage of DEA lies in its ability to endogenously determine the weights assigned to different pollutants according to the “benefit-of-the-doubt” principle, thereby avoiding arbitrary assumptions about their relative importance and allowing each region to be evaluated under the most favorable weighting scheme consistent with the data.

The resulting eco-efficiency indicator is emissions-oriented and measures the potential for each region to proportionally reduce all greenhouse gas emissions while maintaining its observed level of GDP. Eco-efficiency scores range between zero and one, with a value of one indicating full eco-efficiency – that is, a region operating on the best-practice frontier. Lower scores indicate a greater potential for emission reductions without sacrificing economic output.

The results reveal a generally low level of eco-efficiency across EU regions, suggesting that substantial reductions in greenhouse gas emissions could be achieved without compromising economic performance. However, the degree of eco-efficiency varies dramatically across regions. The most eco-efficient regions are predominantly located in Northern and Western Europe and often correspond to capital regions or major metropolitan areas, such as Brussels, Paris, Berlin, Stockholm, and Vienna. These regions are typically characterized by a strong concentration of high-value-added service activities, advanced technological sectors, and relatively low dependence on carbon-intensive industries.

In contrast, the least eco-efficient regions are mainly found in Central and Eastern Europe, as well as in some Southern European regions. These territories often exhibit a higher reliance on energy-intensive industrial activities, fossil fuel-based electricity generation, or agriculture, resulting in high levels of GHG emissions relative to their economic output. Importantly, the analysis highlights substantial within-country heterogeneity, with pronounced disparities between regions belonging to the same national context. This finding underscores the limitations of country-level analyses and reinforces the importance of adopting a regional perspective when designing and implementing green transition policies. A notable contribution of the study is the comparison between eco-efficiency outcomes and indicators based solely on ecological performance. Regions that perform well in terms of absolute emissions or environmental quality do not necessarily rank highly in eco-efficiency terms once economic output is taken into account. Conversely, some regions with relatively high emissions achieve strong eco-efficiency scores due to their exceptional economic performance. This distinction illustrates the added value of the eco-efficiency framework for policy analysis, as it captures the trade-off between economic activity and environmental impact more accurately than purely ecological indicators.

To further explore the role of productive structures, the paper conducts a meta-frontier analysis that distinguishes between industrial, service-oriented, and mixed regions. This approach allows for the comparison of eco-efficiency across groups characterized by different technological and structural constraints. The results indicate that service-oriented regions operate with more eco-efficient technologies in terms of greenhouse gas emissions, while industrial regions face stronger technological limitations. At the same time, contextual factors – such as institutional quality and economic development – play a particularly important role in explaining eco-inefficiency within service regions.

The robustness of the results is thoroughly assessed through a series of sensitivity analyses. Alternative eco-efficiency indicators are constructed using different DEA specifications, including bias-corrected scores obtained via bootstrapping, non-radial slacks-based measures, models with variable returns to scale, and a normalized GDP-to-emissions ratio. Despite differences in distributional properties, the regional rankings derived from these alternative indicators exhibit very high correlations with the baseline measure, confirming the stability and reliability of the findings.

In a second stage, the paper investigates the determinants of regional eco-efficiency using the two-stage estimation framework proposed by Simar and Wilson. This methodology combines truncated regression models with bootstrapping techniques to correct for the bias and serial correlation inherent in DEA-based efficiency scores. The analysis considers a broad set of potential explanatory variables, including economic, demographic, institutional, and geographical factors.

The results show that economic development, measured by GDP per capita, is a strong and robust determinant of regional eco-efficiency. Wealthier regions tend

to be more eco-efficient, reflecting their greater capacity to invest in cleaner technologies, higher energy efficiency, and stronger societal demand for environmental quality. Regions hosting national capital cities also exhibit significantly higher eco-efficiency, even after controlling for income levels, industrial structure, and institutional quality. This suggests that agglomeration economies, advanced service specialization, and superior governance capacities play a crucial role in reconciling economic performance with environmental sustainability.

The structure of the economy emerges as a critical factor: a higher share of industrial activity in regional gross value added is systematically associated with lower eco-efficiency. By contrast, trade openness and population ageing do not display statistically significant effects once other variables are taken into account. Among institutional factors, both quality of government and social capital exert a positive and significant influence on eco-efficiency. Regions characterized by high levels of trust, civic engagement, and effective governance are better able to implement and sustain policies that promote environmentally efficient economic activity.

Overall, this paper provides novel and policy-relevant evidence on greenhouse gas eco-efficiency across European regions. By integrating economic and environmental dimensions within a unified analytical framework and exploiting newly available regional emissions data, the study offers a powerful tool for monitoring progress towards the objectives of the European Green Deal. The regional focus reveals substantial disparities and highlights the need for place-based policy interventions that account for differences in productive structures, institutional capacity, and social capital.

From a policy perspective, the findings suggest that EU and national funding mechanisms should be more closely linked to regional eco-efficiency performance, prioritizing support for regions with low eco-efficiency and high carbon intensity. Policies aimed at technological upgrading, industrial diversification, and innovation are essential to reduce emissions while maintaining economic growth. Moreover, strengthening governance quality and social capital can enhance policy effectiveness and contribute to sustained improvements in eco-efficiency. Finally, fostering cooperation and knowledge transfer between high- and low-performing regions can help disseminate best practices and support a fair, inclusive, and cohesive green transition across the European Union.