DECARBONIZATION OF EU SERVICES SECTOR: SHADOW CARBON PRICES APPROACH IN ENERGY EFFICIENCY ANALYSIS

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Abstract
The transition to a climate-neutral economy positions energy efficiency as a cornerstone of the European Union's (EU) strategy. While significant attention has been paid to the industrial and residential sectors, the service sector has emerged as a critical area due to its rapid growth and increasing energy demand. This paper addresses the urgent need for effective methods to monitor and improve energy efficiency within this complex sector. The primary objective is to provide a comprehensive review of the existing literature on tracking energy efficiency in the EU service sector and to highlight the potential of the shadow carbon price (SCP) approach as an advanced analytical tool for policy analysis. This paper synthesises findings from recent studies and policy documents, examining the theoretical foundations of the SCP approach based on non-parametric techniques like Data Envelopment Analysis (DEA) to assess the marginal cost of CO_2 abatement. The main findings from the literature indicate that while the EU has a robust policy framework, including the Effort Sharing Regulation (ESR) and the new Emissions Trading System (ETS2), there are significant disparities in energy efficiency performance across EU member states. The originality of this paper lies in its focused application of the SCP concept to the under-researched tertiary sector, proposing it as a vital tool for evaluating policy effectiveness and guiding the EU's transition to a low-carbon service economy by providing a more nuanced understanding of the economic trade-offs involved in reducing environmental impact of energy consumption in the service sector.

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Introduction

The aim to achieve transition towards climate-neutral economy has positioned energy efficiency as a cornerstone of the European Union's (EU) long-term strategy. The EU has established an ambitious climate goal, including the targets set forth in the European Green Deal and the REPowerEU plan. The EU has intensified its focus on reducing energy consumption in all sectors of the economy. While significant attention has historically been directed towards the industrial and residential sectors, the service sector—also known as the tertiary sector—has emerged as an area of critical importance. Characterised by its rapid growth and increasing energy demand, the service sector presents both unique challenges and substantial opportunities for energy savings and GHG emission reduction (European Commission, 2023).

The tertiary or service sector, encompassing a wide array of activities from retail and hospitality to finance and public administration, is the fastest-growing economic sector in the EU in terms of energy consumption (Tzeiranaki et al., 2023). Its final energy consumption increased by over 20% between 2000 and 2019, a trend driven by economic expansion, the increase of electric appliances and digital technologies, and a growth in the total floor area of commercial and public buildings. This growth trajectory underscores the urgent need for effective methods to monitor, measure, and improve energy efficiency within this diverse and complex sector.

Traditional approaches to measuring energy efficiency often rely on aggregate indicators that may not fully capture the complex interplay between economic activity and environmental performance (Abu Bakar et al., 2015). The shadow carbon price (SCP) approach offers a more sophisticated and insightful alternative. A SCP represents the marginal cost of abating one additional unit of carbon dioxide (CO_2) emissions, providing a monetary valuation of the environmental cost associated with economic activities. By employing non-parametric techniques such as Data Envelopment Analysis (DEA), this approach can assess the efficiency of production processes that generate both desirable outputs (e.g., economic value) and undesirable outputs (e.g., greenhouse gas emissions) (Balezentis, Streimikiene and Shen, 2025; Zhu et al., 2025). This allows for a more nuanced understanding of energy efficiency, not merely as a measure of energy input per unit of output, but as a reflection of the economic trade-offs involved in reducing environmental impact. Although there are studies applying the SCP in analysing decarbonisation paths in EU industry, agriculture, power sectors (Streimikis, Shen, and Balezentis, 2024; Balezentis, Streimikiene, and Shen, 2025; Shen et al., 2025; Zhu et al., 2025) and other countries industry, power, construction sectors (Lee and Zhang, 2012; Wang et al., 2018; Cheng et al., 2020; Deng and Du, 2020; Shen et al., 2021; Xue et al., 2022) however, there is lack of studies analysing energy efficiency of tertiary sector by applying this approach.

This paper aims to fill this gap and provides a comprehensive review of the existing literature on tracking energy efficiency in the service sector of EU member states and develops case study to assess energy efficiency in the service sector of EU member states by applying the SCP approach. The main input of this paper is to reveal the potential of the SCP price approach as a vital tool for guiding the EU's transition to a low-carbon service economy.

The paper is structured in the following way: first section analyses literature by defining the methodological foundations of carbon shadow pricing and its application in energy efficiency analysis, later analysis covers specific context of the EU's service sector, examining its energy consumption patterns and the key policies and targets designed to promote energy efficiency EU. The section 2 presents the empirical study by applying the SCP approach for assessing the energy efficiency of tertiary sector of EU Member States. The final section concludes.

1. Literature review

1.1 Shadow carbon price approach

The concept of a shadow carbon price is a powerful tool in economic analysis, used to assign a monetary value to goods or externalities that are not traded in a market. In the context of environmental economics, the SCP quantifies the marginal abatement cost of CO_2 emissions, effectively representing the implicit cost that a producer would incur to reduce their emissions by one unit while maintaining the same level of desirable output (Wang et al., 2022). A higher SCP suggests that a firm or a country is operating more efficiently from an environmental perspective, as further reductions in emissions would come at a greater economic cost. Conversely, a low CSP indicates inefficiency, implying that significant emission reductions can be achieved at a relatively low cost (Zhu et al., 2025).

Methodologically, the estimation of carbon shadow prices has increasingly relied on non-parametric frontier analysis, particularly Data Envelopment Analysis (DEA). DEA is a linear programming-based technique used to measure the relative efficiency of decision-making units (DMUs), such as firms or countries, which consume multiple inputs to produce multiple outputs (Lee, Oh and Lee, 2014). A key advancement in this field is the development of the by-production model, which treats undesirable outputs like CO_2 emissions not as inputs or simple reductions from desirable outputs, but as jointly produced by-products of the production process. This framework provides a more accurate representation of the underlying technology and the trade-offs between economic and environmental performance (Shen et al., 2021; Balezentis, Streimikiene and Shen, 2025).

Several recent studies have applied these advanced methodologies to EU countries. Zhu et al. (2025) utilised a By-production DEA model to estimate the CSP for 27 EU member states from 1995 to 2019. Their findings revealed a significant increase in the average CSP over the period, indicating improved environmental performance, although with considerable disparities among member states. The study also highlighted a positive, albeit nonlinear, relationship between green technology innovation and the CSP, suggesting that policy and economic development must reach certain thresholds for innovation to translate into significant environmental performance gains. Similarly, Balezentis, Streimikiene and Shen (2025), while focusing on the EU's manufacturing sector, demonstrated the utility of the by-production model in assessing the costs of GHG emission reduction and identifying the most efficient mitigation policies. Their results showed substantial variation in CSPs across the EU, with countries like Slovakia and Hungary facing higher abatement costs (Balezentis, Streimikiene and Shen, 2025). These studies collectively establish the carbon shadow price, estimated via by-production DEA, as a robust and insightful metric for tracking environmental and energy efficiency.

It is necessary to stress that the main approach used in analysed papers is the by-production model, which treats desirable and undesirable outputs as joint products of the production process. Cheng et al. (2020) and Shen et al. (2021) both utilise this framework, emphasising its theoretical advantage of satisfying the materials balance principle, which is often violated in other models. Shen et al. (2021) further extends the by-production model to ensure a meaningful shadow price estimation by linking the sub-technologies that define production and pollution activities.

Another widely used method is the directional distance function (DDF), which can be either parametric or non-parametric. Lee and Zhang (2012) and Wang et al. (2018) employ a parametric DDF, which requires a predefined functional form, to analyse the Chinese manufacturing and construction industries, respectively. In contrast, Deng and Du (2020) use an endogenous DDF to avoid arbitrary mapping rules and capture the progressive nature of technology in their study of the Belt and Road Initiative (BRI) countries. The non-parametric approach, often implemented using Data Envelopment Analysis (DEA), is favoured for its flexibility and ability to easily impose economic axioms. Streimikis, Shen and Balezentis (2024) demonstrate the sensitivity of shadow price analysis to the assumed optimisation direction within a weak disposability DEA framework, highlighting the importance of methodological choices in policy design.

Recognising the limitations of assuming a single production frontier, Shen et al. (2025) introduce a novel spatially adaptive nonparametric framework. This approach addresses the often-overlooked issue of spatial heterogeneity by defining reference sets based on geographical proximity, providing a more accurate and policy-relevant method for promoting sustainable development in sectors with high spatial variation, such as agriculture,

The reviewed literature reveals significant heterogeneity in carbon shadow prices across different regions and economic sectors. In China, the industrial sector, being a major contributor to carbon emissions, has been a primary focus of research. Cheng et al. (2020) found that the industrial carbon shadow price in China increased by 3.83% annually from 2003 to 2017, with an average provincial price of approximately $562.43 USD/ton. Shen et al. (2021) also observed an increasing trend in the carbon shadow price of China's industrial sector from 1998 to 2017.

Within the industrial sector, there is considerable variation. Lee and Zhang (2012) found that the shadow prices of CO_2 in the Chinese manufacturing industries varied from a high of $18.82 to a low of zero, with an average of $3.13 per ton, indicating a large potential for cost savings through emissions trading. Xue et al. (2022) further emphasise this heterogeneity, showing that technical efficiency, abatement potential, and costs vary significantly across provinces and industries. Their study identifies key provinces and industries with low technical efficiency and high abatement potential as priorities for emission reduction efforts. The construction industry is another significant contributor to carbon emissions, and Wang et al. (2018) highlight the importance of considering both direct and overall emissions from this sector and its supporting materials industries.

Beyond China, Deng and Du (2020) provide a broader perspective by analysing 52 BRI countries. Their findings show that the average shadow prices of CO_2 emissions for all BRI countries increased steadily from 2005 to 2016, with Eastern Europe and Central Asia showing much higher shadow prices than other regions. In the context of the European Union, Streimikis, Shen and Balezentis (2024) analyse the agricultural sector and find spatial and temporal variation in environmental performance, suggesting that agricultural support programmes should be adjusted accordingly. Shen et al. (2025) also focus on the agricultural sector in China, demonstrating the importance of considering spatial heterogeneity in environmental performance analysis.

The reviewed literature provides valuable insights into the estimation and application of carbon shadow prices. A key takeaway is the importance of methodological rigour, as the choice of model and assumptions can significantly impact the results. The by-production approach and spatially adaptive frameworks appear to be promising avenues for future research, offering more theoretically sound and empirically relevant estimations.

The consistent finding of heterogeneity in carbon shadow prices across regions and sectors underscores the need for tailored and differentiated environmental policies. Furthermore, the increasing trend in carbon shadow prices observed in several studies suggests that the opportunity cost of carbon abatement is rising. This highlights the urgency of investing in green technologies and promoting energy efficiency to mitigate the economic impact of carbon reduction policies.

1.2 EU energy policies in the tertiary sector

The EU's energy efficiency policies are deeply intertwined with its broader climate objectives, which are legally enshrined in the European Climate Law. This landmark legislation sets a binding, economy-wide target for the EU to achieve climate neutrality by 2050, with an intermediate target of reducing net greenhouse gas (GHG) emissions by at least 55% by 2030 compared to 1990 levels. More recently, the EU has agreed on a 90% net GHG reduction target for 2040, further solidifying its commitment to a low-carbon future (European Commission, 2023).

The service sector, as a significant energy consumer, plays a crucial role in meeting these targets. GHG Emissions from this sector are primarily addressed through two key mechanisms: the Effort Sharing Regulation (ESR) and the new Emissions Trading System for buildings and road transport (ETS2**)**.

The ESR sets binding annual GHG emission reduction targets for each Member State for the sectors not covered by the existing EU ETS. This includes GHG emissions from buildings, transport, agriculture, and waste. For the period 2021-2030, the ESR aims for a collective EU-wide reduction of 40% in these sectors compared to 2005 levels, with national targets varying based on GDP per capita (European Commission, 2023). As buildings constitute a large portion of the service sector's emissions, the ESR provides a direct regulatory driver for Member States to implement policies that reduce energy consumption and promote decarbonisation in commercial and public buildings.

Recognising the need for a more targeted carbon pricing signal, the EU has introduced the ETS2, which will become fully operational in 2027. This new cap-and-trade system will specifically cover CO_2 emissions from fuel combustion in buildings and road transport. By placing a price on these emissions, the ETS2 is designed to incentivise a shift away from fossil fuels for heating and cooling in commercial buildings and to encourage investment in energy efficiency and renewable energy solutions (European Commission, 2023). The revenues generated from the ETS2 will be channelled into the Social Climate Fund, which will help mitigate the social impacts of the new carbon price on vulnerable households and transport users.

Below, the EU targets for GHG Reduction, Energy Efficiency, and Renewables are established for EU by 2030 are summarised.

The overall EU binding target is of at least a 55% net reduction in total GHG emissions by 2030, compared to 1990 levels. Sector-Specific Obligations include:

- Under revised Effort Sharing Regulation (ESR), Member States have binding national targets that collectively aim for a 40% reduction in emissions from service related sectors (small industry, non-ETS transport and buildings, and waste) at the EU level by 2030, compared to 2005 levels.

- Under Emissions Trading System 2 (ETS2**)** from 2028 (postponed from 2027), GHG emissions from fuel combustion in buildings and road transport will be covered by a new, separate emissions trading system, putting a price on carbon in these key tertiary sector areas.

An EU-wide binding target is to reduce final energy consumption by at least 11.7% by 2030, compared to 2020 projections. Sector-Specific Obligations include:

- A Public sector (a large part of the tertiary sector) is subject to a new annual energy consumption reduction target of 1.9%.

- There is a renovation obligation for Member States to renovate at least 3% of the total floor area of buildings owned by the central government (including all levels of public administration) each year.

- Member States must achieve an average annual energy savings rate of 1.49% from 2024 to 2030 across end-use sectors, including buildings and transport.

- The revised Energy Efficiency Directive introduces obligations for the monitoring and reporting of energy performance of data centres to promote efficiency in this rapidly growing industry.

An Overall EU binding target is of at least 42.5% share of renewable energy in the EU's gross final energy consumption by 2030, with an ambition to reach 45%. Sector-Specific Targets cover:

- The revised Renewable Energy Directive (RED III) introduces an indicative national benchmark of a 49% share of renewable energy in the buildings sector by 2030.

- A national binding target for an annual increase in the share of renewables in heating and cooling of 0.8% by 2026, followed by a 1.1% annual increase until 2030.

- Member States have the flexibility to choose between committing to a 14.5% reduction in GHG intensity in the transport sector or ensuring a renewables share of at least 29% by 2030. This is complemented by stringent CO_2 standards for new cars and vans, requiring zero tailpipe emissions from 2035.

Table 1 summarises the key EU GHG reduction policies and their specific relevance to the service sector.

Table no. 1. EU GHG policies relevant to tertiary sector

Policy Instrument	Key Feature	Relevance to Service Sector
European Climate Law	Legally binding targets for 2030, 2040, and 2050	Sets the overarching framework for all sectoral climate action
Effort Sharing Regulation (ESR)	National GHG reduction targets for non-ETS sectors	Covers the majority of emissions from buildings and service-related transport
EU ETS 2	Carbon pricing for buildings and road transport fuels	Directly incentivises decarbonisation of heating, cooling, and vehicle fleets
Energy Performance of Buildings Directive (EPBD)	Aims for a fully decarbonised building stock by 2050	Drives deep renovation and high-performance standards for commercial buildings

Source: *Created by authors*

The combination of these policies creates a multi-faceted approach to reducing GHG emissions from the service sector. While the EED and EPBD focus on driving energy efficiency improvements, the ESR and ETS2 provide the overarching carbon constraint and price signal necessary to ensure that these improvements translate into real and lasting emissions reductions. The carbon shadow price approach can be a valuable tool in this context, helping to assess the cost-effectiveness of different policy mixes and to identify the most efficient pathways for the service sector to contribute to the EU's ambitious climate goals.

1.3 Energy efficiency performance of EU tertiary sector

The service sector is a cornerstone of the modern European economy, but its growth has been accompanied by a steady rise in energy consumption and related GHG emissions. The sector accounts for approximately 13-14% of the EU's total energy consumption and is responsible for around 5-6% of its direct CO_2 emissions, primarily from the combustion of fossil fuels for heating and on-site electricity generation (Odysee-Mure, 2024). While less energy-intensive than the industrial sector, its expanding economic footprint and reliance on electricity for lighting, cooling, and equipment make it a critical area for energy efficiency interventions. Although the energy intensity of the sector (energy consumption per unit of value added) has been decreasing, absolute energy consumption has remained relatively stable due to the sector's overall growth (Odysee-Mure, 2024).

To track progress in this complex sector, the Odyssee-Mure project utilises the ODEX indicator. For the service sector, the ODEX is calculated as a weighted average of unit consumption trends in six branches: offices, health and social work, wholesale and retail trade, hotels and restaurants, education, and others. The indicator considers both thermal uses (toe/m²) and electrical uses (toe/employee) to provide a comprehensive measure of efficiency progress (Odysee-Mure, 2024).

An analysis by the Odyssee-Mure project provides a detailed scoreboard of member state performance, revealing significant disparities across the EU. Based on a combined score for efficiency levels, trends, and policies, the top-performing countries in the service sector in 2023 were Hungary, France, Poland, Germany, and Spain. However, when looking specifically at the energy savings achieved between 2000 and 2021, a different set of leaders emerges: Slovakia (59.7%), Hungary (50.9%), and Slovenia (48.7%) demonstrated the most substantial improvements. Conversely, countries like Greece, Portugal, and Cyprus showed the lowest energy savings over the same period, indicating a significant untapped potential for efficiency gains.

The policy landscape for energy efficiency in the service sector is similarly varied. The most widely adopted measures in the EU are mandatory building standards and subsidies for investments in efficient technologies. Most member states have implemented energy performance standards and provide financial support for renewable heating technologies and thermal insulation. However, other potentially effective measures, such as specific energy tariffs or tax reductions, are implemented in only a few countries, highlighting a fragmented approach and the opportunity for greater policy harmonisation and knowledge sharing. The Odyssee-Mure project identifies the most successful policies as those that have a significant impact, are cost-effective, overcome market barriers, and are well-integrated with other measures. Based on these criteria, the countries with the most innovative and successful policy measures in the service sector include Slovenia, Finland, Greece, and Spain. This detailed analysis performed by Odyssee-Mure project however does not allow to measure and understand the effectiveness of achieved energy efficiency increase in EU. Therefore, the case study on assessing energy efficiency in EU countries by applying SCP approach is performed.

2. Case study on assessing energy efficiency in EU MS

2.1 Methods

Analysis of the carbon shadow prices relies on the non-parametric approach. Specifically, data envelopment analysis is used to establish the production frontier extended with environmental pressures as undesirable outputs. The DEA models are linear programming problems. Therefore, they have dual expressions. This allows one to gauge the shadow prices of undesirable outputs that would be not available on the market. The multiplier model assigns shadow values to the variables in the production technology and the ratios of these values serve as the shadow prices. Essentially, the shadow price of the carbon emission is the marginal abatement cost indicating the reduction in economic activity necessary to secure a decline in the generation of the undesirable outputs by one unit.

The by-production DEA model developed by Balezentis et al. (2021) is implemented to measure the production possibilities and shadow price of the CO_2 emission. The by-production technology relies on the theory developed by Murty, Russell and Levkoff (2012). The by-production technology assumes that two sub-technologies exist, each describing economic and environmental performance. Variable returns to scale technology is assumed (i.e., the weights in the envelopment model add up to 1). The shadow price of an undesirable output is obtained as the ratio of the multipliers associated with the undesirable and desirable outputs. The multiplier formulation is used to this end. The output used as the numeraire in this case is the value added. It has a price of 1 which makes the calculation of the shadow price quire straightforward.

2.2 Data

The data come from Eurostat. Due to data availability, the empirical research confines to the wholesale and retail trade and repair of motor vehicles (section G under NACE rev. 2). To ensure comparability, we exclude economies with sector-level data publicly unavailable, and 22 countries are retained in total (Austria, Belgium, Czechia, Denmark, Estonia, Greece, Finland, France, Hungary, Ireland, Italy, Lithuania, Luxembourg, Latvia, Malta, the Netherlands, Poland, Romania, Sweden, Slovenia, Slovakia). The period of 2008-2021 is covered. The analysis is implemented within each year independently. By doing this, we ignore temporal variations in the production possibility frontier. The environmental production technology is defined in the standard manner viz., the KLVA (capital, labour, value added) framework augmented with the CO_2 emission. Fixed assets and value added in Euro of 2015 are taken from the national accounts. Labour input is measured in hours worked and also comes from the national accounts. The carbon dioxide emission is taken from environmental accounts. Descriptive statistics of the input and output variables are presented in Table 2. As one can note, the variation in the data – as measured by the coefficient of variation (CV) – is rather high. Specifically, the lowest CV is observed for labour input (1.2). The highest variability is noted for the CO_2 emission (1.6). therefore, the environmental dimension of sustainability is likely to exhibit a more diverse performance compared to the economic one in the EU retail and wholesale trade and vehicle repair sector.

Table no. 2. Descriptive statistics for the input and output variables in the environmental production technology for the EU trade and vehicle repair, 2008-2021

Statistic	Assets, million Euro	Labour, thousand hours	Value-added, million Euro	CO_2 emission, tonnes
Average	43291	1826033	48761	3079291
SD	56757	2277727	70376	5037322
CV	1.3	1.2	1.4	1.6

Source: *Created by authors*

2.3 Discussion of results

The dynamics in the input and output variables for the selected 22 EU countries is shown in Figure no. 1. The labour input appeared as the sole variable that followed a declining trend. Specifically, the aggregate labour input for the selected countries went down by some 6% over 2008-2021. Meanwhile, the value-added generated in the sector went up by some 21%. The growth rates for assets and CO_2 emission stood at around 13%. This picture implies total factor productivity gains at the aggregate level even after taking the CO_2 emission into account.

The assessment of productive efficiency essentially relies on the weighted ratio analysis. Therefore, the input intensities are calculated as ratios of the value added over the input quantities or CO_2 emission. Figure no. 2 presents the dynamics in the indices representing the growth in the aforementioned ratios. It can be noted that all the relative indicators went up compared to their initial levels in 2008. The steepest increase is observed for the labour productivity (a growth of 28%), which is not surprising given the decreasing labour input. These findings imply the improving situation in the EU trade and vehicle repair sector during 2008-2021. The DEA allows not only analysing these macro measures but also (i) aggregate them into a single aggregate measure and (ii) identify the best proactive and measure the performance gaps. One can also note that CO_2 productivity somehow declined after 2016. This can be related to methodological changes in the accounting of the CO_2 emission as well as changes in the fuel mix, especially in Poland who is relatively important producer in the EU.

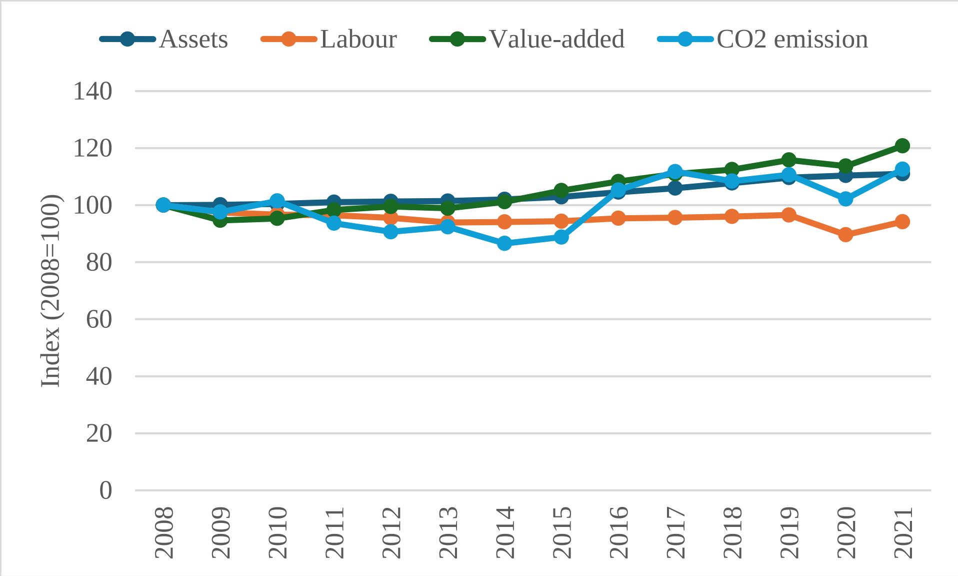

Figure no. 1. Dynamics in the variables in the environmental production technology for the EU trade and vehicle repair sector, 2008-2021

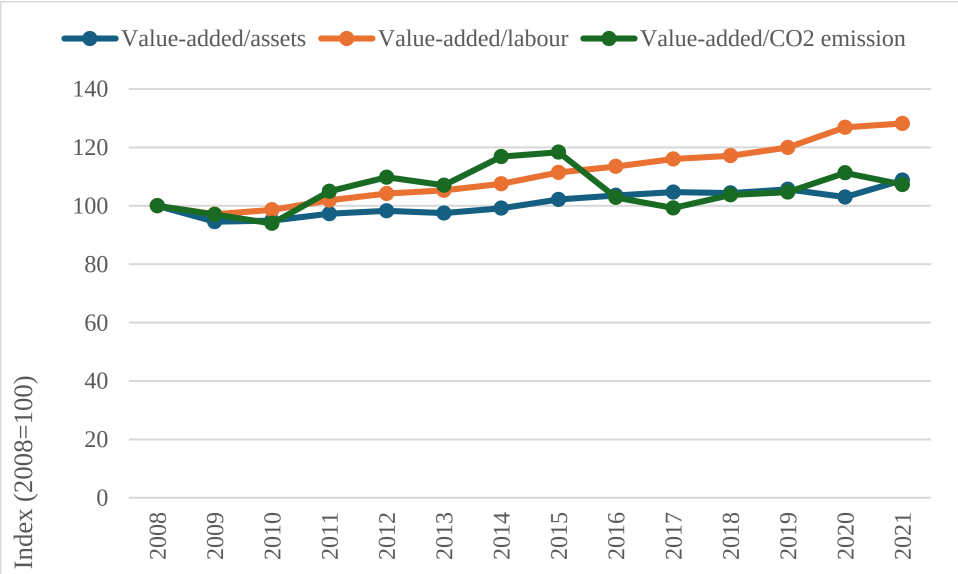

Figure no. 2. Dynamics in the weighted means for the relative variables (partial productivities), EU trade and vehicle repair sector during 2008-2021

The country-specific values of the ratios are presented in Table 3. As one can note, the highest capital productivity is observed for Denmark, Germany, Greece, Finland, France, Ireland, Lithuania, Luxembourg, the Netherlands, and Poland where the relevant coefficient exceeds unity. This indicates that the capital stock allows producing more value-added than the capital stock level itself. This can be explained by the nature of the trade service where transactions may take place with high rate of the asset turnover. Therefore, countries with internationally highly integrated supply chains may benefit from the improved use of the assets in the trade sector. Also, the shift from the traditional trade towards e-commerce may reduce the requirements for assets when generating the value-added.

Labour productivity varies substantially across the countries. The highest values are observed for Belgium, Denmark, Ireland, Luxembourg, the Netherlands, and Sweden. Noteworthy, Central and East European countries (e.g., Czechia, Hungary, Lithuania, Latvia, Estonia, Romania, Slovakia) show the lowest values. All in all, one can note a substantial labour productivity gap by comparing Romania (5.8 Euro per hour) and Luxembourg (66.5 Euro per hour). One can explain these figures by differences in the labour price as a higher labour price induces a labour-saving technical change and, thus, reduces labour inputs further increasing labour productivity.

Value added to CO_2 emission ratio also varies greatly across the countries. The lowest values are noted for Hungary, Poland, Romania, whereas the highest ones are observed for Finland, Lithuania, Austria, Slovakia, Sweden, Denmark. Higher values indicate that there has been decoupling between CO_2 emission and value-added in the trade and vehicle repair sector achieved. This can be done by switching to cleaner energy sources and optimising energy consumption.

Table no. 3. Partial productivities in the EU trade and vehicle repair sector, averages over 2008-2021

Country	Capital productivity, coefficient	Labour productivity, Euro/hour	Value-added per CO_2 emission unit, Euro/kg CO_2
AT	0.731	37.8	34.9
BE	0.766	47.1	16.9
CZ	0.593	12.0	15.3
DE	1.177	33.3	15.4
DK	1.219	51.0	32.2
EE	0.691	13.8	12.9
EL	1.121	11.1	23.1
FI	1.233	38.9	200.4
FR	1.958	35.1	19.7
HU	0.603	9.9	6.0
IE	1.899	42.2	24.9
IT	0.925	24.7	20.6
LT	1.068	14.1	49.8
LU	1.153	66.5	23.2
LV	0.693	11.3	12.7

Country	Capital productivity, coefficient	Labour productivity, Euro/hour	Value-added per CO_2 emission unit, Euro/kg CO_2
MT	0.916	14.6	14.8
NL	1.424	43.3	21.3
PL	1.902	14.0	6.4
RO	0.355	5.8	8.9
SE	0.941	43.7	29.8
SI	0.496	21.7	11.5
SK	0.631	13.3	25.5

Source: Created by authors

As we already noted disparities across the EU countries in the sense of the partial productivity indicators, coefficients of variation are further calculated for each year to ascertain if these disparities persist over time. In general, the highest CVs are observed for the ratio of the value-added to CO_2 emission. Then, the labour and capital productivity ratios come in that order. Therefore, the highest disparities are observed with regard to the environmental performance. One can also note that the CV for the CO_2 emission productivity tended to fluctuate during the period covered indicating that the cross-country disparities were also instable compared to the other ratios. Asset productivity and labour productivity showed rather stable trends in their CVs.

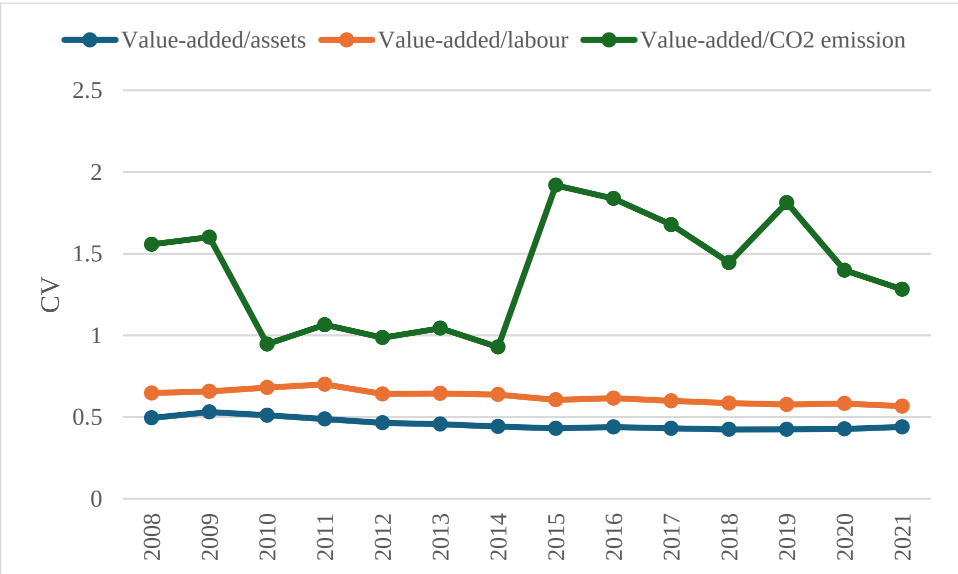

Figure no. 3. Dynamics in the coefficients of variation (CV) for relative variables, EU trade and vehicle repair sector during 2008-2021

Efficiency of the operation of the trade and vehicle repair sector of the EU was measures by applying the proportional output directional distance function as described in Balezentis et al. (2021). The resulting inefficiency scores show how much the desirable (resp. undesirable) outputs should be increased (resp. decreased) compared to their observed levels in order to achieve the production possibilities frontier. In this case, zero indicates full efficiency. The weighted average efficiency scores are presented in Figure no. 4. As one can note, the inefficiency tended to increase over 2008-2021 (from 10% to 12%). Table 3 presents the average efficiency scores for each country.

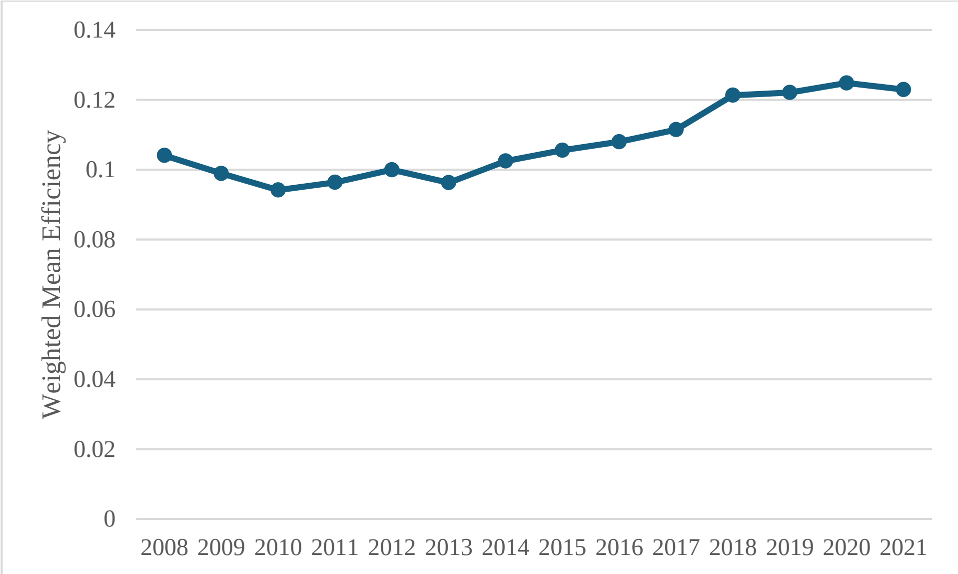

Figure no. 4. The weighted average inefficiency score for the EU trade and vehicle repair sector, 2008-2021

Note: value-added is used as the weighting factor.

The country-level results regarding efficiency of the trade and vehicle repair sector are presented in Table 4. Countries with zero scores are fully efficient (e.g., Germany, Denmark, France, Ireland, Luxembourg, Malta, the Netherlands). These countries determine the production frontier. The least efficient countries are Czechia, Hungary, Latvia, Romania, Slovenia, and Slovakia.

Table no. 4. Average inefficiency scores in the EU trade and vehicle repair sector, 2008-2021

Country	2008	2021	Average
AT	0.20	0.41	0.24
BE	0.00	0.14	0.04
CZ	0.80	0.77	0.78
DE	0.00	0.00	0.00
DK	0.00	0.00	0.00
EE	0.71	0.51	0.63
EL	0.36	0.68	0.59

Country	2008	2021	Average
FI	0.03	0.13	0.06
FR	0.00	0.00	0.00
HU	0.94	0.94	0.94
IE	0.00	0.00	0.00
IT	0.24	0.17	0.19
LT	0.39	0.00	0.38
LU	0.00	0.00	0.00
LV	0.88	0.78	0.74
MT	0.00	0.00	0.00
NL	0.00	0.00	0.00
PL	0.00	0.25	0.10
RO	0.95	0.79	0.88
SE	0.16	0.00	0.09
SI	0.80	0.84	0.80
SK	0.70	0.86	0.76

Source: Created by authors

Shadow price calculation in the non-parametric setting is affected by dimensionality curse in that efficient observations have multiple optimal solutions. Therefore, for relatively small samples, such observations may have undefined shadow prices. In our case, we observe some instances of such undefined prices. Also, for year 2016, multiple countries are attributed with relatively high shadow prices. As this could be a result of the changes in the methodology of the environmental accounts, we remove data for 2016 and replace it with the average value for 2015 and 2017. In case the shadow price for the adjacent period is unavailable, we assume that it is also unavailable for 2016.

The dynamics in the carbon shadow prices and their CV are shown in Figure no. 5. As one can note, the period of 2016-2021 marks an increased volatility in the shadow prices. They also appear to follow a U-shaped trend during 2008-2021. Therefore, the environmental performance tended to decline until 2016 and increased thereafter as lower shadow prices indicate worse environmental performance. The CV also increased after 2016. This indicates that the differences of environmental performance have increased among the EU countries (as far as the trade and vehicle repair sector is considered).

In addition to looking at the average values, one may also be interested in country-specific performance. Table 4 presents the shadow prices for each country (if available based on the DEA model).

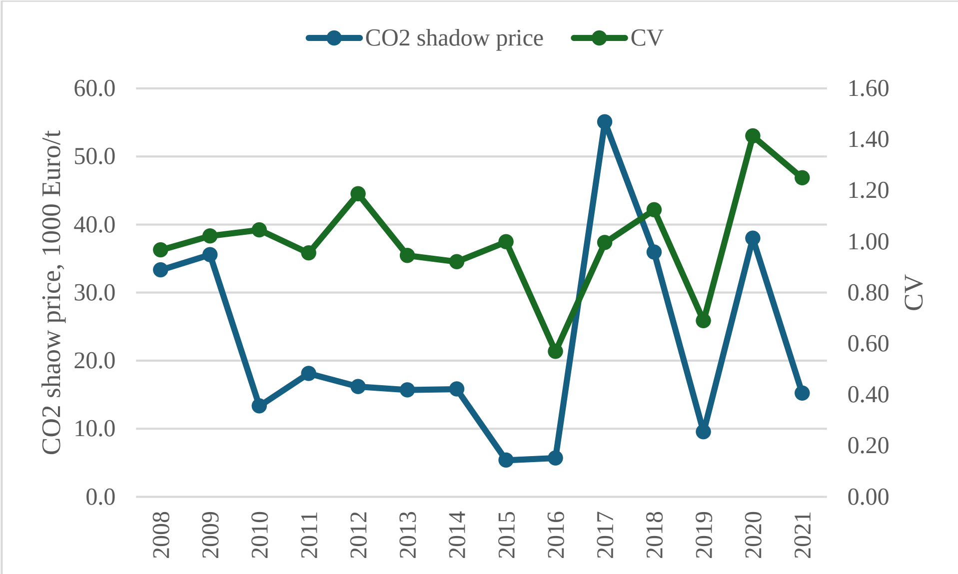

Figure no. 5. Dynamics in the CO_2 shadow price and CV in the trade and vehicle repair sector in the EU, 2008-2021

The results suggest that the highest carbon shadow prices are observed for Estonia, Finland, Hungary, Lithuania, Latvia, Romania, Slovenia, and Slovakia. These countries face the strictest constraints in further reduction of the CO_2 emission in the trade and vehicle repair sector. However, there are a number of countries with shadow price information unavailable. Therefore, further analysis is needed to verify the performance of each country (see Table 5).

Table no. 5. Average CO_2 shadow prices in the EU trade and vehicle repair sector, 2008-2021

Country	2008	2021	Average
AT	4.6	39.5	7.9
BE			0.5
CZ	38.0	48.9	44.5
DE		3.1	1.9
DK			
EE	735.5		560.0
EL	2.5	48.9	36.7
FI	466.8	197.9	419.3
FR		2.3	3.7
HU	466.8	83.3	351.3
IE			
IT	14.5	20.8	20.1

Country	2008	2021	Average
LT	735.5		248.7
LU	24.2	23.3	21.2
LV	735.5		642.5
MT			
NL			
PL	1.0		0.9
RO	466.8	48.9	129.9
SE			
SI	735.5	119.2	359.4
SK	204.3	364.4	437.0

Note: empty cells indicate that shadow price is not available for a certain country-year combination.

The results suggest that Austria, Belgium, Denmark, France, Poland exhibit the lowest shadow price of the CO_2 emission. This implies that such countries have the highest potential for improving their environmental performance through reduction of the CO_2 emission in the trade and vehicle repair sector. However, further analysis is needed by exploiting parametric methods that ensure smoothness of the production frontier.

Conclusions

The research has investigated the energy efficiency in EU countries by applying SCP approach, which provides a robust analytical framework for navigating the complex trade-offs between economic growth and environmental sustainability.

The review of the existing literature and policy landscape confirms that the tertiary sector's rising energy consumption presents an important challenge, yet also a significant opportunity for decarbonisation. The main contribution of this research is the consolidation of the theoretical and methodological framework to apply the shadow carbon price (SCP) approach to the EU service sector. By moving beyond traditional energy intensity indicators, the SCP offers a more sophisticated measure of efficiency, quantifying the marginal economic cost of CO_2 abatement and thus providing a clearer picture of the trade-offs between economic activity and environmental performance.

The originality and importance of this work lie in its specific focus on the tertiary sector, an area that has been largely overlooked in empirical SCP studies compared to the manufacturing, agriculture, or other sectors. This paper establishes that the SCP, estimated via by-production Data Envelopment Analysis (DEA), is a robust and insightful metric for policymakers. It can be used to assess the cost-effectiveness of the current policy mix—including the Effort Sharing Regulation (ESR), the Energy Performance of Buildings Directive (EPBD), and the new ETS2—and to identify the most efficient pathways for decarbonisation across different member states.

The case study includes a new empirical application of the SCP model in tertiary sector EU member states to analyse their performance in energy efficiency increase and ranking EU countries based on energy efficiency performance by generating new data-driven insights. The comprehensive empirical study of the shadow carbon prices for the service sectors of all EU-27-member states over a recent and extended time period provides valuable information on the actual performance of energy efficiency of service sector for each EU country and policy guidance based on calculated SCP.

SCP analysis of the environmental efficiency and carbon shadow prices was implemented for the EU wholesale and retail trade and vehicle repair sector by suing aggregate data. The by-production DEA model allowed one to approximate the production function non-parametrically. The best performing countries in the sense of the CO_2 shadow price are for Estonia, Finland, Hungary, Lithuania, Latvia, Romania, Slovenia, and Slovakia. As one can observe, these countries include mostly transition economies. Note that some countries showed infeasibilities given the nature of the non-parametric model.

The trade and vehicle repair sector is a rather specific one given its nature where transactions may appear online without geographical limits. This makes transition economies particularly appealing as they can offer high-quality labour force and create relatively high value added, often by exploiting online services. Also, the network of the physical outlets needs to be optimised in order to ensure that the CO_2 emission associated with the operation does not become excessive.

The study relied on the DEA—a non-parametric approach with deterministic approach towards measurement of inefficiency. However, further research could employ parametric approaches, whether deterministic or stochastic ones. The data on the performance of the trade and vehicle repair sector could also be verified by considering other data sources and covering different countries and time periods.

Future research should continue to refine the estimation methodologies, expand the sectoral and regional coverage, and explore the dynamic interactions between carbon pricing, technological innovation, and economic development. Further studies could disaggregate the analysis by service sub-sectors (e.g., retail, finance, hospitality) to uncover more granular insights and explore the specific impacts of green technology innovation and individual policy instruments on the calculated shadow carbon prices.

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