Environmental efficiencies in the European Union Fisheries Sector with a focus on CO_2 emissions

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Abstract

This study examines the EU fisheries sector's environmental efficiency based on CO2 emissions from marine gas consumption. We utilize the European Commission's Scientific, Technical, and Economic Committee for Fisheries (STECF) dataset compiled over the period spanning 2013 to 2022. We evaluated environmental efficiencies employing the Tone Slack-Based Measure (SBM) with an undesirable output approach. The analysis involves two models: one assessing the environmental efficiency based on the live weight of landings as the good output and CO_2 emissions as the undesirable outcome, and the other model focusing on revenue derived from fishing activities as the good output and CO_2 emissions as the undesirable outcome. The EU fishery sector's environmental efficiency averages 0.712 based on live weight landings and CO2 emissions, while it increases to 0.831 when considering fishery revenue instead of live weight landings. Results show that it is feasible to reduce CO_2 emissions from fishing activities ranging from 24.6% to 26.2%. Some countries, such as Latvia, Lithuania, Netherlands, Poland, and Estonia, demonstrate exemplary environmental efficiencies with perfect scores.

Keywords: *Fishing sector, European Union, CO_2 emissions, Environmental efficiency.*

1. Introduction

Carbon dioxide (CO_2) is a greenhouse gas that traps heat in the atmosphere, contributing to global warming and climate change (IEA, 2023a). The world's industrialization and rapid economic growth have led to a sharp increase in CO_2 emissions (Krátký *et al.*, 2024). These emissions result from various human activities, including burning fossil fuels, producing materials, farming, and fisheries (Krátký *et al.*, 2024). Oil and gas production, transport, and processing resulted in 5.1 billion tonnes (Gt) CO_2 equivalent in 2022 – just under 15% of global energy sector GHG (greenhouse gas) emissions (IEA, 2023b). Fuel usage is among the most significant factors. In the fishing sector, fuel use requires taking necessary precautions regarding environmental damage. While continuing to generate revenue from fishing operations such as landing amount, developing methods to reduce the volume of CO_2 emissions is essential. Reducing GHGs remains an international priority for reducing the ecological and social impact of climate change (UN, 2015).

Global energy-related CO_2 emissions grew by

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0.9% or 321 Mt in 2022, reaching a new high of over 36.8 Gt[2]. The primary sources of CO_2 emissions were coal (42%), oil (30%), and natural gas (25%) (Ritchie & Roser, 2020; IEA, 2023b). There is an opportunity to reduce the impact of CO_2 released as a result of production activities. For example, technologies for capturing and using CO_2 that can be transformed into advanced biofuels (such as methane, ethanol, and butanol), chemicals (such as urea, methanol, and formic acid) or building materials (including inorganic and organic carbonates) through various chemical, electrochemical, photochemical or biochemical processes (Anonymous, 2023).

The EU ranks fourth in the world in fish production, accounting for approximately 3.1% of global production, behind China, Indonesia, and India. 80% of the production comes from fishing, while 20% comes from aquaculture (Anonymous, 2020). The Common Fisheries Policy (CFP) is the management tool for the EU's fisheries and aquaculture, adopted at the Union level and implemented in each member country. The CFP aims to ensure that fishing and aquaculture are environmentally, economically, and socially sustainable while providing a healthy food source for EU citizens and ensuring a fair standard of living for fishing communities. The EU is developing policies to ensure that fishing practices do not harm the reproductive capacity of fish populations (Anonymous, 2020).

1.1. *Objective*

This study aims to analyze the volume of CO_2 emission resulting from the consumption of marine gas oil, in calculating the environmental efficiencies (or eco-efficiencies) of European Union (EU) countries in the fisheries sector. The analysis will lead to stakeholders in the fisheries sector having a better understanding of their environmental impact. Understanding the relationship between energy usage and CO_2 emissions can facilitate more efficient resource management practices in the fisheries sector, thus reducing environmental impact. By identifying areas where energy consumption can be reduced or optimized, fisheries can operate more efficiently and sustainably. The EU's policies aim to reduce fishing sector emissions through sustainability, climate action, and a low-carbon transition, promoting energy efficiency, renewables, and resource management. This study supports these efforts by evaluating marine gas oil consumption and CO_2 emission efficiencies, providing empirical insights for policy development, resource optimization, and alignment with the EU's Blue Growth Strategy while highlighting the competitive edge of low-emission fisheries.

1.2. *Literature Review*

While several studies have assessed environmental efficiency in fisheries, they primarily focus on economic performance, resource utilization, or sustainability without explicitly incorporating CO_2 emissions as an undesirable output. Research on carbon emissions in fisheries primarily investigates emission trends, policy implications, or mitigation strategies. However, these studies do not integrate environmental efficiency modeling to quantify the extent to which emissions can be reduced while maintaining fishery output. The study bridges this gap by employing the Slack-Based Measure (SBM) approach, which explicitly accounts for undesirable outputs in efficiency assessments. By addressing this gap, our research provides a novel contribution to the field, offering empirical insights that inform both policy and industry stakeholders on optimizing resource management and reducing the environmental footprint of the fisheries sector in the EU.

Shirazi *et al*. (2020) assessed the environmental efficiency of airline companies with undesirable output, greenhouse gases emission (Shirazi & Mohammadi, 2020; Cui & Li, 2016) while Ozkan *et al*. (2016) measured efficiency with undesirable output in cement sector in Turkey (Ozkan & Ulutas, 2016). Miran *et al*. (2025) measured the environmental efficiencies of milk specialized farms in the European Union concerning CO_2 emissions using the Tone Slacks-Based Measure (Tone-SBM) with undesirable outputs method and conducted country-level analyses (Miran & Güngör, 2025). Wang *et al*. (2017) measured environmental efficiency across ten different coastal fishing regions in China and analyzed the influential factors (Wang & Ji, 2017). Zhou *et al*. (2007) presented a novel approach to measuring environmental performance using non-radial DEA methodology (Zhou, Poh & Ang, 2007). Their research highlights the significance of integrating pollutants into the conventional DEA framework to generate a standardized environmental performance index. Focusing on non-radial efficiency measures, the study provides a comprehensive environmental performance analysis, as demonstrated through a case study involving OECD countries. Li *et al*. (2020) stated that efficiency analysis of fishery output is crucial for sustainable management (Li, Jeon & Kim, 2020). This study evaluates the productivity of fisheries in China's coastal regions using the DEA-Malmquist index. Moreover, the study identified the need for improved technological efficiency in coastal fisheries production by examining input and output indicators over six years. The findings underscore the importance of informed development planning and policy measures for enhancing the regional fishery industry in China's coastal areas. Fare *et al*. (2007) evaluated the issue of unwanted by-catch and excess harvesting capacity in fisheries management is addressed (Fare, Kirkley & Walden, 2007). Their study examined four approaches, primarily employing data envelopment analysis (DEA), to estimate and assess both capacity and technical efficiency in production activities involving desirable and undesirable outputs. Through an analysis of data from fishing vessels operating in the northwest Atlantic Ocean's Georges Bank, the study highlights the challenge fishing vessels face in reducing undesirable outputs without compromising desirable outputs. Okeke-Ogbuafor *et al*. (2024) discussed that climate-smart fisheries policies play a crucial role in balancing CO_2 emissions reduction with food security, particularly in regions like Sierra Leone (Okeke-Ogbuafor *et al*., 2024). Their study emphasized the complementary relationship between CO_2 emissions reduction and food security, suggesting that both objectives can work in tandem to promote sustainable development in coastal fisheries (Okeke-Ogbuafor, *et al*., 2024). Du *et al*. (2021) assessed the efficiency level of marine ranching and its ecological implications is essential for achieving a balance between economy and ecology (Du, Jiang & Li, 2021). This research proposes a comprehensive index system and employs the Super-SBM model to measure Marine Ranching Ecological Efficiency (MREE) in Shandong Province, China. The research identified key factors contributing to efficiency loss in marine ranching and underscores the importance of efficient resource allocation and habitat conservation in ecological management. Durgun (2019) assessed the environmental efficiency level of small-scale fishing activities in the research area as which is low (Durgun, 2019). In the study, fishers were categorized into distinct segments based on their values, attitudes, and job satisfaction, followed by a comparative analysis across different fisher groups. Furthermore, the study examined the relationship between fishers' psychographic attributes and environmental efficiency. Alongside demographic and fishing-related characteristics, environmental efficiency was influenced by their values, environmental attitudes, perspectives on sustainable fishing, job satisfaction, and behavior, with undesirable outputs identified as bycatch and plastic waste. Alsaleh *et al*. (2023) pointed out that marine waste poses critical threats to coastal economies and marine sustainability, impacting tourism, fisheries, and shipping (Alsaleh, Wang & Nan, 2023). According to this study, the fisheries sector is a significant contributor, with production strongly associated with increased marine waste, particularly in affluent EU14. Moreover, the study revealed a significant positive correlation and demonstrated a strong association between fishing output and carbon sink decline across most quantiles. This analysis was conducted using an innovative approach – the method of moments quantile regression – which incorporates a fixed factor across 27 European nations.

1.3. *Data and Methodology*

The data used in this study were sourced from the Technical and Economic Committee for Fisheries (STECF) of the European Commission (STECF, 2023) for the period 2013-2022, a recognized authority in fisheries data analysis. The dataset, provided by EU Member States for the 2022 Economic Report, includes economic and production data by national totals and segments, covering fleet profitability and fish processing.

The study employs the approach of Tone Slacks-Based Measure (SBM) with undesirable outputs (Tone, 2003). Tone (2001) developed the Slacks-Based Efficiency Measure (SBM), which enables the calculation of efficiency values by utilizing slacks (Tone, 2001).

The primary reason for using the Tone SBM approach is its ability to explicitly handle undesirable outputs, such as CO_2 emissions. The Tone SBM approach offers greater flexibility in assessing environmental efficiency by explicitly considering both desirable and undesirable outputs (Tone, 2003). This method allows for a more nuanced evaluation of performance, especially in sectors where the impact of undesirable outputs (e.g., CO_2 emissions) is a significant concern. In contrast, classic parametric models may require complex adjustments to address such issues adequately (Tone, 2003).

Data Envelopment Analysis (DEA) is a robust methodology for computing the efficiencies of a defined number of decision-making units (DMUs). A DMU is referred to as any homogeneous structure, such as firms, businesses, or production facilities, that produces similar outputs from similar inputs (Coelli, Rao, ODonnell, & Battese, 2005). Data Envelopment Analysis (DEA) utilizes linear programming methods to construct a non-parametric efficiency frontier. The frontier formed by efficient units also facilitates the calculation of expected targets for other units. Assuming that there are *N* production units, each utilizing *K* inputs to produce *M* outputs, the input matrix (*X*) would have dimensions *K*×*N*, and the output matrix (*Y*) would have dimensions *M*×*N*. The radial linear programming model of Data Envelopment Analysis (DEA) for this scenario can be defined as follows:

$$\min_{\theta,\lambda}\theta,$$
$$\text{st.} \quad -y_i + Y\lambda \geq 0,$$
$$\theta x_i - X\lambda \geq 0,$$
$$\lambda \geq 0$$

where θ is a scalar representing efficiency, λ is N×1 dimensional vector of constants (Miran, 2021). Production aims to obtain beneficial products that meet human needs through input transformation. Data envelopment analysis measures the ability to determine the optimal levels of inputs and outputs in production and assumes that both inputs and outputs are good. In other words, DEA assumes that all inputs and outputs are "desirable" and will not harm anyone or anything. However, it is possible for the inputs used in production and the outputs obtained to have harmful characteristics for nature and humans. Alongside desired and market-oriented products, unwanted or harmful by-products such as environmental pollutants or hazardous waste may also be generated. The Tone undesirable output-oriented slack-based model has been utilized in accordance with the purpose of the study (Tone, 2003). This model explicitly incorporates undesirable outputs, like pollution or waste, into the efficiency analysis. Unlike input-oriented or output-oriented models, it doesn't prioritize either inputs or outputs. It considers proportional improvements in both while accounting for undesirable outputs.

The general representation of the Tone undesirable output-oriented slack-based model is as follows (Tone, 2003):

$$Z_{min} = t - \frac{1}{m}\sum_{i=1}^{m}\frac{S_i^-}{x_{io}}$$

Subject to:

$$t + \frac{1}{s_1 + s_2}\left(\sum_{r=1}^{s_1}\frac{S_r^g}{y_{ro}^g} + \sum_{r=1}^{s_2}\frac{S_r^b}{y_{ro}^b}\right) = 1$$

(good and undesirable outputs)

$$x\lambda + S^- = tx_{io} \quad \text{(inputs)}$$

$$y^g\lambda - S^g = ty_o^g \quad \text{(good outputs)}$$

$$y^b\lambda + S^b = ty_o^b \quad \text{(undesirable outputs)}$$

Where:

t: a coefficient greater than 0
m: Number of inputs
S_r^g : Slack of the r^th good output
S_r^b : Slack of the r^th undesirable output
y_{ro}^g : Level of the r^th decision unit's good output
y_{ro}^b : Level of the r^th decision unit's undesirable output

x_{io}: Use of input for the r[th] decision unit
S_i^-: Slack of the i[th] input
s_1: Number of good outputs
s_2: Number of undesirable outputs

In this model, each DMU is characterized by its consumption of inputs, production of desirable outputs (e.g., products), and generation of undesirable outputs (e.g., pollution or CO_2 emission). The model introduces slack variables for both inputs and outputs. Positive slacks in inputs indicate potential reduction, while negative slacks in desirable outputs represent potential expansion. Undesirable outputs are minimized through negative slacks. The model calculates an efficiency score for each DMU based on the proportional reduction of inputs and undesirable outputs while potentially expanding desirable outputs. DMUs are compared to the efficient frontier formed by the best-performing units. Those with scores of 1 are considered efficient, while others have scores lower than 1, indicating inefficiency.

The objective function of the Tone Undesirable Output-Oriented Slack-Based Model is not directly minimizing an efficiency score like traditional DEA models. Instead, it focuses on minimizing a weighted sum of proportional slacks associated with inputs and undesirable outputs. The model utilizes slack variables that represent the potential for proportional reduction in inputs and undesirable outputs. These slacks are expressed as a percentage of the original input or undesirable output values. The objective function minimizes a weighted sum of these proportional slacks. This means the model attempts to simultaneously: Lowering the proportional slack associated with each input indicates a potential for input reduction without compromising efficiency; minimizing the proportional slack for undesirable outputs signifies potential reduction in their generation. The weights assigned to each slack variable reflect their relative importance. For example, a higher weight for an undesirable output slack might emphasize its criticality in the efficiency assessment. Therefore, the objective function of aims to find the most proportional reduction in inputs and undesirable outputs for a given DMU, considering their relative weights. This approach allows for a non-radial and non-oriented evaluation of efficiency, focusing on proportional improvements across all dimensions.

The environmental efficiency of the fishery sector in the European Union countries was first analyzed using Tone Slacks-Based Measure (SBM) with undesirable outputs (Tone, 2003) considering both live weight of landings and fishing revenue as good outputs and a undesirable output of CO_2 emissions from energy consumption in fishing sector. The first model assesses efficiency based on live weight of landings, representing biological productivity and fisheries capability, while the second model focuses on fishing revenue, reflecting economic performance. A single integrated model could introduce bias, as variations in fish pricing, species composition, and market conditions might obscure the true efficiency drivers. By analyzing these models separately, we provide clearer insights into whether inefficiencies stem from biological, operational, or economic factors, enabling more targeted policy recommendations. This approach aligns with established environmental efficiency methodologies (e.g., Tone, 2003), ensuring robustness and interpretability in our findings.

Subsequently, effective non-discretionary factors for each environmental efficiency were analyzed in depth using the truncated regression method.

Environmental Efficiency Models

In a typical data envelopment model, specific inputs are considered to produce a particular output. The inputs and outputs that can be used in DEA depend on the specific research question and the data available. This study was carried out with two outputs, one good and the other bad, and five inputs. Thus, there are two different environmental efficiency models, one with the good output as live weight of landings and the other with the good output as fishing revenue.

Good outputs:

In data envelopment analysis (DEA) studies related to fisheries, the most frequently utilized output variables are the quantities, live weight of landings, or value of landings and the gross revenues derived from fishery activities (Ceyhan & Gene, 2014; Pascoe *et al*., 2013; Pipitone & Colloca, 2018; Felthovena & Paul, 2004). In this study, the good outputs are actual annual fishery revenues and the live weight of landings. The Tone *Slacks-Based Measure (SBM) with undesirable outputs* employed in this study for the EU fishery comprises two outputs: live weight of landings and fishery revenue. It involves five inputs contributing to the generation of the outputs.

One of the main outputs is the real fishery revenue of EU countries, deflated to 2012 prices, which is calculated as follows:

Fishery output = Gross Value of Landings (€)
+ Revenue from leasing out quota (€)
+ Lease/rental payments for quota (€)
+ Other revenue (€)

The other good output represents fishery output generated by EU countries the live weight of landings (tonnes). The live weight of landings in fishery refers to the total weight of the fish or seafood caught by fishermen and brought to shore, measured while the catch is still fresh and has not undergone any processing or removal of parts such as guts or scales. It represents the actual weight of the catch as it is landed, including both target species and any by-catch. This metric is vital in fisheries management and research, providing insights into the overall catch volume and composition.

Undesirable output:

The undesirable output variable is CO_2 emissions due to the energy consumption of marine gas oil. It is assumed that consuming 1 liter of marine gas oil produces 2.77539 kg of CO_2 (UNFCCC/Secretariat, 2021).

Inputs:

Some standard inputs and outputs used in fisheries research include vessel size, engine power, crew size, and fuel consumption (Reid & Squires, 2022; Squires & Grafton, 1996; Squires & Ruseski, 2009; Kirkley, Squires, & Ivar, 1995; Fare, Grosskopf, Kirkley, & Squires, 2020). This study includes the following inputs by EU countries:

- Energy consumption - marine gas oil (liter)
- Fishing days (count)
- Total vessel capacity (tonnes)
- Engaged crew (count)
- Real operational costs (€)

The input of operational cost is calculated as follows:

Operational cost = Personnel costs (€)
+ Energy costs (€)
+ Consumption of fixed capital (€)
+ Other non-variable costs (€)
+ Other variable costs (€)
+ Repair&Maintenance costs (€) - Subsidies (€)

Data transformation and sufficiency

We utilized the dataset (STECF, 2023) in the analysis, which presents monetary variables in Euros (EUR) on a nominal basis. If nominal monetary time-series variables are not adjusted for inflation, nominal values include the influence of time-dependent price increases. Without adjustment, observed increases in variable values may be solely attributed to price changes and may not accurately reflect real value growth. Adjustment involves aligning nominal values with changes in purchasing power, facilitating the expression of their real values. Given that nominal output values encompass variations attributed to inflation, deflating these values based on a designated reference year is imperative. To accomplish this, the nominal variables have been adjusted by deflating them in accordance with the Gross Domestic Product (GDP) of each respective country, utilizing the base year of 2012.

All variables utilized in the analysis pertain to the level of EU member countries. The dataset for this investigation encompasses 22 European Union member countries, each representing a decision-making unit (DMU), namely Belgium, Bulgaria, Croatia, Cyprus, Denmark, Estonia, Finland, France, Germany, Greece, Ireland, Italy, Latvia, Lithuania, Malta, Netherlands, Poland, Portugal, Romania, Slovenia, Spain, and Sweden. Both input and output variables incorporate the respective sums from 2013 to 2022. This methodology assumes that the EU fishery sector utilizes all inputs to generate outputs within the same year as aggregated totals, akin to utilizing cross-sectional data.

When determining the minimum number of Decision-Making Units (DMUs) in DEA, the condition under consideration is as follows (Miran, 2021):

DMU >= 2 × Number of inputs × Number of outputs ∴ DMU >= 20

Given that our dataset comprises 22 countries (DMUs), it meets the minimum number of DMUs requirement. This indicates that we have obtained sufficient and reliable data in terms of both the number of countries and the time period.

Considering that environmental efficiency values are equal to or greater than 1, non-discretionary factors affecting it were analyzed using truncated regression (Greene, 2018), as the relevant literature recommends employing truncated regression for efficiency analyses (Simar & Wilson, 2007; Banker & Natarajan, 2008). In truncated regression models, certain dependent variable ranges are excluded from the sample. This means that observations of the dependent variable that fall below or above specific threshold values are systematically removed from the sample. In truncated regression, no observations exist for the dependent and independent variables corresponding to specific threshold values.

Software

Environmental efficiencies were calculated via the library of *deaR* in R package using the model_sbmeff function from the deaR package in R (Coll-Serrano, Benítez, & Bolós, 2018)[1]. These calculations can also be performed on the deaR website at https://rbensua.shinyapps.io/deaR/.

2. Results

The study's findings are reported by initially detailing the environmental efficiencies of the European Union countries, followed by an in-depth analysis of the non-discretionary factors that influence these efficiencies.

The dataset comprises data from 22 countries, including key variables related to the fisheries sector in the European Union. The live weight of landings averages 4.38 billion tonnes, with a minimum of 10.88 million tonnes and a maximum of 25.09 billion tonnes, exhibiting a standard deviation of 6.17 billion tonnes. The real fishing revenue has a mean value of €555.08 million, ranging from €5.41 million to €3.51 billion, with a standard deviation of €883.55 million.

The CO_2 emissions from energy consumption in the fishing sector average 261.31 million kg, with a minimum value of 655,055.81 kg and a maximum of 1.74 billion kg, showing a standard deviation of 422.87 million kg. Similarly, energy consumption averages 94.15 million liters, with a minimum of 236,022.98 liters and a maximum of 625.69 million liters, with a standard deviation of 152.36 million liters.

The gross tonnage fishing days exhibit a wide range, averaging 107.69 million, with values spanning from 31,161.29 to 2.19 billion, and a standard deviation of 464.63 million. The total vessel tonnage has a mean of 122,718.70 tonnes, with a minimum of 1,289.44 tonnes and a maximum of 687,977.46 tonnes, with a standard deviation of 159,346.77 tonnes.

The number of engaged crew members averages 6,300.13 persons, with a minimum of 109.57 persons and a maximum of 32,558.67 persons, with a standard deviation of 9,481.25 persons. Lastly, the operating costs in the fisheries sector average €402.00 million, with a minimum of €1.62 million and a maximum of €2.50 billion, exhibiting a standard deviation of €653.85 million.

2.1. *Environmental Efficiencies by EU Countries*

The environmental efficiencies (EE) of European Union countries in the fishery sector, specifically concerning CO_2 emissions from marine gas oil consumption, are provided in Table 1. Environmental efficiency measures how efficiently a country's fishery sector manages its energy consumption to minimize CO_2 emissions while maintaining or increasing fishery output. A value of 1 indicates maximum environmen-

[1] The R codes used are: model_sbmeff (Data,orientation = "io", rts = "crs") and model_sbmeff (Data, orientation = "oo", rts = "crs").

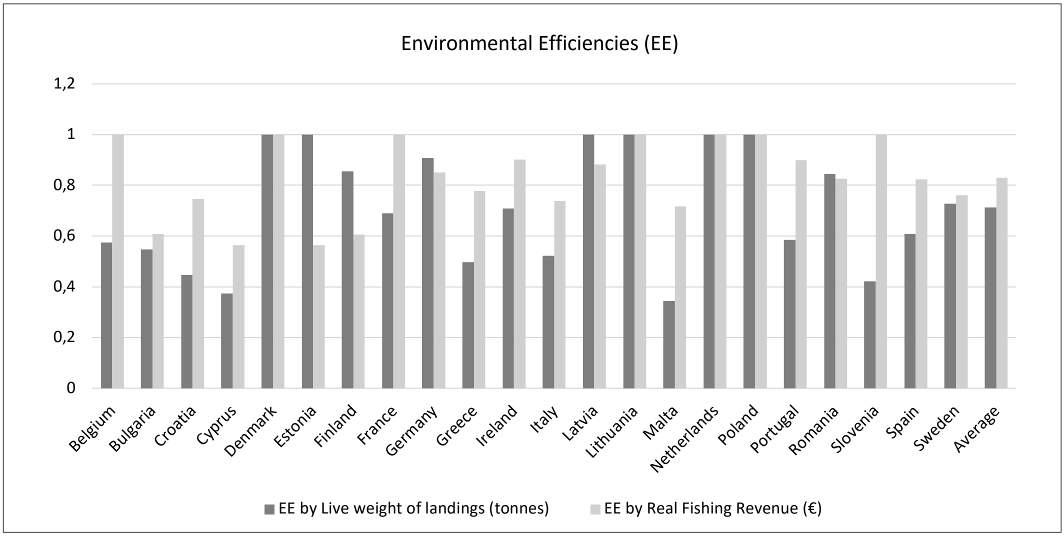
Table 1 - EU countries' fishery sector's environmental efficiencies obtained from Tone Slacks-Based Measure (SBM) with undesirable outputs.

Live weight of landings (tonnes)				*Real Fishing Revenue (€)*			
Country	*EE*	*Country*	*EE*	*Country*	*EE*	*Country*	*EE*
Belgium	0.575	Italy	0.523	Belgium	1.000	Italy	0.739
Bulgaria	0.547	Latvia	1.000	Bulgaria	0.609	Latvia	0.883
Croatia	0.448	Lithuania	1.000	Croatia	0.746	Lithuania	1.000
Cyprus	0.374	Malta	0.344	Cyprus	0.565	Malta	0.718
Denmark	1.000	Netherlands	1.000	Denmark	1.000	Netherlands	1.000
Estonia	1.000	Poland	1.000	Estonia	0.565	Poland	1.000
Finland	0.855	Portugal	0.586	Finland	0.606	Portugal	0.899
France	0.690	Romania	0.844	France	1.000	Romania	0.827
Germany	0.908	Slovenia	0.422	Germany	0.852	Slovenia	1.000
Greece	0.497	Spain	0.608	Greece	0.778	Spain	0.823
Ireland	0.708	Sweden	0.727	Ireland	0.901	Sweden	0.761
Average	0.712			Average	0.831		

tal efficiency, meaning that the country's fishery sector efficiently manages its energy consumption to minimize CO_2 emissions without compromising fishery output. Values closer to 1 indicate high environmental efficiency, reflecting effective energy consumption and CO_2 emission management in the fishery sector, while values below 1 suggest the need for improvements in these areas to sustain fishery output.

In the first model, we considered the *live weight of landings* as the good output and CO_2 emissions resulting from energy consumption as the undesirable output. Regarding environmental efficiency in the fishing sector, Latvia, Lithuania, Netherlands, Poland, and Estonia have achieved a perfect score of 1.000 (Table 2, Figure 1). This accomplishment reflects their ability to maintain high output levels while minimizing

Figure 1 - Environmental efficiencies by the EU countries with respect to live weight of landings (tonnes) and real fishing revenue (€).



CO_2 emissions, underscoring their commitment to sustainable practices. On the other hand, Denmark, Finland, France, Germany, Ireland, Portugal, and Romania demonstrate a moderate level of environmental efficiency, with scores ranging from 0.700 to 1.000. Meanwhile, Belgium, Bulgaria, Croatia, Cyprus, Greece, Italy, Malta, Slovenia, Spain, and Sweden have environmental efficiency scores below 0.700, indicating a need for enhanced efforts to improve sustainability practices and reduce CO_2 emissions per unit of output. Overall, the average environmental efficiency among the European Union countries examined is 0.712, highlighting the need for improvement in adopting more sustainable and environmentally friendly practices within the fishing sector. Results indicate that the European Union fishing sector has the potential to reduce its CO_2 emission volume resulting from energy consumption by 28.8% (Table 2).

In the second model, we examined the good output as the revenue derived from fishing activities and the undesirable output as the CO_2 emissions from energy consumption. Among European Union countries, Belgium, Denmark, France, Lithuania, Netherlands, Poland, and Slovenia stand out with the highest environmental efficiency score of 1.000 (Table 2, Figure 1). These countries have effectively implemented practices in their fishing sectors that minimize CO_2 emissions while maximizing revenue generation. Additionally, Germany, Greece, Ireland, Italy, Latvia, Portugal, and Romania demonstrate significant environmental consciousness, with environmental efficiency scores ranging from 0.700 to 1.000. However, Bulgaria, Croatia, Cyprus, Estonia, Finland, Malta, Spain, and Sweden lag with environmental efficiency scores below 0.700. This indicates a need for improvement in implementing sustainable and environmentally friendly practices to reduce CO_2 emissions while maintaining revenue generation. Overall, the average environmental efficiency for all European Union countries is 0.831, suggesting a relatively good level of environmental consciousness and efficiency in the fishing sector across the EU. Nevertheless, variations among individual countries highlight the necessity for tailored strategies to enhance environmental performance in specific regions. Under current conditions, the European Union fishing sector has the potential to reduce its volume of CO_2 emission volume resulting from energy consumption by 16.9% without reducing its current revenue (Table 1).

By considering both the live weight of landings and fishing revenue, we find that the average environmental efficiency across all European Union countries stands at 0.712 and 0.831 respectively. This indicates that while there is room for improvement in implementing more sustainable and environmentally friendly practices based on the live weight of landings, the fishing sector demonstrates a relatively good level of environmental consciousness and efficiency when revenue is taken into account. This difference suggests that EU countries are more efficient at generating higher revenue per unit of CO_2 emissions than at maximizing the physical quantity of fish caught per unit of emissions, highlighting an opportunity to enhance sustainability in terms of production volume.

Environmental efficiencies obtained from Tone Slack-Based Measure (SBM) with undesirable outputs are based on both live weight of landings and real revenues as good outputs and CO_2 emissions as undesirable outputs. The difference between the two environmental efficiencies is statistically significant ($t = -2.388$, $p = 0.026$), indicating that the environmental efficiency based on real fishery revenues is greater than the one based on the live weight of landings.

Table 2 displays the percentage difference between actual and target inputs and outputs in the fishing sector of EU countries, calculated based on the live weight of landings. Even if Belgium were to reduce its energy consumption by 56.3%, vessel capacity by 13.14%, vessel personnel by 30.68%, and operating expenses by 23.15%, it could still potentially increase the live weight of landings by 91.62% while simultaneously decreasing emissions by 56.30%. Belgium needs to make the most significant reduction in energy consumption, with a reduction of 56.3%, France with 44.8%, and Italy with 42.27%. Malta has the potential to increase its live weight of landings, which is considered a good output, by 3.81 times.

Table 2 - Percentage difference of actual and target inputs-outputs in the fishing sector of EU countries, based on live weight of landings.

Country	*Energy Consumption (liter)*	*Fishing Days (count)*	*Total Vessel Tonnage (tonnes)*	*Engaged Crew (count)*	*Operational Costs (€)*	*Weight of landings (tonnes)*	*CO_2 Emission (kg)*
Belgium	-56.30	0.00	-13.14	-30.68	-23.15	91.62	-56.30
Bulgaria	0.00	-17.73	0.00	-66.76	0.00	165.34	0.00
Croatia	0.00	-29.22	0.00	-25.03	0.00	246.13	0.00
Cyprus	0.00	-81.00	0.00	-69.05	0.00	335.13	0.00
Denmark	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Estonia	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Finland	-21.76	-64.25	-14.27	0.00	0.00	12.02	-21.76
France	-44.58	-33.62	0.00	0.00	-53.13	45.24	-44.58
Germany	0.00	-43.21	-40.76	0.00	-2.34	20.28	0.00
Greece	-15.29	-91.69	0.00	-89.16	0.00	187.27	-15.29
Ireland	-30.54	0.00	-24.81	-71.95	-9.06	51.86	-30.54
Italy	-42.27	-85.14	0.00	-82.81	0.00	140.41	-42.27
Latvia	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lithuania	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Malta	0.00	-24.63	0.00	-50.45	0.00	381.48	0.00
Netherlands	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Poland	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Portugal	-17.30	-19.39	0.00	-37.43	-28.50	123.86	-17.30
Romania	-32.51	0.00	-26.76	-68.69	0.00	4.32	-32.51
Slovenia	0.00	-65.30	0.00	-35.06	0.00	273.42	0.00
Spain	-24.86	-56.71	0.00	-78.86	0.00	104.04	-24.86
Sweden	-40.36	-25.19	0.00	0.00	0.00	34.79	-40.36

According to Table 3, the countries that need to reduce marine gas oil the most to achieve environmental efficiency are Italy with 70.78% and Greece with 57.02%, based on fishing revenue. Since our model associates CO_2 emissions with marine oil consumption, the reduction in CO_2 emissions in these countries is proportionate to the decrease in usage. The countries that can obtain the most significant increase in fishing revenue in response to the reduction in CO_2 emissions are Estonia with 131.26% and Cyprus with 112.72%.

Regarding real fishing revenue, there is a decrease ranging from 11% to 39.8% across all inputs, while fishing revenue has experienced a 6% increase. Moreover, there is a 26.2% reduction in CO_2 emissions.

When considering overall aggregates (Table 4), in terms of the live weight of landings, a decrease ranging from 3.2% to 62.1% is observed across all inputs, with a notable increase of 70% in the live weight of landings. Additionally, there is a 24.6% reduction in CO_2 emissions.

Model countries for minimizing CO2 emissions

EU countries that fail to achieve environmental efficiency in the fishing sector can take the most suitable countries as models and work to reduce their CO_2 emissions (Table 5). Concerning live weight of landings, in the reduction of CO_2 emissions caused by the fishing sector, Denmark could serve as a model for Belgium; Estonia and Latvia for Bulgaria; Estonia and Latvia for Croatia; Estonia and Latvia for Cy-

Table 3 - Percentage difference of actual and target inputs-outputs in the fishing sector of EU countries, based on fishing revenue.

Country	*Energy Consumption (liter)*	*Fishing Days (count)*	*Total Vessel Tonnage (tonnes)*	*Engaged Crew (count)*	*Operational Costs (€)*	*Weight of landings (tonnes)*	*CO_2 Emission (kg)*
Belgium	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Bulgaria	-50.72	0.00	-62.93	-80.43	-0.00	77.43	-50.72
Croatia	-13.12	0.00	-37.51	-51.34	0.00	55.07	-13.12
Cyprus	-40.98	-25.51	-0.00	-48.25	-39.85	112.72	-40.98
Denmark	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Estonia	-22.62	-0.00	-57.94	-40.02	-35.56	131.26	-22.62
Finland	-22.93	-11.08	-14.63	0.00	0.00	107.27	-22.93
France	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Germany	0.00	0.00	-41.03	-2.93	-1.90	34.85	0.00
Greece	-57.02	-46.89	-0.00	-55.23	-49.17	0.00	-57.02
Ireland	-21.86	0.00	-16.41	-68.95	-3.92	0.00	-21.86
Italy	-70.78	0.00	-0.00	-14.00	-49.73	-0.00	-70.78
Latvia	-5.10	0.00	-31.42	-60.88	0.00	21.28	-5.10
Lithuania	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Malta	-31.91	0.00	-50.88	-74.29	-0.00	46.62	-31.91
Netherlands	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Poland	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Portugal	-22.48	0.00	-27.57	-69.71	-29.78	0.00	-22.48
Romania	-33.40	0.00	-58.14	-84.17	-0.00	8.55	-33.40
Slovenia	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Spain	-33.58	0.00	-0.00	-53.74	-12.36	9.43	-33.58
Sweden	-43.92	0.00	-17.37	-33.06	-0.00	18.75	-43.92

prus; Denmark and Latvia for Finland; Denmark and Latvia for France; Denmark and Latvia for Germany; Denmark and Latvia for Greece; Denmark for Ireland; Denmark and Latvia for Italy; Estonia and Latvia for Malta; Latvia for Portugal; Estonia and Latvia for Romania; Estonia and Latvia for Slovenia; Denmark and Latvia for Spain; Denmark and Latvia for Sweden. Denmark appears to be the most favorable model country, as it is recommended as a model for multiple countries, including Belgium, Finland, France, Germany, and Sweden for reducing CO_2 emissions the fishing sector generates.

When considering the fishing revenue, in the context of reducing CO_2 emissions the fishing sector generates, Denmark and Slovenia could serve as models for Bulgaria; Denmark and Slovenia for Croatia; Slovenia for Cyprus; Slovenia for Estonia; Denmark and Slovenia for Finland; Denmark and Slovenia for Germany; France and Slovenia for Greece; Denmark and Netherlands for Ireland; Denmark, France, and Slovenia for Italy; Denmark and Slovenia for Latvia; Denmark and Slovenia for Malta; Denmark and Slovenia for Portugal; Denmark and Slovenia for Romania; Denmark and Slovenia for Spain; Denmark and Slovenia for Sweden (Table 5). Denmark and Slovenia emerged as the most considered model countries in the context of reducing CO_2 emissions the fishing sector generates, as they are recommended as models for multiple countries, including Bulgaria, Croatia, Estonia, Finland, Germany, Greece, Ireland, Italy, Latvia, Malta, Portugal, Romania, Spain, and Sweden.

Table 4 - EU countries' fishery sector's differences in total actual and target inputs/outputs.

Inputs	*Live weight of landings (tonnes)*				*Real Fishing Revenue (€)*			
	Target Total	*Actual Total*	*Difference*	*%*	*Target Total*	*Actual Total*	*Difference*	*%*
Energy Consumption	1,522,916,987	2,071,376,134	-548,459,147	-26.5	1,486,704,505	2,071,376,134	-584,671,629	-28.2%
Fishing Days	2,180,147	5,747,472	-3,567,325	-62.1	5,113,525	5,747,472	-633,947	-11.0%
Total Vessel tonnage	2,614,242	2,699,811	-85,569	-3.2	2,495,753	2,699,811	-204,058	-7.6%
Engaged Crew	58,301	138,603	-80,302	-57.9	83,500	138,603	-55,103	-39.8%
Operational Cost	7,396,426,936	8,629,241,555	-1,232,814,619	-14.3	7,412,869,438	8,629,241,555	-1,216,372,117	-14.1%
Outputs								
Good Output	164,365,520,658	96,357,731,374	68,007,789,284	70.6	12,941,487,441	12,211,712,180	729,775,261	6.0%
Undesirable output (CO_2 Emission)	4,226,688,577	5,748,876,610	-1,415,024,600	-24.6	4,126,184,815	5,748,876,610	-1,508,452,805	-26.2%

Table 5 - Model countries to reduce CO_2 emissions with respect to live weight of landings.

Countries to be Modeled after	*Model countries with respect to live weight of landings*			*Model countries with respect to real fishing revenue*		
Belgium	Denmark			Denmark	Slovenia	
Bulgaria	Estonia	Latvia	Poland	Denmark	Slovenia	
Croatia	Estonia	Latvia	Poland	Slovenia		
Cyprus	Estonia	Latvia	Poland	Slovenia		
Finland	Denmark	Latvia		Denmark	Slovenia	
France	Denmark	Latvia		Denmark	Slovenia	
Germany	Denmark	Latvia		France	Slovenia	
Greece	Denmark	Latvia		Denmark	Netherlands	
Ireland	Denmark			Denmark	France	Slovenia
Italy	Denmark	Latvia		Denmark	Slovenia	
Malta	Estonia	Latvia	Poland	Denmark	Slovenia	
Portugal	Latvia			Denmark	Slovenia	
Romania	Estonia	Latvia		Denmark	Slovenia	
Slovenia	Estonia	Latvia	Poland	Denmark	Slovenia	
Spain	Denmark	Latvia		Denmark	Slovenia	
Sweden	Denmark	Latvia	Poland			

2.2. *Non-Discretionary Factors Affecting Environmental Efficiency*

Identifying non-discretionary factors influencing environmental efficiency is pivotal in formulating strategies to mitigate CO_2 emissions. Therefore, we will investigate these influential non-discretionary factors using a truncated regression model, employing environmental efficiency variables derived from the live weight of landings and fishing revenue as dependent variables (Table 6). Environmental efficiency is transformed by computing its reciprocal and by construing it within the 0-1 range. This reciprocal

Table 6 - Non-discretionary factors in the regression models and units.

Non-discretionary factors	*Unit*
Population	Number of people
Coastal Length	Kilometer
Real GDP	$US of 2012
Number of fishery enterprises with 2-5 vessels	Count
Number of fishery enterprises with less than 5 vessels	Count
Number of fishery enterprises with 1 vessel	Count
Mean vessel age	Years
Atlantic	Dummy (1: having a coast by the Mediterranean Sea; 0: having a coast by the North Sea)
Mediterranean	Dummy (1: having coast by the Atlantic Ocean; 0: having coast by the North Sea)

transformation yields a value of 1 for efficient countries and greater than 1 for inefficient countries. Truncated regression methodology was employed due to the reciprocal transformation of the environmental efficiency variable serving as the dependent variable, confined to the interval [1, ∞], within the left-limit truncation regression model (Simar & Wilson, 2007).

Truncated regression estimation results are presented in Table 7 for two different good outputs, both of which are statistically significant at α=0.05. It is important to note that the coefficients in the estimation results are interpreted with an inverse sign, as the dependent variable is 1/EE.

Based on the truncated regression model estimated for live weight of landings (Table 7), as the number of fishery enterprises with 1 vessel increases in a European Union country, the environmental efficiency of the fishing sector, which considers CO_2 emissions from fuel consumption, increases. This implies that the more the fishery enterprises, represented by those with only one vessel, tend to be more environmentally efficient in terms of CO_2 emissions per unit of output. As the number of fishery enterprises with 2 to 5 vessels increases in a European Union country, the environmental efficiency of the fishing sector, which considers CO_2 emissions from fuel consumption, increases. This suggests that larger fishery enterprises may be less environmentally efficient, possibly due to higher fuel consumption associated with larger fleets. As a country's population increases, the fishing sector's environmental efficiency, which considers CO_2 emissions from fuel consumption, increases. This suggests that countries with larger populations may invest more in sustainable fishing practices or have stricter regulations, leading to higher environmental efficiency in the fishing sector. As per capita income increases, the environmental efficiency of the fishing sector, which considers CO_2 emissions from fuel consumption, increases. This indicates that higher-income countries may have better technology or resources to reduce CO_2 emissions per unit of output in the fishing sector. The environmental efficiency of the fishing sector, considering CO_2 emissions from fuel consumption, is lower in countries with a coastline on the Mediterranean Sea compared to those with a coastline on the North Sea. Similar to the previous statement, this highlights regional differences in environmental efficiency, specifically between countries bordering the Mediterranean Sea and those bordering the North Sea. As the average age of fishing vessels increases, there is, in the younger fishing vessels, a decrease in environmental efficiency considering CO_2 emissions from fuel consumption in the fishing sector, followed by an increase in environmental efficiency as vessels get older. This suggests a non-linear relationship between the age of fishing vessels and environmental efficiency, with efficiency initially decreasing as vessels age, possibly due

Table 7 - Truncated regression estimation results (dependent variable is 1/EE).

Independent variable	*Live Weight of Landings (tonnes)*		*Real Fishing Revenue (€)*	
	Coefficient (Z value)	*Marginal effect*	*Coefficient (Z value)*	*Marginal effect*
Number of fishery enterprises with 1 vessel	-0.000055* (-1.83)	-0.0000552	-0.00016*** (-2.84)	-0.000160
Number of fishery enterprises with 2-5 vessels	-0.001198*** (-3.86)	-0.0011982	-0.00026 (-0.39)	-0.000260
Number of fishery enterprises with less than 5 vessels	0.000967 (1.36)	0.0009671	0.002157 (1.52)	0.002157
Population	-0.002994*** (-4.27)	-0.002994	-0.002572* (-1.79)	-0.002572
Coastal Length	0.000038* (1.76)	0.0000377	0.00007* (1.92)	0.000070
Real GDP	-0.000008*** (-3.12)	-70.60e-06	-0.00001** (-2.01)	-0.000010
Atlantic	-0.062827 (-0.31)	-0.062827	0.773028** (1.99)	0.773028
Mediterranean	0.944889*** (6.5)	0.9448894	0.64569** (2.52)	0.645690
Mean Vessel Age	0.374386*** (9)	0.374386	0.205692** (2.01)	0.205692
Squared Mean Vessel Age	-0.005957*** (-9.01)	-0.0059569	-0.004265** (-2.34)	-0.004265
Constant	-3.4176*** (-5.54)		-0.704067 (-0.52)	
Wald test	$\chi^2(10) = 660.15$***		χ^2 (10) = 19.22**	

[a] *Since it is calculated as 1/IO(CRS), the signs of the coefficients should be interpreted inversely.*
,, and *** represent significance at 0.1, 0.05, and 0.01 levels, respectively.*
Truncated regression estimation results for live weight of landings.

to increased fuel consumption or emissions, followed by improvements in efficiency at later stages, potentially through technological upgrades or retrofits (Table 7).

Truncated regression estimation results for Fishing Revenue

According to the truncated regression model estimated for the live weight of landings for fishing revenue (Table 7), as the number of fishery enterprises with 2-5 vessels increases, environmental efficiency also increases. As the number of fishery enterprises with 1 vessel increases, environmental efficiency also increases. This suggests that smaller-scale fishing operations have a lower environmental impact than more extensive operations. This might be because smaller operations are more likely to use sustainable fishing practices or have less intensive fishing methods. As the population increases, environmental efficiency decreases. This could indicate that higher population densities lead to more pollution or resource depletion, thus reducing environmental efficiency. It might also imply that larger populations put more pressure on natural resources. As the coastal length increases, environmental efficiency decreases. This suggests that longer coastlines may face more significant challenges in maintaining environmental quality, possibly due to increased human activity or difficulty in managing pollution. As the real national income increases, environmental efficiency increases. This implies that wealthier countries have the resources to invest in environmental protection measures or technologies, leading to higher environmental efficiency.

As the environmental efficiency of countries with coastlines on the Mediterranean Sea increases compared to countries with coastlines on the North Sea, environmental efficiency is lower. This indicates that countries with coastlines on the Mediterranean Sea tend to have lower environmental efficiency than those on the North Sea. This could be due to differences in governance, economic development, or environmental policies between these regions. As the average age of fishing vessels increases, there is initially a decrease in environmental efficiency in newer vessels, considering CO_2 emissions from fuel consumption in the fishing sector, followed by an increase in environmental efficiency at later ages. This suggests a non-linear relationship between the age of fishing vessels and environmental efficiency, with efficiency initially decreasing as vessels age, possibly due to increased fuel consumption or emissions, followed by improvements in efficiency at older vessels, potentially through technological upgrades or retrofits. As the environmental efficiency of countries with coastlines on the Atlantic Ocean increases compared to countries with coastlines on the North Sea, environmental efficiency is higher. This implies that countries with coastlines on the Atlantic Ocean tend to have higher environmental efficiency than those on the North Sea. This could be due to various factors, such as different environmental policies, levels of industrialization, or natural resource management practices in these regions (Table 7).

3. Discussion

Our study's findings align with various studies in the literature that have examined environmental efficiency in different sectors, including specialized milk farms in the EU, aviation, cement production, and coastal fisheries. Focusing on the European Union's fishing sector and specifically considering CO_2 emissions as a measure of environmental efficiency, our study fills a gap in the existing literature.

Shirazi *et al.* (2020) have previously measured environmental efficiency in airline companies based on greenhouse gas emissions. At the same time, Ozkan *et al.* (2016) examined efficiency in Turkey's cement sector concerning environmental impacts. These studies provide a foundation for understanding how environmental efficiency can be assessed in different industries, laying the groundwork for our study to apply similar methodologies to the EU fishing sector. Zhou *et al.*'s (2007) novel approach to measuring environmental performance using non-radial DEA methodology is relevant to our study as it emphasizes the importance of integrating pollutants into efficiency analysis frameworks. This aligns with our study's focus on CO_2 emissions and highlights the significance of considering environmental impacts in efficiency assessments. Li *et al.*'s (2020) study on fisheries productivity in China's coastal regions using the DEA-Malmquist index underscores the importance of evaluating technological efficiency in fisheries production, which resonates with our study's emphasis on identifying areas for improvement in the EU fishing sector's environmental efficiency. Fare *et al.*'s (2007) examination of undesirable outputs in fisheries management using DEA methodology is relevant to our study as it addresses the challenge of reducing undesirable outputs without compromising desirable outputs, a key consideration in assessing environmental efficiency in the fishing sector. Okeke-Ogbuafor *et al.*'s (2024) discussion on climate-smart fisheries policies in Sierra Leone highlights the importance of balancing CO_2 emissions reduction with food security, which is relevant to our study's broader implications for policy development in the EU fishing sector. Wang *et al.* (2017) found that the average environmental efficiency is approximately 0.714, which is very close to that of the European Union (EU) that we calculated. Durgun's (2019) study on small-scale fishing activities and their environmental efficiency, considering the personal values, attitudes, and job satisfaction of fishers, provides insight into the factors influencing environmental efficiency in the fishing sector, complementing our study's findings on specific EU countries' environmental efficiencies concerning CO_2 emissions. Both our paper and Alsaleh *et al.*'s (2023) study focus on the environmental impacts of the fishing industry in the EU, particularly concerning sustainability and CO_2 emissions. While Alsaleh *et al.* (2023) emphasized the relationship between fisheries production, governance, and marine waste, our paper specifically highlights environmental efficiency variations across EU nations, focusing on CO_2 emissions as an undesired output. Key overlaps include the identification of disparities among EU countries in sustainability practices and the potential for improvement. Our findings that CO_2 emissions can be reduced without revenue loss complement Alsaleh *et al*.'s (2023) argument for adopting sustainable and environmentally friendly technologies. Both studies emphasize the role of tailored policies and innovations to enhance sustainability while maintaining economic performance in the fishing sector, supporting shared goals of environmental and economic balance. Our study and Alsaleh *et al*.'s (2023) second study both examine the environmental challenges of the EU fisheries sector, focusing on emissions and sustainability. However, while our paper primarily addresses CO_2 emissions and environmental efficiency, Alsaleh *et al*.'s (2023) study explores blue carbon degradation and its links to fishing practices, fossil fuel use, and socio-economic factors. Both this study and Miran *et al.* (2025) assess environmental efficiency in EU sectors using Tone's SBM with undesirable outputs, but fisheries show higher efficiency (0.712–0.831) than specialized milk farms (0.599). While Latvia, Lithuania, the Netherlands, Poland, and Estonia lead in fisheries, Malta, Ireland, Italy, and the Netherlands are top performers in specialized milk farming. Estonia and Bulgaria rank among the least efficient in both sectors, indicating persistent sustainability challenges. Unlike specialized milk farming, where larger farms improve efficiency, fisheries benefit from smaller-scale operations (1-5 vessels) due to lower fuel consumption per unit. These findings highlight the need for sector-specific sustainability policies, including fleet modernization and fuel efficiency measures in fisheries.

Our findings contribute to the existing literature by providing a comprehensive assessment of environmental efficiency in the EU fishing sector, specifically considering CO_2 emissions, and offer insights that can inform policy development and sustainability efforts in the industry.

4. Policy implications

The findings of this study carry several policy implications for the European Union (EU) fisheries sector in terms of environmental efficiencies, particularly for CO_2 emissions. Firstly, targeted interventions are needed to support the EU member states with lower environmental efficiencies, especially those scoring below the average. Tailored interventions can help these countries adopt more sustainable and environmentally friendly practices. Secondly, economic incentives should be considered to encourage member states with higher environmental efficiencies to share best practices and promote the adoption of sustainable methods.

Additionally, research and innovation funding should be allocated to develop technologies and practices that enhance environmental efficiency, such as fuel-efficient vessels and renewable energy use. International collaboration is crucial to address climate change and reduce CO_2 emissions in the fisheries sector, requiring engagement in global initiatives and knowledge-sharing among member states. Furthermore, policies should integrate environmental considerations into broader fisheries strategies, with robust monitoring and reporting mechanisms established to assess environmental efficiencies regularly.

Using renewable energy sources such as solar, wind, or hydrogen to power fishing vessels can significantly reduce or eliminate diesel fuel usage. Incorporating hybrid or fully electric fishing vessels into operations can significantly reduce or eliminate the need for diesel fuel. Utilizing more efficient and fuel-efficient diesel engines can help reduce fuel consumption and emissions for the same amount of work. Transitioning from traditional, fuel-intensive fishing methods (e.g., trawling) to less fuel-intensive methods (e.g., longline fishing) can help reduce diesel fuel usage. Better planning and rotation can minimize travel during the fishing season, reducing diesel fuel consumption. Educating and raising awareness among fishermen about less fuel-intensive practices is crucial for reducing diesel fuel usage.

To enhance sustainability in the fisheries sector, targeted policy interventions are essential for countries with lower environmental efficiency, such as Belgium, Bulgaria, Croatia, Cyprus, Greece, Italy, Malta, Slovenia, Spain, and Sweden. These nations should prioritize the adoption of fuel-efficient fishing technologies and vessel retrofitting programs to reduce CO_2 emissions per unit of output. The European Union could support these efforts by providing subsidies or tax incentives for investments in energy-efficient engines and alternative propulsion technologies. Additionally, policymakers in low-efficiency countries should establish fuel consumption limits for fisheries, promoting the use of alternative fuels such as biofuels or hybrid engines to minimize emissions. The implementation of onboard energy monitoring systems would further enable better tracking and enforcement of sustainable energy consumption practices.

Countries with lower environmental efficiency should look to Latvia, Lithuania, the Netherlands, Poland, and Estonia as models, as these nations have successfully minimized CO_2 emissions while maintaining high productivity. Establishing an EU-wide knowledge-sharing platform could facilitate the transfer of best practices, including quota management, fleet optimization, and the use of selective fishing gear, to improve efficiency in lower-performing nations.

Furthermore, financial incentives should be introduced to encourage the adoption of low-emission fishing techniques and participation in sustainability certification programs, such as MSC (Marine Stewardship Council) certified fisheries. Governments could also implement carbon pricing mechanisms, where vessels exceeding emission thresholds are subject to levies, thereby incentivizing more sustainable fishing practices.

While moderately efficient countries, such as Denmark, Finland, France, Germany, Ireland, Portugal, and Romania, may focus on technological advancements to enhance efficiency, countries with lower environmental efficiency may first prioritize regulatory reforms and fleet restructuring to align with sustainability objectives.

Our findings indicate that Mediterranean countries generally exhibit lower environmental efficiency compared to North Sea and Atlantic fisheries. To address these disparities, stronger regional cooperation within the EU sustainability framework is necessary to harmonize regulations and introduce tailored marine spatial planning strategies that balance economic and environmental priorities. By implementing these targeted policy measures, countries with lower environmental efficiency can significantly reduce their CO_2 emissions while ensuring the long-term sustainability of the fisheries sector.

Finally, incentives for innovation targeting CO_2 emission reduction can drive a shift towards cleaner and more sustainable approaches in the EU fisheries sector.

5. Conclusion

This study examines how European Union (EU) countries perform environmentally in the fishing industry, focusing on CO_2 emissions from using marine fuel. We used a method that analyzes both good outputs (like the live weight landings or revenue) and undesired output (like CO_2 emissions).

The study highlights significant variations in environmental efficiencies across EU member states, drawing from extensive data compiled by the Scientific, Technical, and Economic Committee for Fisheries (STECF) of the European Commission. While certain countries demonstrate exemplary environmental efficiency, achieving perfect scores in minimizing CO_2 emissions per unit of output, others exhibit lower efficiency scores, indicating areas for improvement in sustainability practices.

We found significant differences among EU countries in how efficiently they manage environmental issues in fishing. Some countries are excellent at keeping CO_2 emissions low while maintaining high levels of live weight landings. Others are less efficient, indicating they have room to improve their sustainability practices.

Importantly, our research shows that the EU fishing sector could greatly reduce CO_2 emissions without losing revenue. For example, based on the live weight landings, the sector could cut CO_2 emissions by 28.8%, and by 16.9% based on fishing revenue. This highlights the potential to make fishing more sustainable while still being profitable.

When we looked at the live weight landings as the good output and CO_2 emissions as the undesired one, countries like Latvia, Lithuania, the Netherlands, Poland, and Estonia scored the highest in environmental efficiency. This means they catch a lot of fish while keeping emissions low. Countries like Denmark, Finland, and France had moderate scores, while others like Belgium, Greece, and Spain had lower scores, indicating a need to reduce emissions per unit of fish caught. On average, EU countries scored 0.712 out of 1, showing there's room for improvement in eco-friendly fishing practices.

When considering revenue from fishing as the good output, countries like Belgium, Denmark, and France achieved the highest efficiency scores. They effectively reduce CO_2 emissions while maximizing earnings. Some countries lagged behind and need to adopt better sustainable practices to lower emissions without hurting revenue. The overall average efficiency score was 0.831, which is relatively good, but differences among countries suggest the need for tailored strategies to improve environmental performance.

We also found that environmental efficiency based on revenue is higher than that based on the live weight landings. This suggests that focusing on revenue may lead to better environmental outputs. Additionally, countries like Belgium and Italy could significantly reduce energy use and emissions while increasing the amount of fish caught. For instance, Belgium could reduce energy consumption by 56.3%, boost fish catches by 91.62%, and lower emissions by 56.3%. These findings show there's potential for specific actions to enhance sustainability and efficiency in the EU fishing sector.

In conclusion, this study provides valuable insights into the environmental sustainability of the EU fishing industry. It offers data-driven recommendations for policymakers and stakeholders. By prioritizing sustainability and innovation, EU countries can work together to make the fishing industry more environmentally friendly and economically viable, aligning with global climate and sustainability goals.

References

Alsaleh M., Wang X., Nan Z., 2023. Estimating the impact of fishery industry on marine pollution: New insights from Method of Moments Quantile Regression. *Energy & Environment*, 36(4).

Anonymous, 2020. *Avrupa Birliği Uluslararası Kuruluşlar Sözleşmeler.* Ankara: Tarım ve Orman Bakanlığı-Avrupa Birliği ve Dış İlişkiler Genel Müdürlüğü.

Anonymous, 2023, November 23. *National Energy Technology Laboratory CO_2 Utilization Focus Area* (https://netl.doe.gov/sites/default/files/2021-10/FY21-Carbon-Utilization-Peer-Review-Overview-Report_07262021.pdf).

Banker R.D., Natarajan R., 2008. Evaluating contextual variables affecting productivity using Data Envelopment Analysis. *Operations Research*, 56(1): 48-58.

Ceyhan V., Gene H., 2014. Productive efficiency of commercial fishing: evidence from the Samsun Province of Black Sea, Turkey. *Turkish Journal of Fisheries and Aquatic Sciences*.

Coelli T., Rao D.P., O'Donnell C.J., Battese G.E., 2005. *An introduction to efficiency and productivity analysis.* 2nd ed. New York: Springer.

Coll-Serrano V., Benítez R., Bolós V.J., 2018. *Tutorial: Data Envelopment Analysis with deaR*. University of Valencia (Spain).

Cui Q., Li Y., 2016. Airline energy efficiency measures considering carbon abatement: A new strategic framework. *Transportation Research Part D: Transport and Environment*, 49: 246-258.

Du Y.-W., Jiang J., Li C.-H., 2021. Ecological efficiency evaluation of marine ranching based on the Super-SBM model: A case study of Shandong. *Ecological Indicators*, 131.

Durgun D., 2019. *Balıkçılığın ekosistem üzerindeki etkilerinin azaltılmasında balıkçıların kişisel değerleri, çevre tutumları ve balıkçılık davranışlarının analizi: ege balıkçılığı örneği.* İzmir: Ege Üniv. Fen Bil. Enst. Yayınlanmamış doktora tezi.

Fare R., Grosskopf S., Kirkley J.E., Squires D., 2020. *Data Envelopment Analysis (DEA): A Framework for Assessing Capacity In Fisheries When Data are Limited*. IIFET 2000 Proceedings.

Fare R., Kirkley J.E., Walden J.B., 2007. *Estimating Capacity and Efficiency in Fisheries with Undesirable Outputs.* Tech. rep., Virginia Institute of Marine Science, College of William and Mary.

Felthovena R.G., Paul C.J., 2004. Directions for productivity measurement in fisheries. *Marine Policy*, 28: 161-169.

Greene W.H., 2018. *Econometric Analysis*, 8th ed. London: Pearson.

IEA, 2023a. *CO_2 Emissions in 2022*. Paris: IEA - International Energy Agency.

IEA, 2023b. *Tracking Clean Energy Progress 2023.* Paris: IEA - International Energy Agency.

IEA, 2023c. *World Energy Outlook 2023*. Paris: International Energy Agency.

Kirkley J., Squires D., Ivar S., 1995. Technical efficiency in commercial fisheries. *American Journal of Agricultural Economics*, 77(4).

Krátký L., Ledakowicz S., Slezak R., Bělohlav V., Peciar P., Petrik M., Jirout T., Peciar M., Siménfalvi Z., Šulc R., Szamosi Z., 2024. Emerging Sustainability in Carbon Capture and Use Strategies for V4 Countries via Biochemical Pathways: A Review. *Sustainability*, 16(3).

Li C.-J., Jeon J.-W., Kim H.-H., 2020. An Efficiency Analysis of Fishery Output in Coastal Areas of China. *International Journal of Advanced Smart Convergence*, 9: 127-136.

Miran B., 2021. *Verimlilik ve Etkinlik Analizleri-Productivity and Efficiency Analyses*. Mountain View, CA: Google Books.

Miran B., Güngör E., 2025. Driving environmental sustainability in the EU specialized milk farms: Strategic CO_2 emission reductions for a greener future. *Outlook on Agriculture,* 54(1): 91-104.

Okeke-Ogbuafor N., Gray T., Kamara S., Sesay E., Dauda A., Stead S.M., Robinson D., Ani K.J., 2024. Climate-smart fisheries: CO_2 emissions reduction and food secuity are complementary. *Marine Policy*, 159.

Ozkan N.F., Ulutas B.H., 2016. Efficiency analysis of cement manufacturing facilities in Turkey considering undesirable outputs. *Journal of Cleaner Production*, 156.

Pascoe S., Hutton T., van Putten I., Dennis D., Skewes T., Plagányi É., Deng R., 2013. DEA-based predictors for estimating fleet size changes when modelling the introduction of rights-based management. *European Journal of Operational Research*, 230(3): 681-687.

Pipitone V., Colloca F., 2018. Recent trends in the productivity of the Italian trawl fishery: The importance of the socio-economic context and overexploitation. *Marine Policy*, 87: 135-140.

Reid C., Squires D., 2022. Measuring fishery capacity in tuna fisheries: Data envelopment analysis, industry surveys and data collection. *FAO Fisheries Technical Paper*, 433: 87-91.

Ritchie H., Roser M., 2020. *CO_2 emissions*. OurWorldInData.org.

Shirazi F., Mohammadi E., 2020. Evaluating efficiency of airlines: A new robust DEA approach with undesirable output. *Research in Transportation Business & Management*.

Simar L., Wilson P.W., 2007. Estimation and inference in two-stage, semi-parametric models of production processes. *Journal of Econometrics*, 136(1): 31-64.

Squires D., Grafton R.Q., 1996. Fisheries productivity measurement: Issues and methodologies. *Marine Resource Economics*, 11(1): 19-34.

Squires D., Ruseski J.E., 2009. Assessing the efficiency and productivity of US marine fisheries: A review of the literature. *Reviews in Fisheries Science*, 17(2): 235-247.

STECF E.C., 2023, 1 19. *Economic and Social Analyses (fleet, processing, aquaculture)*. Retrieved from Fisheries and Aquaculture: https://stecf.jrc.ec.europa.eu/documents/43805/40008637/STECF+22-17+-+Aquaculture+economic+data+tables.xlsx/271d1c 48-b7a7-4679-a6c9-7b7cab262102?version=1.1& download=true

Tone K., 2001. A Slacks-Based Measure of Efficiency in Data Envelopment Analysis. *European Journal of Operational Research*, 130: 498-509.

Tone K., 2003. *Dealing with undesirable outputs in DEA: a Slacks-Based Measure (SBM) approach*. GRIPS Research Report Series I-2003-0005.

UN, 2015. *General Assembly: Paris Agreement to the United Nations Framework Convention on Climate Change*. United Nations General Assembly resolution. Transforming our world: the 2030 Agenda for Sustainable Development. United Nations.

UNFCCC/Secretariat, 2021, 3 29. *Greenhouse Gas Emissions Calculator*. Retrieved from United Nations Climate Change: https://unfccc.int/sites/default/files/resource/GHG_emissions_calculator_ver02.6.xlsx

Wang P., Ji J., 2017. Research on China's mariculture efficiency evaluation and influencing factors with undesirable outputs—an empirical analysis of China's ten coastal regions. *Aquacult Int*, 25: 1521-1530.

Zhou P., Poh K.L., Ang B.W., 2007. A non-radial DEA approach to measuring environmental performance. *European Journal of Operational Research*, 178(1): 1-9.