MEASURING THE EUROZONE'S TOURISM ECOEFFICIENCY AND PRODUCTIVITY SUSTAINABLE CHARACTER: A SLACK-MODELED TOURISM-INDUCED DATA ENVELOPMENT ANALYSIS

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Abstract

The purpose of this study is to investigate how technical efficiency and productivity patterns changed in the Eurozone's tourism sector over the period 1996-2019. To achieve this, a Slack-Based Measure (SBM) within the Data Envelopment Analysis (DEA) framework was employed. A key strength of this study lies in the carefully selected, multidimensional set of variables that captures the economic and structural heterogeneity of the tourism sector. To strengthen our approach, we also used proxies for environmental degradation. Results reveal an average efficiency score of 0.53 for input-oriented DEA and 0.81 for output-oriented DEA, whereas the Malmquist index score is 1.026. Panel results indicate a positive and significant effect of renewables on technical efficiency. Granger's causality test reveals a unidirectional relationship from renewables to output-oriented technical efficiency. Practical implications call for practices that reduce environmental burdens while simultaneously increasing desirable revenue outcomes.

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1. Introduction

The complexity of economic systems and the contemporary demand for their resilience calls for a comprehensive analysis of 'sectoral' and 'regional' resilience (Tsiotas et al., 2025), indicatively within various temporal and functional contexts (Tsiotas and Kallioras, 2025). The economic performance of the tourism sector is combined with environmental concerns to create more value with less impact (Rashidi and Saen, 2015). As indicated by Jiang and Wang (2025), the World Travel Tourism Council forecasts that by 2033, the tourism industry will account for more than 11.6% of the global economy. Moreover, the global carbon footprint of tourism increased from 3.9 to 4.5 $GtCO_2e$ from 2009 to 2013, accounting for about 8% of global greenhouse gas emissions (Lenzen et al., 2018). Eco-efficiency measures provide insights into sustainability in the tourism sector (Xia et al., 2022), whereas Gossling et al. (2005) argue that eco-efficiency is an advantageous means of assessing the combined environmental and economic performance of tourism. Since tourism uses a wide range of resources (e.g., human, natural), it is crucial to maintain balance among key stakeholders to cater tourist's requirements (Harish and Rao, 2025). Moreover, multidisciplinary thinking advances comprehensive empirical research yielding evidence-based results (Tsiotas, 2022).

In light of these concerns, this study investigates the technical efficiency and productivity patterns of the Eurozone's tourism sector from 1996 to 2019, while also considering eco-efficiency in terms of a nation's primary energy consumption and carbon dioxide emissions. Moreover, this study examines whether the adoption of renewables is a core determinant of efficiency and productivity patterns. The effects of the environment on people's experiences and behaviors are broadly recognized in research (e.g., in tourism and marketing) (Liu et al., 2026). Consequently, this study addresses the following questions: How many inputs could be saved in tourism while keeping tourism revenues unchanged and reducing energy use and emissions? Given the inputs a country already uses, how much more tourism revenue could countries generate (expand) while improving environmental performance? To what extent can these countries simultaneously close desirable-output shortfalls and undesirable-output excesses? On average, do the Eurozone countries meet the performance rates implied by the efficiency frontier? Is any efficiency 'gap' identified? Is there any causality between input- and output-oriented technical efficiencies and renewables? Can a causality be evidenced between total factor productivity change and renewables? If confirmed, what are the directions of these causalities? What are the effects of renewables on technical efficiency and total factor productivity change?

The structure of this study is as follows: the theoretical background section presents the rationale for implementing a tourism-induced DEA analysis under eco-efficiency concerns, whereas the methodology section outlines the steps for conducting the analysis. The following section includes the results. The discussion section presents the practical implications of the analysis. The last section concerns the conclusions.

2. Theoretical Framework

The central role in sustainable tourism accomplishments belongs to eco-efficiency measures, given the need for development or expansion. The term refers to the value or cost associated with the economic aspects of products and/or services (Petchkaewkul et al., 2016), mirroring an empirical relationship in economic activities between environmental cost or value and environmental impacts (Huppes and Ishikawa, 2005), indicating for instance reduction in the energy intensity of goods or services and maximum use or renewables (Cabeza et al., 2015). Interestingly, Yu et al. (2026) indicate that DEA is a mainstream tool for assessing eco-efficiency due to its nonparametric nature (Jomthanachai et al., 2023) and its flexibility in handling undesirable outputs (Zhou et al., 2012). Rozenberg (2021) claims that measuring the efficiency of a complex system, such as tourism, can advance the sector's sustainable development efforts.

Despite its broad applicability, DEA has been criticized in the field of operational research. As stated by Nurmatov (2021), based on the work of Ramanathan (2003) and Rouse (1997), DEA has limitations, mostly concerning the type, number, and selection of DMUs used, as well as its nonparametric nature, which does not allow for conducting statistical hypothesis tests, raising validity concerns. Also, as an extreme point technique, noise (e.g., in measurement error) can be an issue of high importance, whereas it measures relative efficiency (comparisons to 'peers') and not absolute efficiency scores (comparison to a 'theoretical maximum') (Trick, 1996). Interestingly, Assaf et al. (2025) claim that homogeneity and scale assumptions across DMUs, as well as dimensionality issues related to the number of inputs and outputs relative to the number of DMUs, warrant attention.

Many outstanding research efforts in tourism-induced DEA analysis rely on aggregate tourism indicators, such as tourism receipts, nights spent, or arrivals. For instance, a strand in literature examines hotel-oriented proxies to elaborate on DEA and efficiencies (Hsieh and Lin, 2010; Assaf and Josiassen, 2012; Huang et al., 2016; Li et al., 2022; Choi and Kim, 2024; *inter alia*) whereas as indicated by Pulina and Santoni (2018), high-impact research efforts discuss tourism's economic performance concerning a destination perspective, at the regional and/or city level, or a hotel perspective (e.g., Hathroubi et al., 2014; Perrigot et al., 2009; Ramanathan et al., 2016).

Explicit channels through which tourism contributes to the economy are rarely modeled as core variables in the T-DEA framework. Hence, the economic transmission mechanisms of tourism remain less investigated and insufficiently quantified. Moreover, viewing the Eurozone's tourism system as a homogeneous reserch topic might lead to overlooking structural differences among tourism segments. Ekonomou (2022) argues that investigating the unnoticed power of market segments in the tourism growth nexus discussion helps define practical implications concerning sustainable economic growth and tourism demand issues.

This study addresses this gap by first examining tourism's direct contribution to employment and investment capital flows in the travel and tourism industry. Second, it implements an SBM T-DEA analysis across two distinct, high-leverage tourism market segments, using business and leisure tourism spending as the desirable output variables. Indicatively, in 20019, business trips accounted for 15% of tourism expenditure, whereas they recorded the highest average expenditure per trip. Interestingly, Europeans spent an average of €1 053 on foreign trips and €303 on domestic trips in 2024 (Eurostat, 2025), whereas in 2023, business travelers were estimated to have spent more than 1.4 trillion U.S. dollars worldwide (Statista, 2025a). Furthermore, in 2018, the leisure tourism market accounted for 78.5% of tourism sector spending (WTTC, 2019). Notably, leisure tourism is the largest sector of the tourism industry, with global leisure tourism spending projected to reach 9,332 billion U.S. dollars in 2029 (Statista, 2025b).

In this way, the study highlights the heterogeneous nature of tourism rather than relying on aggregate proxies. As Peng et al. (2017) indicate, tourism revenue and tourist arrivals are widely used as desirable output variables (Barros and Matias, 2006a; Medina et al., 2012) in DEA analyses. In light of these concerns, a research opportunity arises to avoid assuming homogeneity in tourism demand. If not, we might overlook that business and leisure tourism have distinct characteristics and spending patterns, resource intensity, seasonality, and economic spillovers within the Eurozone. The tourism sector closely monitors fiscal stimulus policies during economic downturns, as these policies are generally assumed to increase consumer spending to aid recovery (Nie and Song, 2025).

Third, it considers an energy-efficiency proxy (e.g., primary energy consumption), alongside carbon dioxide emissions. Interestingly, according to the European Environment Agency, the European Union's recast Energy Efficiency Directive provides an indicative EU-wide target of 992.5 million tonnes of oil equivalent (Mtoe) for primary energy consumption and a binding EU-wide target of 763 Mtoe for final energy consumption, to be achieved by 2030. This approach is closely related to Porter's Hypothesis on whether environmental regulations and innovation factors can increase efficiency patterns. Arguably, Porter's Hypothesis holds that environmental regulations can facilitate innovation by partially or fully offsetting compliance costs (Porter and van der Linde, 1995). This is an interesting research approach, since the literature debates whether adopting renewable energy sources increases costs (by reducing efficiency) or reduces long-term operational costs (by increasing efficiency). Based on Porter's hypothesis, the benefits of innovation initiatives can offset enterprises' losses from environmental regulations and promote social development (Xu et al., 2022). These aspects concern whether destinations can demonstrate an eco-friendly profile in terms of energy efficiency (e.g., primary energy consumption) and whether renewables are key drivers of technical efficiency and performance. Despite its significance for tourism and environmental economics, the adopted set of variables is either less visible or entirely unobserved in relevant SBM T-DEA studies.

3. Methodology

The present research applies a tourism-induced DEA to countries (DMUs) of the Eurozone economic space from 1996 to 2019. We adopted both DEA orientations, namely, input- and output-oriented variable returns-to-scale (VRS) analyses under a Slack-Based Measure. It considers good (desirable) and bad (undesirable) outputs. The undesirable variables were transformed using a monotonic decreasing function. Furthermore, the change in total factor productivity is calculated. Moreover, a panel analysis was conducted to regress efficiencies and productivity scores on renewables. This study uses data from the World Travel and Tourism Council, Eurostat, and the World Bank.

3.1 Technical efficiencies

To perform the T-DEA analysis, two input and four output variables were used. The input variables comprise the number of jobs totally generated in the travel and tourism sector (tce) and capital investment spending by all industries directly involved in the travel and tourism sector (invest). The output variables consisted of business tourism spending and leisure tourism spending (desirable outputs) and primary energy consumption and carbon dioxide emissions (CO_2) (undesirable outputs). Business tourism spending is the amount spent on business travel within a country by residents and international visitors. Leisure tourism spending is the amount residents and international visitors spend on leisure travel within a country. Primary energy consumption denotes the total energy demand of the country of reference, whereas CO_2 emissions refer to those from liquid fuel consumption. Technical efficiency scores for both input- and output-oriented frameworks are bounded between 0 and 1. A value of one denotes full efficiency. Values below one indicate inefficiency arising from input excess and/or output shortfalls.

Under the SBM DEA framework, for inputs, a slack value of zero indicates that the input is used efficiently relevant to the best-practice frontier, while a positive slack indicates excess in input use, implying that the input can be reduced without worsening performance. For desirable outputs, a slack value of zero indicates that the output lies on the frontier, whereas a positive value reflects output shortfall and indicates potential for output expansion. For undesirable outputs, a slack value of zero indicates that no excess environmental burden exists relative to the frontier, while a positive value reflects pollution excess and indicates potential for reduction. Normalized slack values are obtained through the form: $Normalized\ slack = \frac{slack\ movement}{input\ (or\ output)\ values} \times 100$, absolute values are taken for inputs. Table 1 presents the descriptive statistics of variable to process the T-DEA.

Table 1. Descriptive statistics.

	Input variables			**Output variables**		
Country	**tce**	**invest**	**bts**	**lts**	**energy**	**CO_2**
Austria	16,570	4,890	6,928	36,786	30.765	10.721
Belgium	6,575	2,417	6,071	17,352	50.390	21.574
Cyprus	23,423	0,420	0,271	2,940	2.440	0.940
Estonia	14,870	0,410	0,622	1,768	5.260	0.960
Finland	11,330	1,632	4,935	14,513	33.230	9.359
France	11,017	30,996	33,235	146,560	245.930	51.355
Germany	12,772	26,335	64,761	301,176	311.490	97.556
Greece	21,259	6,150	2,383	22,839	26.540	7.905
Ireland	7,138	5,489	3,114	8,851	14.100	4.232
Italy	13,017	14,296	36,969	141,085	161.468	54.024
Latvia	6,942	0,267	0,329	1,187	4.377	1.013
Lithuania	5,464	0,270	0,497	1,608	7.195	1.311
Luxembourg	13,489	0,692	0,346	4,597	4.170	1.267
Malta	12,763	0,251	0,158	1,505	0.870	0.026
Netherlands	11,000	4,422	9,397	30,084	67.452	24.064
Portugal	15,779	2,865	3,336	18,906	22.438	7.529
Slovakia	5,167	0,605	1,216	2,502	16.353	8.220
Slovenia	12,147	0,640	0,671	3,483	6.745	1.942
Spain	14,301	18,617	16,519	102,114	120.525	41.572
mean	12,370	6,403	10,093	45,256	59.565	18.190
Standard deviation	4,797	9,050	16,591	75,181	86.352	25,108

Notes: i) tce is measured in thousands of jobs; invest, bts, and lts are measured in US$ billion (in real prices); primary energy consumption (energyp) in million tonnes of oil equivalent (TOE); and $C0_2$ in kt. ii) The sample refers to countries that entered the Eurozone economic space till 2019.

3.2 Panel Data Analysis

First, cross-section dependence tests (CD) were implemented following Pesaran’s (2004) procedure. The unit root tests based on Lee and Tieslau's (2019) approach helped detect whether panel series carry unit roots and identify relevant structural breaks. Moreover, a fixed-effects standard error panel model is implemented, following the work of Driscoll and Kraay (1998) and Hoechle (2007). The adopted approach accommodates structural breaks and treats heteroscedasticity, serial correlation, and cross-section dependence in panel series. Country fixed effects are included to control for unobserved time-invariant heterogeneity across panel units. Essentially, this study’s regression models integrate fixed-effects panel equations with regime-dependent slopes (via interactions) and level shifts (via break dummies). Efficiency scores are logit-transformed to account for their bounded nature and to permit estimation within a linear regression model. Total factor productivity values are based on raw (original) data (not logit transformed). The following equations (1), (2), and (3) depict the adopted regression models.

$$lecoinput_{it} = a_i + \beta_0 renew_{it} + \beta_1(renew_{it} \times D_t^{2006}) + \beta_2(renew_{it} \times D_t^{2019}) + \gamma_{2010}1(t \geq 2010) + u_{it} \quad (1)$$

$$lecooutput_{it} = a_i + \beta_0 renew_{it} + \beta_1(renew_{it} \times D_t^{2006}) + \beta_2(renew_{it} \times D_t^{2019}) + \delta_{2003}1(t \geq 2003) + \delta_{2018}1(t \geq 2018) + u_{it} \quad (2)$$

$$\boldsymbol{ecotfpc_{it} = a_i + \beta_0 renew_{it} + \beta_1\left(renew_{it} \times D_t^{2006}\right) + \beta_2\left(renew_{it} \times D_t^{2019}\right) + \theta_{2008}1(t \geq 2008) + \theta_{2010}1(t \geq 2010) + u_{it}} \quad \textbf{(3)}$$

where i is the index for panel countries, t is the index for time (years), $lecoinput_{it}$ and $lecooutput_{it}$ are the logit-transformed input- and output-oriented technical efficiencies received from the DEA analysis, $ecotfpc_{it}$ is the total factor productivity change, $renew_{it}$ are renewable energy consumption, a_i is the country fixed-effects, D_i^{2006}, D_i^{2019} are break dummies for 2006 and 2019 for renewables, $1(t \geq 2010)$ dummy variable after 2010 for input-oriented technical efficiency, $1(t \geq 2003)$ and $1(t \geq 2018)$ dummy variables for out-put oriented technical efficiency after the years 2003 and 2018 respectively, $1(t \geq 2008)$ and $1(t \geq 2010)$ dummy variables for total factor productivity change after the years 2008 and 2010 respectively, β_0 denotes the marginal effect of renewable energy, $\beta_1$and $\beta_2$are changes in the renewable effect across regimes indicating the interaction coefficients, γ, δ, θ denote coefficients measuring level shifts after structural breaks, u_{it} is the eror term. The 1996 structural break for the input-oriented variable is excluded from the model because it coincides with the first year of the sample period and would therefore be perfectly collinear with the intercept. Lastly, a panel Granger causality test (pVAR) based on Wald statistics (chi-square) was performed to assess linkages among the variables of interest. In the pVAR framework, Granger causality tests the null hypothesis that the coefficients on all lagged values of a given variable in another variable's equation are jointly equal to zero. Rejection of the null hypothesis indicates the presence of a Granger causality relationship.

4. Results

4.1 Results of T-DEA

Results of input-oriented and output-oriented DEA are provided in Table 2. An average input-oriented technical efficiency score of 0.53 indicates that, over the period 1996-2019, Eurozone countries operated substantially below the best-practice frontier. On average, this corresponds to an efficiency gap of 47%, suggesting a significant excess of inputs relative to efficient production levels, while holding outputs constant. Germany has the highest value (0.93), whereas Greece has the lowest (0.24).

The average output-oriented technical efficiency score is 0.81. This result suggests that, over the period 1996-2019, Eurozone countries operated at 81% of the best-practice production frontier. The findings indicate that the Eurozone's tourism sector does not fully exploit its output potential given its current inputs, implying room for performance improvements. A roughly 19% performance gap relative to best practice is confirmed. This highlights opportunities for productivity-enhancing and sustainability-oriented tourism policies that aim at better utilizing available resources. Germany has the highest value (0.9), while Belgium and Slovakia have the lowest (0.73).

In Table 2, the Malmquist productivity index over the period 1996-2019 is 1.026. This result shows that Eurozone countries depicted a sustained positive productivity trajectory during the study period. This pattern of productivity change depicts an improvement in the Eurozone countries' ability to transform inputs into desirable outputs, while accounting for environmental factors. Technological progress (frontier shifts) and efficiency changes, or a combination of both, account for this observed growth.

Table 2. Mean values of technical efficiencies and Malmquist productivity index over the period 1996-2019 (country-year).

Country	input	output	MI (tfpc)

Austria	0.51	0.89	1.03
Belgium	0.54	0.73	1.03
Cyprus	0.45	0.76	1.03
Estonia	0.37	0.75	1.03
Finland	0.60	0.81	1.03
France	0.50	0.83	1.03
Germany	0.93	0.90	1.03
Greece	0.24	0.82	1.03
Ireland	0.38	0.84	1.03
Italy	0.70	0.86	1.02
Latvia	0.55	0.78	1.02
Lithuania	0.71	0.81	1.02
Luxembourg	0.58	0.84	1.02
Malta	0.85	0.88	1.02
Netherlands	0.42	0.75	1.02
Portugal	0.35	0.82	1.02
Slovakia	0.62	0.73	1.02
Slovenia	0.36	0.75	1.03
Spain	0.35	0.81	1.03
Arithmetic mean	0.53	0.81	
Geomean			1.026
Stand. Deviation	0.18	0.05	0.005

Notes: i) output stands for output-oriented technical efficiency, MI denotes the Malmquist Productivity Index and provides values for total factor productivity change (tfpc), ii) The output averages are arithmetic means, the MI averages are geometric means. Iii) The sample refers to countries that entered the Eurozone economic space till 2019.

Interestingly, descriptive trend analysis of temporal evolution discloses that while ecoinput exhibits a relatively strong and consistent upward trend (Fig. 1), ecooutput increases at a significantly lower rate (Fig. 2). This imbalance suggests that sectoral growth is primarily driven by input accumulation rather than improvements in efficiency or productivity. The lowess smoothed trend (Fig. 3) reveals a non-linear evolution of productivity. Specifically, productivity patterns declined in the early 2000s, then recovered through the late 2000s, followed by subsequent fluctuations without a clear long-term direction. Productivity gains seem not to have kept pace with resource expansion.

Figure 1. Trend analysis for ecoinput.

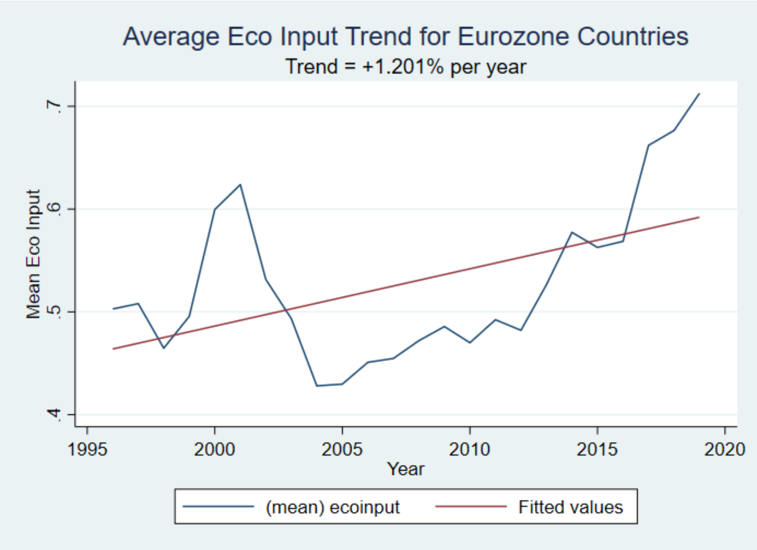


Figure 2. Trend analysis for ecooutput.

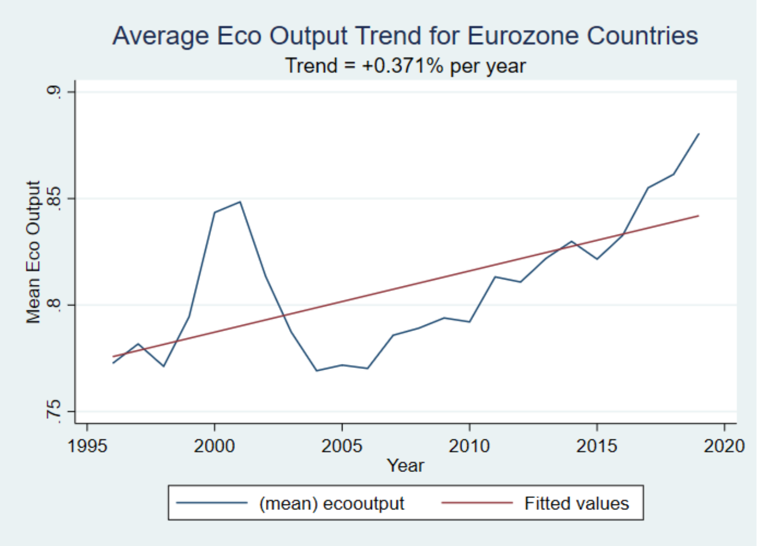
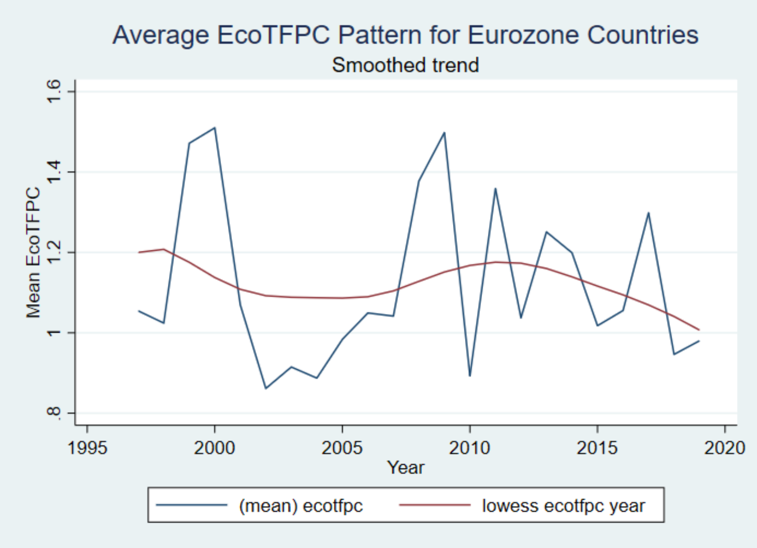


Figure 2. Trend analysis for ecotfpc.



Results for the slack movements of the input-oriented framework (Table 3) indicate that tourism employment exhibits substantial excess use. On average, employment exceeds the efficient level by approximately 44% relative to observed values, suggesting considerable scope for refunction alongside output adjustments. Similarly, investments in the tourism sector exhibit an average excess of about 36%, indicating the need for improved capital allocation and cost efficiency. For desirable outputs, business tourism spending shows an average shortfall of approximately 20% relative to observed levels, implying a meaningful expansion potential. Likewise, leisure tourism spending could be increased by roughly 15%, reflecting underperformance in generating tourism-related revenues. For undesirable outputs, energy consumption shows an average reduction requirement of about 12.5%, while CO_2 emissions exhibit a reduction potential of approximately 18.5%. These findings indicate environmental inefficiency across Eurozone countries, with scope to reduce undesirable outputs and improve performance on desirable outputs.

Table 3. Input-oriented normalized slack movement values for technical efficiencies.

	tce	invest	bts	lts	energy	CO_2
mean	-43.846	-36.105	19.889	15.284	12.531	18.461
St. Dev.	25.867	24.943	56.819	29.779	29.779	21.294

Notes: i) Slack values are normalized. ii) Input slacks with a negative sign indicate the direction of adjustment. The negative sign indicates an excess of input use. The input must be reduced to reach the efficiency frontier.

Results from the slack movements of the output-oriented framework (Table 4) suggest that, on average, tourism employment exceeds efficient levels by about 2.2%. Moreover, on average, investments show an excess of nearly 17%. These results account for slack adjustments in outputs. For desirable outputs, on average, tourism business spending exhibits a shortfall of approximately 13.5%, whereas leisure tourism spending shows a larger shortfall of about 20.5%. These figures reflect non-negligible underperformance in generating desirable tourism outputs.

For undesirable outputs, primary energy consumption shows a substantial reduction of about 38%, on average, whereas CO2 emissions have an even larger reduction potential of about 53%, on average. These findings reflect significant inefficiencies in energy use and a pronounced gap between current environmental performance and best-practice production across the Eurozone.

Table 4. Output-oriented normalized slack movement values for technical efficiencies.

	tce	**invest**	**bts**	**lts**	**energy**	**CO_2**
mean	-2.150	-16.895	13.435	20.570	37.851	53.042
St. Dev.	7.662	25.019	16.760	38.958	24.357	29.042

Notes: i) Slacks are normalized. ii) Input slacks with a negative sign indicate the direction of adjustment. The negative sign indicates an excess of input use. The input must be reduced to reach the efficiency frontier.

4.2 Panel Data Analysis

4.2.1 Results of cross-section dependence tests

Results of the cross-section dependence (CD) tests based on Pesaran's (2004) approach (Table 5) indicate that both technical efficiencies and renewable energy exhibit cross-section dependence (p-values lower than 0.01). Moreover, total factor productivity change is cross-sectionally dependent, rejecting the null hypothesis of cross-sectional independence (p-value = 0.000). Given that this study concerns Eurozone countries, CD might be due to trade openness, the abolition of artificial borders, capital mobility, similar responses to external shocks and financial crises, and common regulatory frameworks that the countries of interest must follow.

Table 5. Results of CD tests.

Variable	**Test**	**Statistic**	**p-values**
input	Pesaran CD test	10.372	0.000
output		16.945	0.000
tfpc		-0.402	0.000
renew		54.704	0.000

Ho: cross-section independence

4.2.2 Results of unit root tests

Results of unit root tests (Table 6) based on Lee and Tieslau's (2019) approach indicate that the variables under consideration are stationary, as all obtained p-values are below 0.01. For each variable, two break years were detected. These break years are considered in the following panel regression analyses and Granger causality tests. The identified breaks (e.g., 2003 and 2008) likely reflect broad regime shifts in the tourism production process and in Eurozone countries' ability to expand tourism spending while containing energy use and CO_2 emissions. These dates coincide with periods of major structural changes in tourism markets and the diffusion of energy- and emissions-efficiency practices, consistent with a shift in the efficiency frontier under the SBM DEA framework. For instance, a regime distinction at the start of the sample (e.g., 1996) can reflect the baseline technology used to assess subsequent improvements. Moreover, a substantive break around 2010 is consistent with post-crisis restructuring in the tourism sector, in which Eurozone countries intensified cost discipline and labor utilization and reoriented tourism investment toward productivity-enhancing and energy-efficient upgrades. In turn, these changes altered how employment and investment translate into tourism spending while managing energy use and $C0_2$ emissions, leading to a shift in the efficiency frontier.

Table 6. Results of unit root tests.

Variables tested	Individual value	Break 1	Break 2	Lags	PDLM	p values
input	-8.164	1996	2010	0	-8.693	0.000
output	-9.226	2018	2003	5	-11.002	0.000
tfpc	-19.473	2010	2008	0	-28.380	0.000
renew	-8.748	2019	2006	1	-9.842	0.000

Notes: i) PDLM stands for Panel Lagrange Multiplier with level and trend shifts, ii) p-values lower than 0.01 indicate significance at 1% level, iii) 2003 break due to the European Union's energy efficiency directives, emissions policy, 2018 break due to greening strategy and de-coupling effects, break in 1996 due to mid-90s less optimized investment planning, 2010 break due to post 2008-2009 crisis, break in 2006 accelerated EU renewable policy roll out, break in 2019 due to clean energy EU transition (e.g., Green deal)

4.2.3 Results of regression and causality tests

In the regression results of Table 7, lecoinput denotes the logit-transformed input-oriented technical efficiency. The variable renew represents renewable energy consumption and captures the baseline marginal effect of renewables on input-oriented technical efficiency (lecoinput). The variables renew_post2006 and renew_post2019 are interaction terms that capture the product of renewable energy and regime indicators, allowing the renewable effect to change after the 2006 and 2019 structural breaks. The break dummy post2010_in captures the shift in the intercept in efficiency after 2010. The constant term represents the regression's baseline intercept.

The fixed-effects regression results indicate that renewable energy is positively and statistically significantly associated with input-oriented technical efficiency (Table 7). This regression is consistent with Eq (1) provided in the Methodology section. The baseline coefficient (coeff. = 0.27, p-value = 0.27) indicates that renewable expansion improves efficiency in the early period (before 2006). Interaction terms reveal that this effect weakens after 2006 but strengthens again after 2019. Regime-specific marginal effects confirm that the renewable impact remains positive and significant across all periods, with estimated effects of 0.27 before 2006, 0.193 during 2006-2018, and 0.296 after 2019 (Tables 7.1, 7.2, and 7.3). Exponentiating these coefficients implies that renewable expansion increases the odds of higher efficiency by approximately 31%, 21%, and 34% across these regimes, respectively. The structural break dummy in 2010 is not statistically significant, suggesting that efficiency dynamics are driven primarily by changes in the renewable effect rather than by discrete level shifts. P-values lower than 0.01 indicate statistical significance at the 1% level.

Table 7. Regression results when the logit-transformed input-oriented technical efficiency (ecoinput) is the dependent variable.

lecoinput	Coef.	Drisc/Kraay Std. Err.	t	P>|t|	[95% Conf. Interval]	
renew	.2704	.06771	3.99	0.001	.12818	.41271
renew_post2006	-.07757	.02409	-3.22	0.005	-.12818	-.02695
renew_post2019	.10279	.00801	12.83	0.000	.08596	.119624
post2010_in	-.27737	.72214	-0.38	0.705	-1.7945	1.23978
constant	-2.2924	.6028	-3.80	0.001	-3.5588	-1.02596

renew: renewable energy consumption
renew_post2006:

Table 7.1. Regime-specific marginal effects of renewables pre-2006 (dependent variable: logit-transformed input-oriented technical efficiency).

lecoinput	Coef.	Drisc/Kraay Std. Err.	t	P>|t|	[95% Conf.	Interval]
Pre 2006 marginal effect	.27045	.06771	3.99	0.001	.12818	.41271

Table 7.2. Regime-specific marginal effects of renewables between 2006 and 2008 (dependent variable: logit-transformed input-oriented technical efficiency).

lecoinput	Coef.	Drisc/Kraay Std. Err.	t	P>|t|	[95% Conf.	Interval]
2006-2008 marginal effect	.19287	.05556	3.47	0.003	.07613	.30961

Table 7.3. Regime-specific marginal effects of renewables after 2019 (dependent variable: logit-transformed input-oriented technical efficiency).

lecoinput	Coef.	Drisc/Kraay Std. Err.	t	P>|t|	[95% Conf.	Interval]
Post 2019 marginal effect	.29567	.05255	5.63	0.000	.18524	.40609

In the regression results of Table 8, lecooutput denotes the logit-transformed output-oriented technical efficiency. The variable renew represents renewable energy consumption and captures the baseline marginal effect of renewables on output-oriented technical efficiency (lecooutput). The variables renew_post2006 and renew_post2019 are interaction terms that capture the product of renewable energy and regime indicators, allowing the renewable effect to change after the 2006 and 2019 structural breaks. The break dummy variables post2003_out and post2018_out indicate a level (intercept) shift in output efficiency after 2003 and a level shift after 2018, respectively. The constant is the regression's baseline intercept. P-values lower than one indicate statistical significance at 1% level, whereas values greater than 0.05 denote no statistical significance.

In the case of output-oriented technical efficiency, the fixed-effects regression results indicate that renewable energy is positively and statistically significantly associated with it (Table 8). This regression is consistent with Eq (2) provided in the Methodology section. The baseline coefficient shows that renewable expansion improves output efficiency in the early period (before 2006, coeff. = 0.21, p-value = 0.001). The interaction terms renew_post2006 and renew_post2019 indicate that this effect weakens after 2006 but strengthens again after 2019. Regime-specific marginal effects confirm that the renewable impact remains positive and significant across all periods, with estimated effects of 0.216 before 2006, 0.170 during 2006-2018, and 0.224 after 2019 (Tables 8.1, 8.2, and 8.3). Exponentiating these coefficients implies that renewable expansion increases the odds of higher output efficiency by approximately 24%, 19%, and 25% across the three regimes, respectively. The structural break dummy for 2003 indicates a significant downward level shift in output efficiency, while the 2018 break is not statistically significant, suggesting that most dynamics arise from changes in the renewable effect rather than persistent level shifts.

Table 8. Regression results when the logit-transformed output-oriented technical efficiency (ecooutput) is the dependent variable.

lecooutput	Coef.	Drisc/Kraay Std. Err.	t	P>|t|	[95% Conf.	Interval]
renew	.21636	.05298	4.08	0.001	.10505	.32767
renew_post2006	-.04637	.02038	-2.28	0.035	-.08919	-.00355
renew_post2019	.05448	.02669	2.04	0.056	-.00160	.11057
post2003_out	-1.2136	.53877	-2.25	0.037	-2.3455	-.08170
post2018_out	1.1857	.91797	1.29	0.213	-.74282	3.11436
constant	.25366	.72495	0.35	0.730	-1.2694	1.77673

Table 8.1. Regime-specific marginal effects of renewables pre-2006 (dependent variable: logit-transformed output-oriented technical efficiency).

lecooutput	Coef.	Drisc/Kraay Std. Err.	t	P>|t|	[95% Conf.	Interval]
Pre 2006 marginal effect	.216362	.05298	4.08	0.001	.10505	.32767

Table 8.2. Regime-specific marginal effects of renewables between 2006 and 2018 (dependent variable: logit-transformed output-oriented technical efficiency).

lecooutput	Coef.	Drisc/Kraay Std. Err.	t	P>|t|	[95% Conf.	Interval]
2006-2018 marginal effect	.16998	.04150	4.10	0.001	.08278	.25718

Table 8.3. Regime-specific marginal effects of renewables after 2019 (dependent variable: logit-transformed output-oriented technical efficiency).

lecooutput	Coef.	Drisc/Kraay Std. Err.	t	P>|t|	[95% Conf.	Interval]
Post 2019 marginal effect	.22446	.05455	4.11	0.001	.10985	.33908

The effects of renewable energy on total factor productivity change are not statistically significant (Table 9). This regression is consistent with Eq (3) provided in the Methodology section. It should be noted that coefficients denote direct marginal effects since total factor productivity values are in raw levels. As a result, we do not interpret in odds. Specifically, the marginal effect of renewables in total factor productivity change before the 2006 regime is insignificant, implying no measurable productivity response to renewable energy adoption. In the subsequent periods 2006-2018, and post-2019, the regime marginal effects remain statistically insignificant. These results suggest that structural changes in renewables did not significantly affect the dynamics of total factor productivity. In contrast, the baseline model of Table 9 indicates that structural break controls associated with tourism productivity itself are highly significant. The post-2008 period shows a positive shift, whereas the post-2018 period justifies a negative adjustment, following the global financial crisis and subsequent economic restructuring. Interestingly, this negative sign reflects the adverse impact of financial constraints, reduced investments, and structural adjustments associated with macroeconomic instability. One explanation is that these macroeconomic structural disruptions, rather than environmental policy, were the primary drivers of the slowdown in productivity growth. These findings suggest that while tourism productivity experienced structural shifts, renewable energy expansion did not act as a statistically significant driver during the sample period. Tables 9.1, 9.2, and 9.3 present regime-specific regression results.

Table 9. Regression results when the total factor productivity change (ecotfpc) is the dependent variable.

ecotfpc	Coef.	Drisc/Kraay Std. Err.	t	P>|t|	[95% Conf.	Interval]
renew	.00212	.02167	0.10	0.923	-.04340	.04766
renew_post2006	-.00326	.00595	-0.55	0.590	-.01578	.00924
renew_post2019	-.00310	.00231	-1.34	0.197	-.00796	.00175
post2008_tfpc	.39639	.06841	5.79	0.000	.25266	.54011
post2010_tfpc	-.32202	.07490	-4.30	0.000	-.47939	-.16465
constant	1.0596	.21862	4.85	0.000	.60031	1.5189

Table 9.1. Regime-specific marginal effects of renewables pre-2006 (dependent variable: total factor productivity change).

ecotfpc	Coef.	Drisc/Kraay Std. Err.	t	P>|t|	[95% Conf.	Interval]
Pre 2006 marginal effect	.00212	.02167	0.10	0.923	-.04340	.04766

Table 9.2. Regime-specific marginal effects of renewables between 2006 and 2018 (dependent variable: total factor productivity change).

ecotfpc	Coef.	Drisc/Kraay Std. Err.	t	P>|t|	[95% Conf.	Interval]
2006-2018 marginal effect	-.00113	.01706	-0.07	0.948	-.03698	.03471

Table 9.3. Regime-specific marginal effects of renewables after 2019 (dependent variable: total factor productivity change).

ecotfpc	Coef.	Drisc/Kraay Std. Err.	t	P>|t|	[95% Conf.	Interval]
Post 2019 marginal effect	-.00424	.01506	-0.28	0.781	-.03588	.02739

Across specifications, renewable energy exhibits statistically significant effects on efficiency measures after accounting for fixed effects, structural breaks, and cross-sectional dependence. While renewable energy clearly improves efficiency on average, aggregate estimates might obscure important temporal dynamics. To examine whether the renewable effect evolves across structural regimes, the adopted approach allowed slope coefficients to vary over time.

The Granger pVAR test between input and renewables (Table 10) suggests no causal link from renewables to input (p-value = 0.439), meaning that past values of renewables do not help predict input-oriented technical efficiency. Also, input-oriented technical efficiency does not Granger-cause renewables (p-value = 0.981). This type of relationship (neutrality) suggests that increases in renewables do not improve input-oriented technical efficiency, likely because they do not reduce inefficiencies in energy and emissions, and because feedback effects on renewable energy dynamics are absent.

Table 10. Results of pVAR Granger causality tests (dependent variable: input-oriented technical efficiency).

Equation / Excluded		Chi2 (χ^2)	Prob. > chi 2
ecoinput	renew	1.645	0.439
	ALL	1.645	0.439
renew	input	0.038	0.981
	ALL	0.038	0.981

Panel VAR-Granger causality Wald test
input: input-oriented technical efficiency
Ho: Excluded variable does not Granger-cause Equation variable
Ha: Excluded variable Granger-causes Equation variable

Panel VAR Granger test between output and renewables and vice versa (Table 11) indicates a unidirectional predictive causality from renewables to output-oriented technical efficiency (p-value=0.098), with no evidence that output predicts renewables (p-value=0.549). The results suggest that higher renewable energy use supports output-oriented technical efficiency gains by enabling greater tourism spending, whereas efficiency improvements themselves do not influence renewable energy adoption.

Table 11. Results of pVAR Granger causality tests (dependent variable: output-oriented technical efficiency).

Equation / Excluded		Chi 2 (χ^2)	Prob. > chi 2
ecooutput	renew	4.760	0.093
	ALL	4.760	0.093
renew	output	1.199	0.549
	ALL	1.199	0.549

Panel VAR-Granger causality Wald test
output: output-oriented technical efficiency
Ho: Excluded variable does not Granger-cause Equation variable
Ha: Excluded variable Granger-causes Equation variable

Test results for the p(VAR) framework between tfpc and renewables, and vice versa (Table 12), indicate no evidence of directional predictability. Results fail to reject the null hypothesis from renewables to tfpc (p-value=0.285), nor from tfpc to renewables (p-value=0.353), confirming the neutral hypothesis. The absence of Granger causality in either direction indicates that productivity changes driven by technological progress and efficiency shifts are largely independent of short-run dynamics in renewable energy (total factor productivity change = technological progress × efficiency change).

Table 12. Results of pVAR Granger causality tests (dependent variable: total factor productivity change).

Equation / Excluded		Chi2 (χ^2)	Prob. > chi 2
ecotfpc	renew	1.536	0.464
	ALL	1.536	0.464
renew	tfpc	3.065	0.216
	ALL	3.065	0.216

Panel VAR-Granger causality Wald test
tfpc: total-factor productivity change
Ho: Excluded variable does not Granger-cause Equation variable
Ha: Excluded variable Granger-causes Equation variable

5. Discussion

Maintaining environmental protection amid tourism economic expansion features prominently in tourism literature, yet it has also prompted research on tourism's eco-efficiency (Wu and Liang, 2023). Although significant progress has been made in perceiving the financial benefits of sustainability practices in the tourism sector, much remains unexplored in other critical areas, such as operational efficiency, employee engagement, and long-term competitiveness (Shin et al., 2026).

From the European Union's (EU's) perspective, research findings align with the objectives of EU Tourism Transition Pathways, which emphasize productivity gains, digitalization, and skills upgrading rather than quantitative expansion of tourism capacity. The high dispersion of input slacks across countries further suggests that efficiency gaps are heterogeneous, reinforcing the need for country-specific tourism reform strategies rather than uniform EU-wide policies. Enhancing the interaction of the digital economy, tourism development, and eco-efficiency is crucial for achieving sustainability goals (Wu and Xie, 2026). Place-policy interventions, particularly under Cohesion Policy and the Recovery and Resilience Facility, should provide funding to support well-structured tourism initiatives. Also, there is a need to reskill and upskill (e.g., for tourism employment) and to allocate capital more efficiently (e.g., for tourism-related investments). One particular issue is the concept of green finance, which mitigates the negative environmental externalities of tourism's development (Gan et al., 2026).

The output-oriented SBM DEA results shift attention to environmental consequences, given the goal of maximizing tourism revenues. This approach is consistent with the EU's broader competitiveness agenda and its emphasis on value creation rather than volume-driven growth in tourism. The substantial positive slack in primary energy consumption and CO_2 emissions indicates that output expansion in the absence of efficiency constraints risks disproportionately increasing environmental pressures. Supportively, the results underscore the need to decouple tourism output growth from energy use and carbon emissions, a core objective of the European Green Deal.

The positive and significant relationship with renewables indicates that greater integration of renewables into the tourism system can support the expansion of desirable outputs without proportionate increases in environmental pressures, increasing operational efficiency. In contrast to the strong efficiency results, renewable energy exhibits a statistically insignificant association with total factor productivity. This finding is consistent with the transitional nature of energy decarbonization, in which initial investments in infrastructure and energy-efficiency measures may impose adjustment costs, organizational changes, and technological adaptation before productivity gains are realized. The significant structural shifts observed after the years of financial crisis and instability further suggest that macroeconomic conditions, investment cycles, and structural reforms play a more dominant role in shaping tourism productivity than energy composition alone.

These findings discuss that although renewables enhance static efficiency (e.g., technical efficiency change), their contribution to dynamic productivity growth in the Eurozone's tourism sector remains limited. Practically, renewable deployment alone may not be sufficient to drive long-term productivity gains. Causality results imply that improvements in input efficiency rates alone do not automatically lead to greater renewable adoption, underscoring the need for policy-led renewable expansion rather than relying on market-driven efficiency gains. The absence of a causal relationship in productivity change calls for a more intensive integration of innovation and technological progress into the tourism system. Attention is needed to avoid negative externalities arising from market failure when pursuing tourism-related growth patterns (desirable outputs) while neglecting environmental pressures (undesirable outputs) from unregulated resource use.

The findings widely support the European Green Deal and 'Fit for 55' frameworks, which rely on regulatory targets, public investments, and coordinated actions to decarbonize energy-intensive sectors such as tourism. Last, the core issue in capturing sustainability lies in establishing an equilibrium between management requirements and well-being (Kuhlman and Farrington, 2010). Still, additional efforts should be made to analyze feedback from current practices and take lessons learned to guide future tourism accomplishments.

All in all, it is crucial to keep in mind that the crises of the current era not only call for ecological sustainability but also for a reconsideration of the ontological and ethical foundations of development itself (Robinson et al., 2026). Through encouraging the science–policy–society interface and the co-production of knowledge and future scenarios with innovative policy options, new linkages between the sciences and society should be investigated to drive effective actions for operationalizing and implementing Sustainable Development Goals at local, national, regional, and global scales (Takeuchi et al., 2017). Hence, tourism development and expansion should not miss this opportunity to enter the equation and make a solid contribution to this long-lasting effort. As a result, new efforts might focus on addressing tourism seasonality by detecting interregional patterns (Tsiotas et al., 2021) or investigating relationships between regional economic resilience and COVID-19 effects (Tsiotas et al., 2023) and integrating these findings into effective decision-making processes to incrreae efficiency rates and total factor productivity in terms od sustainability.

6. Conclusions

The present study examines technical efficiency scores and productivity change patterns for the Eurozone over the period 1996-2019. For this reason, a Slack-Based Measure (SBM) under the input- and output-oriented technical efficiency measures of the Data Envelopment Analysis (DEA) framework was applied. To strengthen our scientific approach, the SBM DEA analysis results were regressed on renewable use in final energy consumption.

Results indicate that most Eurozone countries operate below their attainable revenue frontier at current input levels. This result underscores the need for efficiency improvements and the creation of higher value-added tourism segments. Furthermore, output expansion should proceed without worsening the undesirable outputs identified in the model. Research findings are consistent with EU strategies to strengthen tourism competitiveness while avoiding overtourism and resource-intensive growth models. In practical terms, this challenging and long-term endeavor underscores the need to link decarbonization to innovation and productivity. Moreover, renewables have a positive and significant impact on technical efficiency scores, whereas productivity change is negatively affected, highlighting the need to accelerate energy transition. Granger causality tests reveal one unidirectional link from renewables to output-oriented technical efficiency. The neutrality hypothesis provides no causal links between output-oriented technical efficiency and changes in total factor productivity. Results indicate that further actions are required to advance renewable adoption and the energy transition, supporting efficiency improvements and tourism expansion.

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