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Transition Pathways Towards Sustainable Maritime Logistics in Europe: A PCA–Cluster Analysis Based on Eurostat Indicators

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Abstract

Background: Sustainable maritime logistics has become a strategic priority for achieving the European Green Deal objectives and accelerating the transition towards low-carbon and resource-efficient transport systems. Nevertheless, existing studies mainly focus on isolated sustainability dimensions, providing limited evidence on the heterogeneous transition patterns followed by European countries. This study proposes an integrated analytical framework to identify and characterise longitudinal transition patterns towards sustainable maritime logistics across Europe. Methods: A harmonised database was developed using Eurostat indicators covering European countries for the period 2015–2023. Following data preprocessing, missing-value treatment and standardisation, Principal Component Analysis (PCA) was employed to reduce dimensionality, while cluster analysis was applied to identify groups of countries sharing similar sustainability and logistics transition characteristics. Results: The proposed framework reveals that the transition towards sustainable maritime logistics does not follow a single homogeneous pattern but multiple differentiated pathways. The analysis identifies distinct country profiles associated with energy transition, modal integration, circular economy performance and environmental sustainability, highlighting heterogeneous convergence dynamics throughout the study period. Conclusions: The findings provide a robust and transferable benchmarking framework for monitoring sustainable maritime logistics transition at the European level. By identifying differentiated transition pathways rather than static rankings, the proposed approach offers valuable evidence for supporting strategic planning, policy design and decision-making aimed at accelerating the transformation of maritime logistics systems towards sustainability.

Keywords: sustainable maritime logistics; transition pathways; principal component analysis; cluster analysis; energy transition

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Academic Editors: Giada La Scalia, Lang Xu, Shaorui Zhou and Guangnian Xiao

Received: 30 June 2026
Revised: 16 July 2026
Accepted: 31 July 2026
Published: 6 August 2026

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1. Introduction

The transition towards climate-neutral transport systems has become one of the defining challenges of European sustainability policy, requiring profound transformations

in the organisation of freight transport, energy systems and logistics networks. Maritime transport occupies a central position within this process, accounting for approximately 80% of global merchandise trade while supporting the competitiveness and resilience of international supply chains. Its strategic relevance extends beyond shipping activities, influencing port operations, hinterland connectivity, multimodal transport corridors and industrial development across Europe [1,2].

The European Union has progressively reinforced this transformation through an integrated regulatory framework combining the European Green Deal, the Sustainable and Smart Mobility Strategy and the Fit for 55 package. Within this policy architecture, the FuelEU Maritime Regulation establishes legally binding mechanisms to accelerate the adoption of renewable and low-carbon fuels, reduce greenhouse gas intensity and promote zero-emission technologies in ports and shipping operations [1,3]. Decarbonisation consequently emerges as a systemic objective involving energy production, transport organisation and logistics governance rather than isolated technological improvements.

Sustainable maritime logistics has therefore evolved into a multidimensional concept integrating operational efficiency, modal integration, environmental performance, circular economy principles and energy transition. Port systems are increasingly expected to operate as energy hubs, digital platforms and intermodal gateways capable of coordinating material flows while reducing emissions and resource consumption. This transformation is reinforced by advances in smart port technologies, digitalisation and renewable energy integration, all of which contribute to redefining the role of maritime logistics within sustainable transport systems [2,4].

Research addressing sustainable maritime logistics has expanded considerably during the last decade. Existing contributions analyse decarbonisation strategies, alternative fuels, port electrification, digital twins, energy management systems and environmental governance from multiple disciplinary perspectives. Nevertheless, empirical investigations frequently concentrate on individual technological or operational dimensions, limiting the understanding of how different sustainability drivers interact across national logistics systems. Comparative assessments at the European scale remain relatively limited, particularly when longitudinal evidence is incorporated into the analytical framework.

Methodological approaches adopted in previous benchmarking studies commonly rely on composite indices or predefined weighting schemes that introduce subjective assumptions regarding the relative importance of different sustainability dimensions. Such approaches may obscure latent relationships among variables and reduce the reproducibility of cross-country comparisons. Multivariate statistical techniques provide an alternative perspective by allowing the underlying structure of complex indicator systems to emerge directly from observed data without imposing ex ante weighting criteria. Principal Component Analysis (PCA) synthesises correlated variables into latent dimensions, whereas cluster analysis identifies homogeneous groups characterised by similar transition patterns, facilitating the interpretation of structural differences among countries.

The availability of harmonised statistical information through Eurostat creates an opportunity to investigate sustainable maritime logistics from a broader systemic perspective. Indicators related to energy transition, freight transport, circular economy, labour markets and environmental sustainability jointly capture complementary dimensions shaping the transformation of European logistics systems. Their combined analysis enables the identification of differentiated transition pathways rather than static performance rankings, providing a dynamic representation of sustainability processes and convergence patterns.

Although the selected indicators do not measure operational port performance directly, they capture the structural conditions within which maritime logistics systems evolve. Energy transition, freight transport patterns, environmental performance, circular economy

and socioeconomic capacity constitute complementary dimensions that influence the implementation of sustainable maritime logistics policies at the national level. Consequently, the analytical framework should be interpreted as an assessment of the national transition context supporting sustainable maritime logistics rather than as a direct evaluation of port or shipping performance.

The present study develops a multivariate analytical framework based on Eurostat indicators covering European countries during the period 2015–2023. PCA and cluster analysis are integrated to identify latent transition dimensions and classify countries according to their structural characteristics, generating an evidence-based typology of national transition profiles associated with sustainable maritime logistics. By replacing deterministic benchmarking with the identification of transition profiles, the proposed approach contributes to a more comprehensive understanding of the heterogeneous trajectories shaping the sustainable transformation of European maritime logistics systems.

The analysis is conducted at the national level, reflecting the territorial scale at which harmonised Eurostat indicators are available. Consequently, the framework characterises national structural conditions associated with sustainable maritime logistics rather than the operational performance of individual ports or freight corridors.

Within this study, the term transition profiles refers to the longitudinal evolution of countries across the multidimensional sustainability space identified through PCA and cluster analysis. The proposed framework describes temporal changes in these profiles rather than modelling causal transition dynamics or identifying deterministic development pathways.

2. Literature Review

2.1. Sustainable Maritime Logistics and the Green Transition

Sustainable maritime logistics has undergone a profound conceptual transformation over the last two decades. Initially associated with pollution prevention and environmental compliance in ports and shipping activities, the concept has progressively evolved towards an integrated perspective in which energy systems, multimodal transport, digital technologies and resource efficiency constitute interconnected dimensions of a single transition process. The increasing complexity of global supply chains and the acceleration of climate policies have reinforced the need to understand maritime logistics as a systemic component of sustainable economic development rather than as an isolated transport activity [1,2].

The European regulatory agenda has played a decisive role in this transformation. The European Green Deal established climate neutrality by 2050 as the overarching objective for all transport sectors, while the Sustainable and Smart Mobility Strategy identified maritime transport as one of the strategic pillars supporting the decarbonisation of freight mobility. More recently, FuelEU Maritime has introduced binding measures to reduce greenhouse gas intensity through the progressive deployment of renewable and low-carbon fuels, encouraging innovation across shipping companies, ports and logistics operators [1,3].

These regulatory developments have modified the traditional role of ports. Contemporary port systems increasingly operate as integrated logistics platforms where energy generation, digital information exchange and multimodal connectivity coexist with conventional cargo handling functions. Shore-side electricity, hydrogen infrastructure, alternative fuels, automated terminals and smart energy management systems illustrate the emergence of a new generation of ports capable of supporting both environmental objectives and supply chain resilience. Sustainability is therefore interpreted as the outcome of coordinated transformations affecting infrastructure, governance, logistics organisation and technological innovation rather than isolated investments [4,5].

Academic literature reflects this evolution by progressively expanding its analytical scope. Early studies primarily examined environmental externalities associated with maritime transport and port emissions, whereas more recent contributions incorporate circular economy strategies, renewable energy integration, artificial intelligence, digital twins and smart logistics management into a unified sustainability framework. Such diversification demonstrates that the environmental transition of maritime logistics depends upon the interaction between technological innovation and institutional adaptation, requiring integrated analytical approaches capable of capturing multidimensional relationships [5,6].

The growing relevance of resilience has also reshaped research priorities. Disruptions associated with global crises have demonstrated the vulnerability of maritime supply chains and highlighted the strategic importance of logistics flexibility, energy diversification and multimodal redundancy. Sustainable maritime logistics consequently emerges not only as an environmental objective but also as a mechanism for strengthening the adaptive capacity and long-term competitiveness of European transport systems [2,6].

2.2. Sustainability Assessment Frameworks in Maritime Logistics

The increasing complexity of sustainable maritime logistics has stimulated the development of numerous assessment frameworks designed to measure environmental, operational and economic performance. Existing methodologies generally combine indicators associated with emissions, energy consumption, logistics efficiency, infrastructure capacity and resource productivity, generating composite measures intended to support benchmarking and strategic decision-making. Despite their practical usefulness, considerable heterogeneity persists regarding indicator selection, weighting procedures and aggregation methods, limiting comparability among studies [7,8].

Indicator-based approaches constitute the most widely adopted methodology because they allow sustainability dimensions to be operationalised through measurable variables obtained from official statistical sources. International organisations and European institutions have promoted harmonised datasets facilitating comparative analyses across countries and regions. Eurostat, in particular, provides a comprehensive repository of transport, energy, environmental and socioeconomic indicators whose methodological consistency offers substantial advantages for longitudinal investigations and cross-national benchmarking exercises [2].

Composite sustainability indices provide useful benchmarking tools but often rely on predefined weighting schemes whose underlying assumptions may differ across studies. Data-driven approaches offer a complementary perspective by deriving latent structures directly from the statistical relationships observed in the data.

Different weighting assumptions may produce substantially different rankings even when identical datasets are employed, introducing methodological uncertainty and reducing the transparency of comparative evaluations. Several authors have consequently argued that data-driven approaches capable of extracting latent structures directly from observed information provide a more robust alternative for sustainability assessment [8,9].

Another limitation identified in the literature concerns the predominance of static benchmarking exercises. Most comparative studies evaluate countries or ports at a single point in time, providing snapshots of relative performance while neglecting the dynamic nature of sustainability transitions. The evolution of transport systems is characterised by gradual structural adjustments influenced by technological innovation, regulatory change and economic development. Capturing these temporal dynamics requires analytical frameworks capable of identifying transition trajectories rather than merely ranking observations according to current performance [9,10].

Recent research has therefore shifted attention towards multidimensional benchmarking systems integrating environmental, energy and logistics indicators within coherent analytical structures. These frameworks acknowledge that sustainability cannot be adequately represented through isolated variables because improvements in one dimension may coexist with deterioration in another. Integrated assessment models seek to identify balanced transition patterns reflecting the simultaneous evolution of complementary sustainability domains, thereby providing more informative evidence for policy design and strategic planning [5,7].

2.3. Multivariate Approaches in Transport and Sustainability Research

The multidimensional nature of sustainability has favoured the increasing application of multivariate statistical techniques capable of reducing complexity while preserving the essential information contained within large indicator systems. PCA represents one of the most widely employed dimensionality reduction methods because it transforms correlated variables into orthogonal latent components summarising the dominant patterns of variability. The resulting factors facilitate interpretation while mitigating multicollinearity problems commonly associated with environmental and socioeconomic datasets [11,12].

Cluster analysis complements PCA by identifying groups of observations sharing similar structural characteristics without requiring predefined classifications. Unlike conventional benchmarking procedures based on arbitrary thresholds, clustering algorithms allow homogeneous profiles to emerge directly from observed data structures, revealing similarities and differences that may remain hidden under traditional ranking approaches. Their application has expanded considerably within transport research, regional development studies and sustainability assessment due to their capacity to identify typologies supporting evidence-based policy formulation [12,13].

The combination of PCA and clustering has demonstrated particular value in studies involving heterogeneous territorial units characterised by multiple interacting variables. PCA reduces dimensionality and enhances interpretability, whereas clustering exploits the reduced latent space to construct robust classifications reflecting structural relationships among observations. This sequential methodology has been successfully applied to regional innovation systems, environmental performance assessment, urban sustainability and transport policy evaluation, offering a reproducible alternative to composite indices based on subjective weighting procedures [13,14].

Applications within maritime logistics remain comparatively limited. Existing studies frequently concentrate on operational port performance, shipping efficiency or environmental indicators considered independently, while integrated analyses combining energy transition, logistics performance and circular economy dimensions at the European scale remain scarce. The absence of harmonised multivariate frameworks limits the capacity to identify common transition patterns and to compare the evolution of national logistics systems under a shared analytical perspective [5,14].

Data-driven methodologies also provide advantages regarding reproducibility and transparency. Because latent structures emerge from statistical relationships rather than expert-defined assumptions, the resulting classifications are less dependent on subjective methodological decisions. Such characteristics are particularly valuable when analysing official statistical databases covering multiple countries and extended time periods, where robustness and comparability constitute essential requirements for policy-oriented research [11,13].

2.4. Research Gap

Current literature demonstrates substantial progress in understanding sustainable maritime logistics, energy transition and environmental performance. Significant advances have been achieved in the analysis of green ports, alternative fuels, digitalisation, circular economy practices and logistics innovation, while multivariate techniques have progressively strengthened sustainability assessment methodologies. Nevertheless, these research streams have largely evolved independently, resulting in fragmented analytical perspectives that rarely integrate transport, energy, environmental and socioeconomic dimensions within a unified framework.

Benchmarking studies continue to rely predominantly on composite indicators based on predefined weighting schemes or expert judgement, reducing methodological transparency and limiting reproducibility across different territorial contexts. Dynamic analyses examining how countries evolve throughout sustainability transitions remain considerably less frequent than static assessments, despite the inherently evolutionary character of decarbonisation processes and logistics transformation. Comparative evidence describing heterogeneous transition pathways across European maritime logistics systems therefore remains insufficiently developed.

Recent review studies also highlight the need for transparent and reproducible benchmarking frameworks based on harmonised statistical sources, objective multivariate methods and longitudinal analyses capable of capturing heterogeneous sustainability transition pathways across transport systems [15–17].

The availability of harmonised Eurostat indicators offers a unique opportunity to overcome these limitations by integrating multiple sustainability dimensions into a coherent analytical framework supported by official statistical information. The combination of PCA and cluster analysis provides an objective methodology capable of identifying latent transition structures and homogeneous country profiles without imposing subjective weighting assumptions. Such an approach shifts the analytical focus from static benchmarking towards the interpretation of structural transition pathways, generating evidence directly relevant for European transport policy and strategic planning.

The present research addresses this gap by developing a harmonised multivariate framework based exclusively on Eurostat indicators covering the period 2015–2023. Through the integration of dimensionality reduction and unsupervised classification techniques, the study identifies differentiated transition pathways towards sustainable maritime logistics across Europe and contributes a reproducible methodological approach for monitoring the evolution of sustainable logistics systems under the objectives established by the European Green Deal and related policy initiatives.

3. Materials and Methods

3.1. Research Design

The methodological framework was designed to identify structural transition pathways towards sustainable maritime logistics across European countries through a multivariate analytical approach based on official statistical information. Rather than constructing a composite sustainability index through predefined weighting schemes, the proposed framework exploits latent statistical relationships among indicators to reveal common transition patterns emerging from the observed data structure. The analytical strategy combines dimensionality reduction and unsupervised classification techniques, allowing countries to be characterised according to their multidimensional sustainability profiles instead of deterministic performance rankings [11–14].

Figure 1 summarises the complete methodological workflow adopted in this research, from data acquisition and preprocessing to the identification of transition pathways and the interpretation of country profiles.

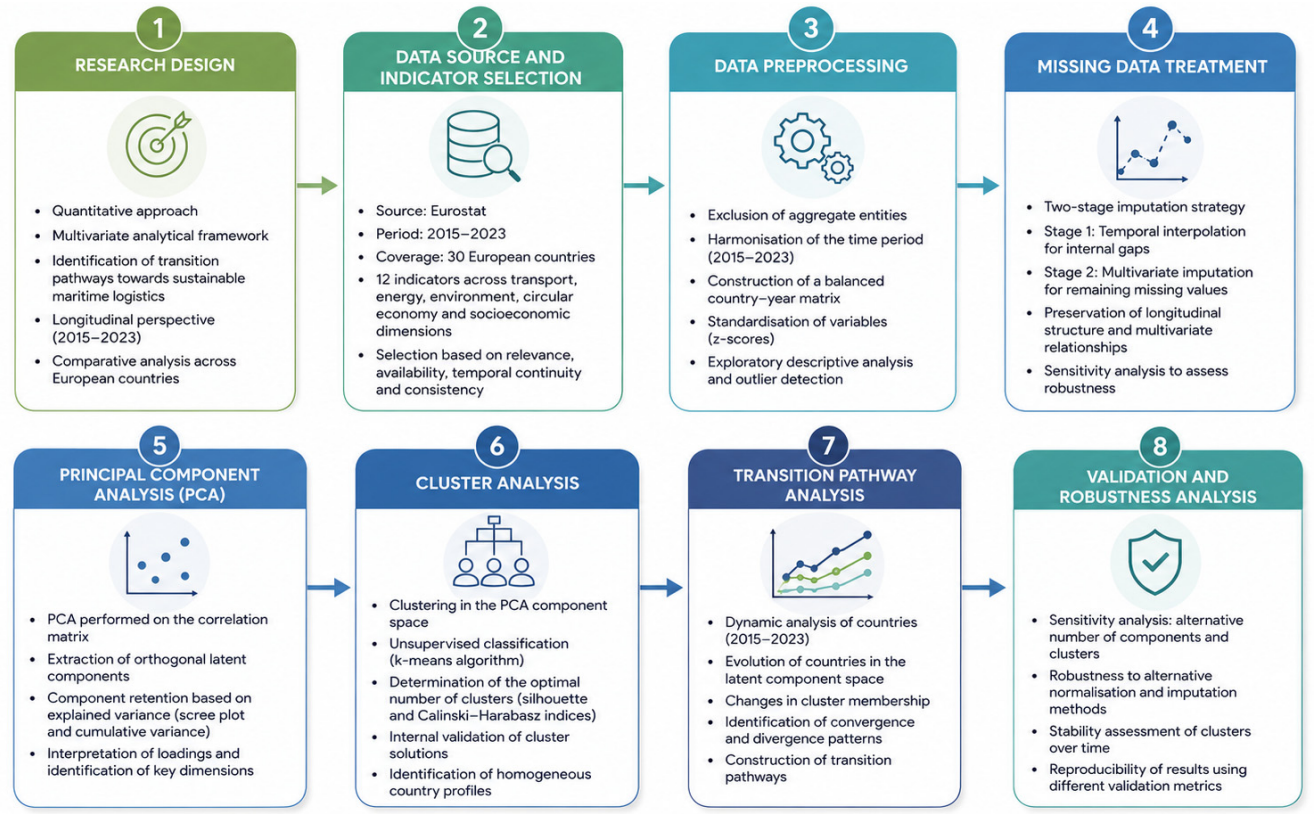


Figure 1. Methodological framework adopted in the study.

3.2. Data Source and Indicator Selection

The empirical analysis relies exclusively on harmonised statistical information obtained from Eurostat, ensuring methodological consistency, temporal comparability and reproducibility across European countries. The initial database comprised a broad collection of indicators associated with transport activity, energy transition, environmental sustainability, circular economy performance and socioeconomic development. Indicator selection followed a sequential screening process based on conceptual relevance, geographical coverage, temporal continuity and statistical consistency.

The final dataset covers 30 European countries over the period 2015–2023: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and Türkiye. The resulting balanced panel comprises 270 country-year observations.

The sample includes both coastal and landlocked European countries. Although landlocked countries do not possess maritime coastlines, they constitute essential components of the European logistics system through multimodal freight corridors, inland logistics hubs, dry ports and cross-border supply chains. Furthermore, the selected Eurostat indicators describe broader logistics, transport, energy and sustainability dimensions rather than port-specific operational performance. Including both coastal and landlocked countries therefore provides a more comprehensive assessment of sustainable logistics transition across Europe.

The country was adopted as the unit of analysis because it represents the highest level at which harmonised Eurostat indicators are consistently available across the study period. This choice ensures methodological comparability while allowing the identification of structural similarities and differences among national logistics systems.

This level of analysis is consistent with the objective of identifying national transition contexts rather than evaluating the operational performance of individual ports, terminals or maritime corridors.

Variables presenting insufficient country-level information, discontinuous temporal series or excessive redundancy with other indicators were progressively excluded from the analytical framework. The resulting database integrates twelve complementary indicators representing the national transport, energy, environmental and socioeconomic conditions associated with sustainable maritime logistics transition.Their combined interpretation captures the interaction between transport systems, energy transformation and environmental performance without imposing subjective weighting criteria during the selection process [2,9,14].

Table 1 summarises the selected indicators, their Eurostat codes, units of measurement and their conceptual relationship with the structural dimensions of sustainable maritime logistics considered in this study.

Table 1. Selected Eurostat indicators and their conceptual relationship with sustainable maritime logistics.

Eurostat Code	Indicator	Unit	Sustainability Dimension	Relevance to Sustainable Maritime Logistics
tag00076	Short sea shipping of goods	Thousand tonnes	Maritime transport	Captures the intensity of maritime freight activity and the role of short sea shipping within European logistics networks.
tran_hv_frmod	Rail freight modal share	%	Modal integration	Reflects the degree of freight modal diversification supporting more sustainable hinterland transport connections.
tran_im_urail	Rail freight transport	Billion tonne-km	Multimodal transport	Represents the capacity of national logistics systems to integrate rail transport with maritime freight flows.
tran_im_uroad	Road freight transport	Million tonne-km	Freight transport	Characterises the relative importance of road transport within national logistics systems and complements modal balance assessment.
tran_im_umar	Maritime freight transport	Billion tonne-km	Maritime transport	Measures the contribution of maritime transport to national freight activity and logistics structure.
sdg_07_30	Energy productivity	EUR per kg of oil equivalent	Energy transition	Reflects the efficiency with which national economies use energy resources, an enabling condition for low-carbon logistics systems.
sdg_07_40	Share of renewable energy in gross final energy consumption	%	Energy transition	Indicates the degree of renewable energy deployment supporting the decarbonisation of transport and logistics activities.

Table 1. *Cont.*

Eurostat Code	Indicator	Unit	Sustainability Dimension	Relevance to Sustainable Maritime Logistics
sdg_07_50	Energy import dependency	%	Energy security	Represents the dependence on external energy sources, affecting the resilience and long-term sustainability of transport systems.
sdg_13_10	Greenhouse gas emissions index	Index (1990 = 100)	Environmental performance	Captures national progress in reducing emissions within the broader context of climate transition.
cei_srm030	Circular material use rate	%	Circular economy	Reflects resource efficiency and circular economy performance, both increasingly linked to sustainable logistics strategies.
sdg_08_10	GDP per capita	Euro per inhabitant	Socioeconomic capacity	Represents the economic capacity available to support investment in sustainable transport and logistics infrastructure.
lfsi_emp_a	Employment rate	%	Socioeconomic capacity	Reflects labour market strength, supporting the implementation and long-term resilience of logistics transition processes.

The information reported in Table 1 provides the complete identification of all Eurostat datasets used in this study, enabling the reconstruction of the database directly from the official Eurostat repository and ensuring the full reproducibility of the proposed analytical framework.

Indicator selection was guided by the objective of representing the structural context supporting sustainable maritime logistics at the national scale. Rather than focusing exclusively on port-specific operational variables, the framework integrates harmonised indicators describing transport organisation, energy transition, environmental performance and socioeconomic conditions. This approach reflects the systemic perspective adopted by recent European transport policies, where the transition of maritime logistics is understood as the result of interactions between maritime activity and broader national sustainability processes.

The final dataset covers thirty European countries over the period 2015–2023, generating a balanced longitudinal database suitable for multivariate statistical analysis and comparative assessment.

3.3. Data Preprocessing

Prior to statistical modelling, the database underwent a harmonisation process intended to maximise temporal and geographical consistency. Aggregated observations corresponding to supranational entities were excluded to preserve comparability at the country level. Only observations belonging to the common study period were retained, generating a homogeneous country-year matrix suitable for longitudinal analysis.

Differences in measurement scales among variables required subsequent standardisation. Indicators expressed in percentages, physical quantities or economic values were transformed into standardised scores through z-score normalisation, ensuring that all variables contributed equally to the covariance structure explored by Principal Component Analysis. This procedure prevents variables characterised by larger numerical ranges from dominating the extraction of latent dimensions and represents a standard practice in multivariate sustainability assessment [11,13].

Exploratory descriptive analysis was simultaneously conducted to identify potential outliers and verify the internal coherence of the statistical distributions. No transformations altering the original conceptual interpretation of the indicators were introduced beyond standardisation and missing-value treatment.

Missing values were handled using the K-Nearest Neighbours (KNN) imputation method with k = 5. Approximately 12.9% of the analytical data values required imputation. This approach preserves the multivariate structure of the dataset while avoiding the exclusion of observations due to incomplete data.

To ensure comparability among indicators measured in different units and scales, all variables were standardised before the multivariate analysis using z-score normalisation. This transformation assigns each variable a mean of zero and a standard deviation of one, preventing indicators with larger numerical ranges from exerting disproportionate influence on the subsequent PCA.

Equation (1). Z-score standardisation:

$$z_{ij} = \frac{x_{ij} - \mu_j}{\sigma_j} \quad (1)$$

where x_{ij} is the original value of indicator j for country-year observation i, μ_j denotes the sample mean of indicator j, and σ_j represents its standard deviation. The resulting standardised variables constitute the input matrix used throughout the multivariate analysis.

3.4. Missing Data Treatment

Official statistical databases frequently contain missing observations associated with methodological revisions, reporting inconsistencies or temporary interruptions in national statistical series. Eliminating incomplete observations would substantially reduce sample size and compromise the longitudinal structure of the dataset. Consequently, missing values were addressed through a two-stage imputation strategy designed to preserve both temporal continuity and multivariate relationships among variables.

Internal gaps located between observed values within the same country were estimated through temporal interpolation, preserving the trajectory of the original statistical series. Remaining missing observations were subsequently completed using multivariate imputation procedures exploiting the covariance structure among indicators and auxiliary information contained within the complete dataset. This sequential strategy minimises information loss while preserving the underlying statistical relationships required for dimensionality reduction and clustering analyses [13,14].

Sensitivity analyses comparing the original and completed databases confirmed that the imputation process did not substantially alter the global distribution of the indicators, supporting the robustness of the subsequent multivariate analyses.

Remaining missing observations were estimated through a k-nearest neighbours (KNN) imputation procedure following temporal interpolation of internal gaps. The imputed value corresponds to the average of the nearest observations identified according to their multivariate similarity.

Equation (2). KNN imputation

$$\hat{x}_i = \left(\frac{1}{k}\right) \sum_{j=1}^{k} x_j \quad (2)$$

where $\hat{x}_i$ denotes the estimated value for the missing observation, x_j represents the values of the k nearest neighbours, and k is the number of neighbours used for the imputation. This

procedure preserves the multivariate structure of the dataset while minimising distortions associated with isolated missing observations.

3.5. Principal Component Analysis Procedure

Principal Component Analysis was employed to reduce the dimensionality of the indicator system while preserving the maximum proportion of total variance contained within the original dataset. The method transforms correlated variables into orthogonal latent components representing independent dimensions of sustainable maritime logistics transition. Each principal component corresponds to a linear combination of the original indicators, ordered according to the amount of explained variance [11].

The analysis was performed on the standardised correlation matrix derived from the harmonised database. Component retention considered the cumulative proportion of explained variance together with interpretability criteria, ensuring that the retained dimensions represented coherent sustainability constructs rather than purely statistical artefacts. Loadings associated with each component were subsequently examined to identify the dominant thematic dimensions underpinning the transition process, facilitating substantive interpretation of the latent factors extracted from the data.

The resulting reduced-dimensional representation constitutes the analytical basis for the subsequent classification stage, mitigating multicollinearity effects and enhancing the stability of the clustering procedure.

The proportion of variance explained by each principal component was calculated according to the associated eigenvalue.

As PCA is an exploratory statistical technique, the retained components were interpreted according to the variables with the highest loadings rather than predefined theoretical constructs. The component labels should therefore be understood as descriptive summaries of the dominant statistical patterns identified in the data rather than as unique latent constructs.

Each principal component is computed as a linear combination of the standardised indicators. Each principal component is computed as a linear combination of the standardised indicators.

Equation (3). Principal component calculation

$$PC_k = \sum_{j=1}^{p} a_{(kj)z_j} \tag{3}$$

where PC_k denotes the k-th principal component, a_{kj} is the loading associated with indicator j, and z_j represents the standardised value of indicator j.

Equation (4). Explained variance

$$EV_k = \left(\frac{\lambda_k}{\sum_{j=1}^{p} \lambda_j} \right) \times 100 \tag{4}$$

where λ_k is the eigenvalue associated with the k-th principal component. Components were retained according to the cumulative explained variance criterion and their interpretability.

3.6. Cluster Analysis Procedure

Country typologies were identified through unsupervised cluster analysis applied to the reduced-dimensional space generated by PCA. Operating within the latent component space rather than the original indicator matrix reduces redundancy among variables and improves the discrimination capacity of the clustering algorithm, generating more stable and interpretable classifications [12].

The objective of the clustering procedure is not to establish deterministic rankings but to identify groups of countries characterised by similar transition structures. Countries belonging to the same cluster share comparable sustainability profiles despite possible differences in individual indicator values, reflecting common structural characteristics rather than isolated performance measures.

Alternative clustering solutions were evaluated through internal validation criteria, including cohesion and separation metrics, before selecting the final classification used throughout the study. The resulting groups constitute empirical transition profiles derived directly from observed statistical relationships without imposing predefined categories.

The retained principal component scores were subsequently used as input for the clustering procedure. Similarity between observations was evaluated through Euclidean distance within the reduced multidimensional space.

Equation (5). Euclidean distance

$$d(x_i, x_j) = \sqrt{\sum_{m=1}^{p} (x_{im} - x_{jm})^2} \quad (5)$$

where $d(x_i, x_j)$ represents the Euclidean distance between observations i and j, calculated across the retained principal components. This distance metric constitutes the basis for grouping country-year observations into homogeneous transition profiles.

The final number of clusters was selected by jointly considering internal validation metrics and the interpretability of the resulting country profiles. Given the heterogeneity of national sustainability systems, moderate overlap between groups is expected. The objective of the clustering procedure is therefore to identify structurally similar profiles rather than perfectly separated classes.

3.7. Identification of Transition Pathways

Static benchmarking provides limited information regarding the dynamics of sustainability transitions. The analytical framework therefore incorporates a longitudinal interpretation of country evolution by examining changes in cluster membership and latent component scores throughout the observation period.

In this study, transition pathways are understood as the longitudinal evolution of country profiles within the multidimensional space defined by the retained principal components and the associated cluster classification. This interpretation focuses on structural changes over time rather than on modelling the dynamic mechanisms that drive those changes.

This dynamic perspective enables the identification of convergence processes, persistent structural differences and heterogeneous transition patterns across Europe, extending conventional benchmarking approaches towards a longitudinal interpretation of sustainable logistics development.

The Maritime Sustainable Transition Score is introduced exclusively as an interpretative measure to facilitate the comparison of country trajectories throughout the study period. It should not be interpreted as a normative sustainability index or as a replacement for the multidimensional information provided by the retained principal components and the cluster analysis.

To facilitate interpretation and comparison across countries, the retained principal components were integrated into a composite Maritime Sustainable Transition Score (MSTS). The score was obtained as a weighted aggregation of the retained components according to their explained variance.

Equation (6). Maritime Sustainable Transition Score

$$MSTS_i = \sum_{k=1}^{m} w_k PC_{ik} \quad (6)$$

Source : Authors′ elaboration.

where $MSTS_i$ denotes the Maritime Sustainable Transition Score for country i, PC_{ik} is the score of country i on principal component k, and w_k corresponds to the weight assigned to principal component k according to its proportion of explained variance.

Finally, the composite score was rescaled to a 0–100 interval to facilitate interpretation.

Equation (7). Score normalisation

$$MSTS_i = 100\left(\frac{S_i - \min(S)}{\max(S) - \min(S)}\right) \quad (7)$$

where S_i is the raw composite score for country i, and $\min(S)$ and $\max(S)$ represent the minimum and maximum values observed across the sample, respectively. Higher values indicate greater progress towards sustainable maritime logistics transition.

3.8. Validation and Robustness Analysis

The methodological contribution of this research lies in the integration of harmonised Eurostat indicators, advanced preprocessing procedures, dimensionality reduction and unsupervised learning techniques within a unified analytical framework specifically designed for sustainable maritime logistics assessment. The proposed approach replaces subjective weighting schemes with statistically derived latent dimensions and shifts the analytical focus from static rankings towards the identification of transition pathways.

Such a framework provides a reproducible benchmarking methodology that can be replicated in different geographical contexts or extended through the incorporation of additional sustainability indicators, offering a flexible decision-support tool for monitoring the long-term evolution of maritime logistics systems under the objectives established by European transport and climate policies.

Component retention combined statistical and interpretative criteria. Four components were retained because they explained more than 70% of the total variance while preserving a coherent representation of the multidimensional structure of the dataset. This balance between statistical performance and interpretability is consistent with common practice in exploratory multivariate analysis.

4. Results

4.1. Descriptive Analysis of the Analytical Dataset

The final analytical dataset comprised 270 country-year observations corresponding to 30 European countries over the period 2015–2023. The refined model retained 12 indicators after excluding variables with conceptual or temporal inconsistencies. The selected variables covered four analytical domains: maritime and intermodal freight transport, energy transition, environmental performance and socioeconomic readiness.

The descriptive statistics reveal substantial heterogeneity across the European sample. Short sea shipping volumes (tag00076) show a wide dispersion, reflecting the structural differences between large maritime gateways and smaller or more peripheral logistics systems. Modal integration indicators also display marked variability, particularly rail freight and maritime freight shares, confirming that European countries follow highly differentiated logistics configurations. Energy-related indicators show broad dispersion in renewable energy penetration, energy productivity and import dependency, while circular material use rates remain uneven across the sample. This heterogeneity supports the use of

multivariate techniques capable of capturing latent structures that cannot be represented through isolated indicators (Table 2).

Table 2. Descriptive statistics of the final analytical indicators.

Indicator	Mean	Std. Dev.	Min	Median	Max
tag00076	291,396.17	443,438.38	106.44	153,400.10	2,340,674.40
tran_hv_frmod	38.32	40.08	0.00	17.25	100.00
tran_im_urail	25.50	20.00	0.60	18.70	86.90
tran_im_uroad	3303.17	6753.64	11.00	1168.50	40,200.00
tran_im_umar	17.70	9.17	3.60	17.25	43.10
sdg_07_30	7.67	4.11	2.01	6.73	26.90
sdg_07_40	26.37	17.53	4.99	19.92	83.73
sdg_07_50	34.19	123.94	−682.10	57.32	103.05
sdg_13_10	83.36	38.48	27.00	77.65	251.30
cei_srm030	9.29	6.29	1.40	7.92	32.00
sdg_08_10	33,058.85	21,840.92	6690.00	25,480.00	107,570.00
lfsi_emp_a	73.70	6.89	51.00	75.20	87.80

The correlation analysis did not identify any pair of variables with an absolute correlation above 0.90. This result supports the retained indicator framework, suggesting that the final set of variables provides complementary information rather than excessive statistical redundancy. The absence of very high correlations also reinforces the suitability of applying PCA as a dimensionality reduction technique without removing additional variables at this stage (Figure 2).

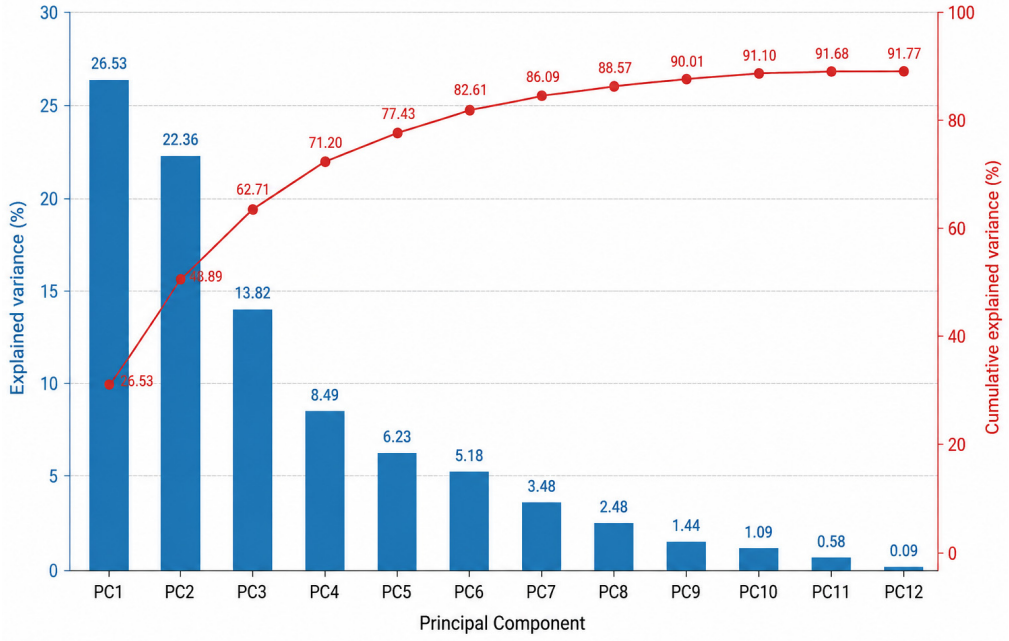


Figure 2. Explained variance by principal component.

4.2. Principal Component Analysis Results

Principal Component Analysis was applied to the standardised indicator matrix to identify the latent dimensions underlying sustainable maritime logistics transition across Europe. Four components were retained for interpretation, jointly explaining 71.20% of the total variance (Table 3). This level of explained variance is adequate for a multidimensional territorial dataset and indicates that the selected indicators can be summarised into a reduced number of interpretable dimensions while preserving most of the original information.

Table 3. Explained variance of the retained principal components.

Component	Explained Variance (%)	Cumulative Variance (%)
PC1	26.53	26.53
PC2	22.36	48.89
PC3	13.82	62.71
PC4	8.49	71.20

The loading structure provides a coherent interpretation of the principal components. PC1 is strongly associated with short sea shipping, renewable energy share, employment and GDP per capita, while energy import dependency loads negatively. PC1 is interpreted as a broad sustainability-readiness dimension because it is primarily associated with short sea shipping, renewable energy, employment, GDP per capita and lower energy import dependency. This interpretation reflects the dominant loading pattern rather than a predefined conceptual category (Table 4). PC2 is mainly associated with rail freight, modal integration, energy productivity and environmental performance, representing an intermodal and energy-efficiency dimension. PC3 is influenced by road freight intensity, circular material use, GDP per capita and energy productivity, suggesting a structural contrast between road-oriented logistics and circular-economy performance. PC4 shows more moderate and distributed loadings, capturing residual differentiation associated with road freight, energy productivity and selected transport variables (Figure 3).

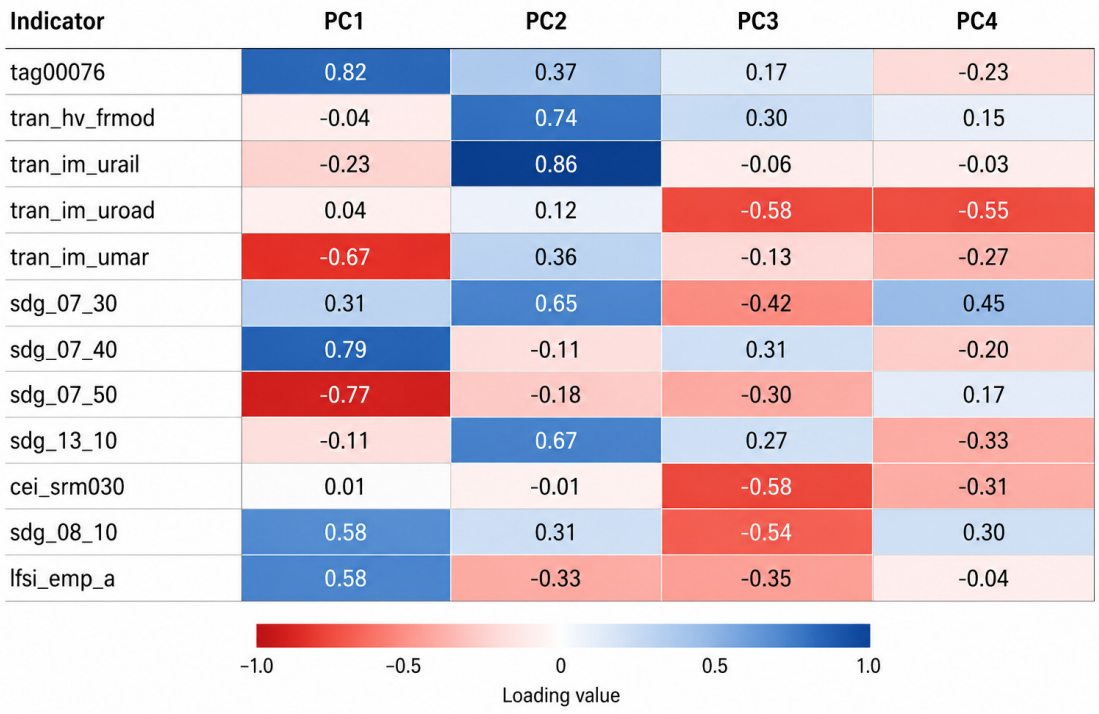


Figure 3. PCA loading structure of the retained components.

These interpretations are intended to facilitate the discussion of the dominant statistical patterns emerging from the selected indicators and should not be interpreted as definitive or uniquely defined sustainability dimensions.

The PCA results confirm that sustainable maritime logistics transition cannot be reduced to a single performance axis. The retained components reveal a multidimensional structure in which maritime activity, energy transition, modal integration, circularity and socioeconomic capacity interact but do not collapse into a single homogeneous pattern. This finding supports the subsequent clustering stage, since country-year observations occupy differentiated positions within the latent sustainability space.

Table 4. PCA loadings for the retained components.

Indicator	PC1	PC2	PC3	PC4
tag00076	0.821	0.365	0.166	−0.234
tran_hv_frmod	−0.038	0.741	0.304	0.149
tran_im_urail	−0.234	0.861	−0.059	−0.032
tran_im_uroad	0.038	0.124	−0.578	−0.551
tran_im_umar	−0.665	0.360	−0.127	−0.266
sdg_07_30	0.307	0.645	−0.419	0.447
sdg_07_40	0.795	−0.112	0.313	−0.195
sdg_07_50	−0.772	−0.184	−0.302	0.175
sdg_13_10	−0.112	0.670	0.266	−0.331
cei_srm030	0.008	−0.007	−0.576	−0.307
sdg_08_10	0.581	0.310	−0.539	0.303
lfsi_emp_a	0.581	−0.329	−0.355	−0.042

4.3. Cluster Analysis Results

Cluster analysis was applied to the PCA scores to identify groups of country-year observations sharing similar structural characteristics (Table 4). A four-cluster solution was retained for interpretability and alignment with the conceptual objective of identifying transition profiles rather than producing fragmented country classifications. The resulting model achieved a silhouette coefficient of 0.425, a Davies–Bouldin index of 1.006 and a Calinski–Harabasz score of 158.24.

The validation metrics indicate an acceptable level of separation between clusters considering the complexity and heterogeneity of macro-level territorial datasets. The selected solution provides a balance between statistical quality and interpretability, allowing the identification of differentiated structural profiles without assuming perfectly distinct group boundaries.

The clustering analysis was performed using the K-means algorithm applied to the retained principal component scores. The number of clusters was determined through an iterative evaluation of alternative solutions, considering the Silhouette coefficient, Davies–Bouldin index and Calinski–Harabasz score (Table 5), together with the interpretability of the resulting transition profiles. The final four-cluster solution provided the best balance between statistical quality and meaningful policy interpretation. All statistical analyses were performed using using Python 3.11 (Python Software Foundation, Wilmington, DE, USA) together with the scikit-learn, pandas and NumPy libraries.

Table 5. Cluster validation metrics.

Metric	Value
Number of clusters	4
Silhouette coefficient	0.425
Davies–Bouldin index	1.006
Calinski–Harabasz score	158.24

The four clusters represent differentiated transition profiles. Cluster 3 corresponds to the strongest profile and was labelled Maritime Sustainability Leaders. This group shows the highest mean transition score and includes country-year observations with advanced sustainability performance (Table 6). Cluster 4 was labelled Advanced Transition Systems, representing countries with favorable but less consolidated transition characteristics. Cluster 1 was labelled Intermediate Transition Economies, grouping observations with moderate performance and mixed structural features. Cluster 2 was labelled Emerging Maritime Logistics Systems, representing the lowest average transition profile within the analysed sample (Figure 4).

Table 6. Cluster profiles.

Cluster	Profile	Country-Year Observations	Mean MSTS	Min MSTS	Max MSTS
1	Intermediate Transition Economies	76	37.18	14.78	65.86
2	Emerging Maritime Logistics Systems	122	16.89	0.00	36.97
3	Maritime Sustainability Leaders	18	70.92	44.43	100.00
4	Advanced Transition Systems	54	39.98	21.17	52.57

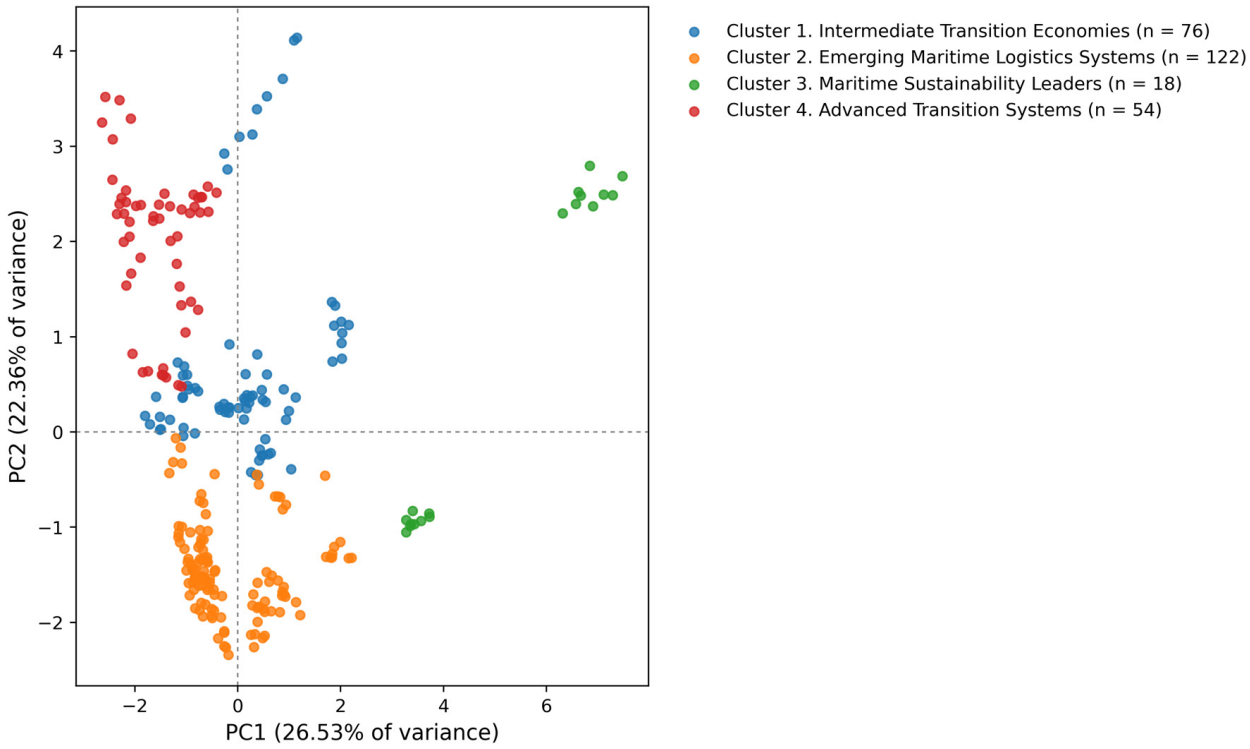


Figure 4. Country-year observations (2015–2023) represented in the retained PCA space according to the four-cluster solution.

The identified clusters should be interpreted as empirical groupings obtained from multivariate similarity patterns rather than as predefined or deterministic stages of sustainable maritime logistics transition. Their primary purpose is to facilitate comparative interpretation across European countries within the proposed analytical framework.

The distribution of countries in 2023 illustrates the structural meaning of the four profiles. Norway and Iceland occupy the Maritime Sustainability Leaders cluster (Table 6). Spain, Portugal, Cyprus, Greece, Slovenia and Türkiye are classified as Advanced Transition Systems. Ireland, the Netherlands, Denmark, Malta, Luxembourg, Austria, Belgium, Italy, France and Germany are grouped as Intermediate Transition Economies. The Emerging Maritime Logistics Systems cluster contains Bulgaria, Czechia, Estonia, Finland, Croatia, Hungary, Lithuania, Latvia, Poland, Romania, Sweden and Slovakia.

Cluster membership should not be interpreted as a hierarchical classification. Countries with similar Maritime Sustainable Transition Scores may belong to different clusters because the classification is determined by their position within the multidimensional PCA space rather than by a single indicator or composite score (Table 7). Consequently, countries sharing comparable overall scores may exhibit different structural configurations across the retained principal components.

Table 7. Country classification by cluster in 2023.

Cluster	Profile	Countries in 2023
1	Intermediate Transition Economies	Austria, Belgium, Germany, Denmark, France, Ireland, Italy, Luxembourg, Malta, Netherlands
2	Emerging Maritime Logistics Systems	Bulgaria, Czechia, Estonia, Finland, Croatia, Hungary, Lithuania, Latvia, Poland, Romania, Sweden, Slovakia
3	Maritime Sustainability Leaders	Iceland, Norway
4	Advanced Transition Systems	Cyprus, Greece, Spain, Portugal, Slovenia, Türkiye

4.4. Transition Pathway Analysis

The longitudinal structure of the database allows the analysis to move beyond static classification. Country trajectories were examined by comparing cluster membership and transition scores between 2015 and 2023. The results show that no country experienced a substantial deterioration over the study period. Fifteen countries displayed an improving trajectory, while fifteen remained broadly stable. This finding suggests a general movement towards more favourable transition conditions, although the pace and intensity of change varied considerably across countries (Figure 5).

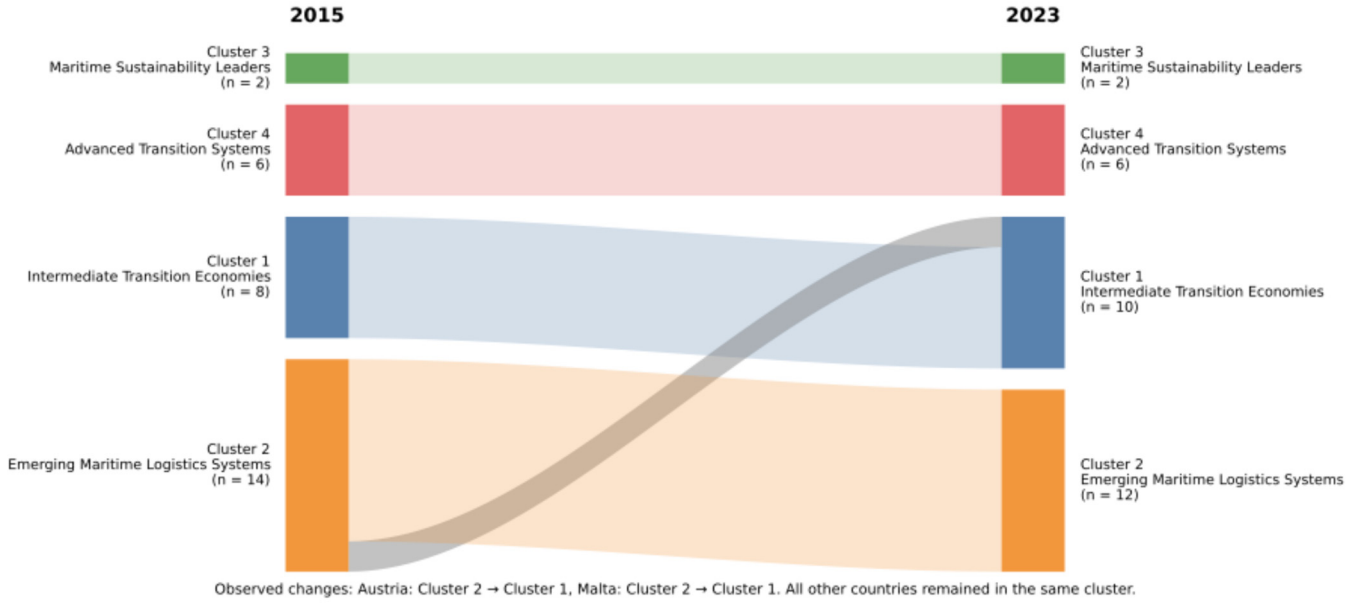


Figure 5. Evolution of cluster composition between 2015 and 2023. Gray flows represent the observed transitions between clusters during the study period.

Figure 5 shows a highly stable cluster structure between 2015 and 2023. Austria and Malta were the only countries that moved from the Emerging Maritime Logistics Systems profile to the Intermediate Transition Economies profile, while the remaining 28 countries retained their initial classification.

The strongest improvements were observed in Malta, Ireland, Türkiye, Greece, Cyprus, Estonia, Slovakia, Croatia, Italy, Portugal, Latvia, Lithuania, Hungary, Czechia and the Netherlands (Table 8). These countries increased their transition scores by more than eight points during the period. Malta registered the largest improvement, moving from an emerging profile to an intermediate transition profile. Several countries improved their scores without changing cluster membership, indicating that progress may occur within an existing structural profile before becoming sufficient to produce a categorical transition.

Table 8. Transition pathway classification, 2015–2023.

Trajectory Type	Number of Countries	Countries
Convergent/improving	15	Croatia, Cyprus, Czechia, Estonia, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Malta, Netherlands, Portugal, Slovakia, Türkiye
Stable	15	Austria, Belgium, Bulgaria, Denmark, Finland, France, Germany, Iceland, Luxembourg, Norway, Poland, Romania, Slovenia, Spain, Sweden
Regressing	0	—

Spain remains classified as an Advanced Transition System throughout the period, with a positive but moderate increase in its transition score (Figure 6). This result indicates a stable advanced profile rather than a disruptive transition. Portugal presents a stronger improvement within the same advanced group, while Ireland and the Netherlands consolidate high positions within the intermediate cluster. Norway remains the dominant leader across the period, whereas Iceland also belongs to the leader profile but with a lower transition score in 2023.

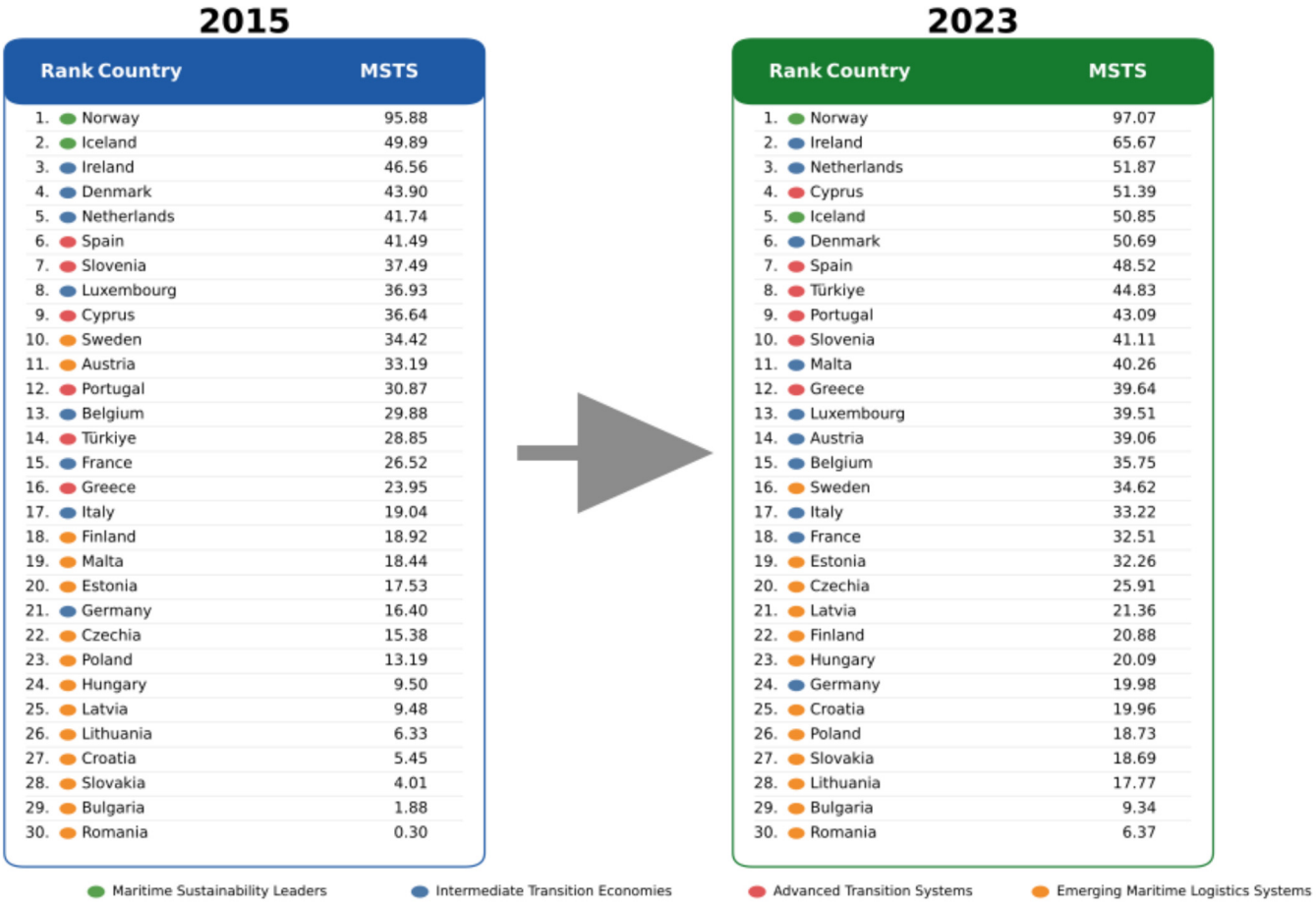


Figure 6. Ranking of European countries according to the Maritime Sustainable Transition Score in 2015 and 2023.

For illustrative purposes, Table 9 presents the relative position of countries according to the Maritime Sustainable Transition Score in 2023. This representation complements the cluster analysis but does not constitute the primary outcome of the proposed framework.

Table 9. Top ten countries according to the 2023 Maritime Sustainable Transition Score.

Rank	Country	Cluster	Profile	MSTS 2023
1	Norway	3	Maritime Sustainability Leaders	97.07
2	Ireland	1	Intermediate Transition Economies	65.67
3	Netherlands	1	Intermediate Transition Economies	51.87
4	Cyprus	4	Advanced Transition Systems	51.39
5	Iceland	3	Maritime Sustainability Leaders	50.85
6	Denmark	1	Intermediate Transition Economies	50.69
7	Spain	4	Advanced Transition Systems	48.52
8	Türkiye	4	Advanced Transition Systems	44.83
9	Portugal	4	Advanced Transition Systems	43.09
10	Slovenia	4	Advanced Transition Systems	41.11

Norway ranks first, followed by Ireland, the Netherlands, Cyprus, Iceland, Denmark and Spain. The lowest scores correspond to Romania, Bulgaria, Lithuania, Slovakia and Poland. This ranking is not interpreted as the main output of the study, but as an auxiliary representation of the relative position of countries within the transition space.

4.5. Robustness of the Analytical Structure

The refined model shows acceptable internal consistency for a multidimensional comparative assessment based on country-level sustainability indicators. The absence of correlations above 0.90 confirms that the retained variables do not suffer from severe redundancy. The PCA summarises 71.20% of the total variance into four interpretable components, providing a compact representation of the data structure without excessive information loss. The clustering solution produces coherent transition profiles with a silhouette coefficient of 0.425, a value consistent with macro-level territorial datasets where complete separation between groups is rarely expected.

The robustness of the interpretation derives from the convergence of three elements: the theoretical coherence of the indicator framework, the empirical structure revealed by PCA and the longitudinal consistency of the cluster trajectories. The results do not support a single linear ranking of countries, but rather a typology of transition pathways. Countries differ not only in their final level of sustainability performance but also in the speed and direction of their evolution over time. This dynamic interpretation constitutes the main empirical contribution of the study and provides the basis for the discussion of policy implications.

5. Discussion

5.1. Interpretation of European Sustainable Maritime Logistics Transition Pathways

The results characterise different national structural contexts associated with the transition towards sustainable maritime logistics, highlighting that these conditions evolve through multiple configurations rather than following a single development pattern.

The resulting typology reflects structural similarities among countries rather than different stages of development. Consequently, cluster membership should be interpreted as describing multidimensional transition profiles rather than a progressive hierarchy of sustainability performance.

Although all countries are subject to the same European regulatory framework, the PCA–Cluster analysis reveals substantial differences in how transport systems, energy transition, environmental performance and socioeconomic conditions interact to shape national transition profiles. This finding suggests that the pace and configuration of sustainability transformation depend not only on regulatory commitments but also on the structural characteristics of each logistics system, confirming that European convergence remains heterogeneous despite the common objectives established under the European Green Deal [1,2].

Accordingly, the proposed typology should be understood as a comparative analytical framework that captures similarities among national transition contexts rather than a fixed evolutionary sequence applicable to all countries.

The four-cluster solution provides further evidence that countries sharing similar levels of overall sustainability may nevertheless reach these positions through different combinations of underlying factors. Maritime Sustainability Leaders combine strong maritime activity with favourable renewable energy performance and robust socioeconomic conditions, whereas Advanced Transition Systems achieve competitive transition scores through alternative configurations in which modal integration and environmental performance play a more prominent role. Intermediate Transition Economies and Emerging Maritime Logistics Systems exhibit different structural constraints, indicating that lower transition scores cannot be attributed exclusively to a single weakness but rather to the interaction of multiple dimensions operating simultaneously. Similar conclusions have recently been reported in studies highlighting the systemic nature of maritime sustainability, where energy, logistics and governance evolve through interconnected processes rather than isolated technological improvements [5,6].

The longitudinal perspective incorporated into this study also provides important insights regarding the dynamics of transition. Approximately half of the analysed countries improved their structural position between 2015 and 2023, whereas the remaining countries maintained relatively stable profiles. Notably, no country experienced a marked regression during the observation period. Rather than indicating complete convergence, these results suggest a gradual reduction in structural disparities, with countries progressing at different speeds according to their institutional capacities, transport structures and energy transition strategies. Such differentiated evolution is consistent with recent European assessments arguing that decarbonisation proceeds through uneven trajectories conditioned by national policy implementation, infrastructure availability and economic specialisation [2,10].

These results indicate that countries follow different patterns of structural evolution over time, reflecting heterogeneous combinations of transport, energy, environmental and socioeconomic conditions.

An equally relevant finding concerns the interpretation of transition itself. Improvements frequently occurred without immediate changes in cluster membership, demonstrating that sustainability transformation is gradual rather than discontinuous. Several countries substantially increased their Maritime Sustainable Transition Score while remaining within the same structural profile, indicating that latent improvements accumulate before reaching the threshold required for a different classification. Consequently, the proposed framework captures transition as a continuous structural process rather than as a sequence of isolated categorical changes. This perspective differs from conventional benchmarking exercises, which typically compare static rankings at specific moments in time and often overlook the evolutionary character of sustainability processes [7–10].

The retained principal components reinforce this interpretation by demonstrating that sustainable maritime logistics cannot be represented through a single latent dimension. Instead, the extracted components reveal complementary dimensions associated with maritime activity, modal integration, renewable energy deployment, environmental performance and socioeconomic readiness. Countries therefore occupy different positions within a multidimensional transition space where strengths in one domain may coexist with weaknesses in another. Similar multidimensional interpretations have been proposed in recent studies addressing sustainability assessment in ports and logistics systems, although these investigations generally focus on individual ports or operational indicators rather than on national transition trajectories across Europe [5,7].

These findings also have broader implications for the understanding of maritime logistics within European sustainability policy. The Green Deal, the Sustainable and Smart Mobility Strategy and FuelEU Maritime establish common strategic objectives for reducing emissions and increasing the resilience of transport systems. The present analysis indicates that achieving these objectives depends on structural interactions extending beyond the maritime sector itself. Renewable energy deployment, labour-market characteristics, freight modal distribution and circular economy performance jointly influence transition outcomes, suggesting that maritime sustainability should be interpreted as the result of coordinated transformations across multiple policy domains rather than as a sector-specific phenomenon [1–3].

5.2. Relationship with Previous Literature

The empirical evidence obtained in this study broadly supports previous research recognising the multidimensional character of sustainable maritime logistics while extending the analytical perspective from individual technological interventions towards integrated transition pathways. Recent literature has consistently highlighted the importance of renewable fuels, digitalisation, modal integration and environmental governance as complementary drivers of maritime decarbonisation [4–6]. The present results reinforce these conclusions by demonstrating that these dimensions do not evolve independently but instead combine to generate distinct structural profiles observable across European countries.

Recent studies have also highlighted the growing importance of transparent, multidimensional benchmarking frameworks for assessing sustainability transitions in maritime logistics. These approaches increasingly combine harmonised statistical indicators with multivariate analytical techniques to improve comparability, reduce methodological subjectivity and support evidence-based policy development [18–20].

Similar conclusions have been reported for the Spanish port system, where digitalisation was identified as a strategic enabler of sustainable transformation rather than merely an operational improvement [21].

Recent evidence also indicates that innovation-oriented investment in port infrastructure contributes to improving environmental performance and long-term sustainability, reinforcing the systemic perspective adopted in the present research [22].

Previous benchmarking studies have generally relied on composite sustainability indices constructed through predefined weighting schemes or expert judgement [8–10]. Although these approaches provide useful policy indicators, they inevitably introduce assumptions regarding the relative importance of individual dimensions. The PCA–Cluster framework adopted here reaches a similar objective through a fundamentally different methodological logic. Instead of assigning ex ante weights, latent dimensions emerge directly from the covariance structure of the observed indicators, allowing the empirical relationships within the data to determine the relative contribution of each variable. Consequently, the resulting transition profiles reflect statistically derived structures rather than normative weighting decisions.

The interpretation of transition pathways also complements recent work examining green ports and sustainable maritime logistics. Cocuzza et al. [5] argue that port sustainability increasingly depends upon integrated environmental, technological and governance strategies rather than isolated operational improvements [23]. The present findings extend this argument from the port level to the national logistics system, suggesting that countries displaying the strongest transition performance simultaneously combine favourable conditions in transport, energy and socioeconomic dimensions. Sustainable maritime logistics

therefore emerges as a systemic property of the broader territorial context in which ports operate rather than solely as the outcome of port-specific interventions.

The longitudinal component of the analysis also contributes to an area that remains comparatively underdeveloped within the literature. Many comparative studies evaluate sustainability at a single point in time, providing valuable benchmarking exercises but offering limited information regarding how countries evolve throughout the transition process [7,9]. By incorporating annual observations covering the period 2015–2023, this research identifies persistent trajectories instead of isolated rankings, allowing countries to be interpreted according to their direction and intensity of change. Such an approach is particularly relevant under current European climate policy, where monitoring transition dynamics is arguably more informative than comparing static positions alone.

Another aspect distinguishing the present work concerns the interpretation of cluster membership. Existing classifications frequently associate higher sustainability exclusively with economically stronger countries. While economic capacity undoubtedly facilitates investment in green technologies and infrastructure, the results indicate that economic performance alone does not determine transition outcomes. Countries with comparable income levels may occupy different structural profiles depending on the interaction between renewable energy deployment, freight modal distribution, environmental indicators and labour-market characteristics. This observation reinforces previous evidence suggesting that institutional coordination and integrated policy design play a decisive role in sustainability transitions beyond purely economic considerations [2,6].

Overall, the comparison with previous research indicates that the principal contribution of this study does not lie in identifying new sustainability dimensions but in demonstrating how these dimensions combine empirically to generate differentiated transition pathways across Europe. The proposed analytical framework therefore complements existing sustainability assessment methodologies by shifting the focus from static benchmarking towards the interpretation of structural evolution, providing a perspective that is particularly valuable for monitoring long-term policy implementation under the European Green Deal.

5.3. Methodological Contribution

Figure 7 summarises the interaction among the different components of the proposed framework. Eurostat indicators are first transformed into a reduced multidimensional representation through Principal Component Analysis. The retained components support both the calculation of the Maritime Sustainable Transition Score and the identification of transition profiles by means of cluster analysis. Together, these complementary outputs provide a structured basis for longitudinal benchmarking and comparative policy assessment using harmonised official statistics.

Beyond its empirical findings, this research contributes methodologically to the assessment of sustainable maritime logistics by proposing a reproducible analytical framework that integrates harmonised Eurostat indicators with unsupervised multivariate techniques. Existing benchmarking exercises frequently rely on composite indices constructed through predefined weighting schemes, expert elicitation or policy-driven aggregation criteria. Although these approaches provide useful decision-support tools, their results inevitably depend on subjective methodological assumptions that may vary considerably across studies, reducing comparability and reproducibility [8,14].

The PCA–Cluster framework adopted in this research addresses these limitations by allowing the latent structure of the dataset to emerge directly from the statistical relationships among the indicators. PCA reduces dimensionality while preserving most of the information contained in the original variables, whereas cluster analysis exploits

the reduced multidimensional space to identify structurally homogeneous transition profiles. Consequently, country classification results from empirical similarities rather than predefined performance thresholds or arbitrary weighting procedures [11–14].

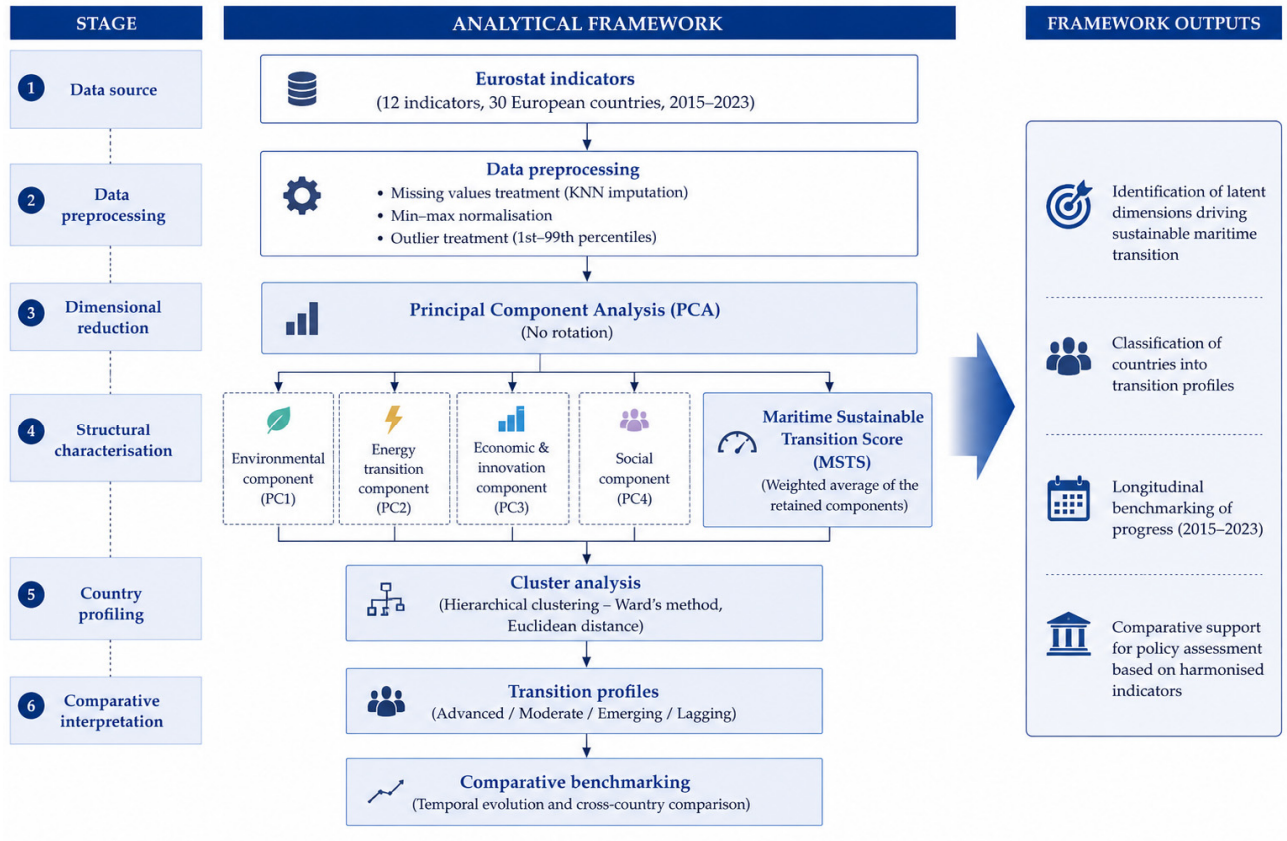


Figure 7. Integrated analytical framework for identifying sustainable maritime logistics transition profiles.

An additional contribution concerns the incorporation of a longitudinal perspective. Rather than evaluating countries at a single point in time, the framework compares their structural profiles across the period 2015–2023, allowing temporal changes in the multidimensional sustainability space to be examined. This longitudinal perspective complements conventional cross-sectional benchmarking by providing a comparative description of how national transition profiles evolve over time. However, the proposed framework does not aim to identify causal transition dynamics or evaluate the effects of specific policy interventions [2,10].

The Maritime Sustainable Transition Score should be interpreted as a descriptive summary derived from the retained principal components rather than as the principal outcome of the analysis. Its role is to facilitate the interpretation of country trajectories over time and to complement the multidimensional classification obtained through the cluster analysis. Unlike conventional composite indices, the score is not based on predefined weighting assumptions but on the statistical structure identified by the PCA. It therefore provides a complementary representation of the reduced multidimensional space without replacing the latent dimensions or the transition profiles identified by the proposed framework.

Another advantage of the proposed methodology is its transferability. Because the analytical framework relies exclusively on harmonised official statistics and widely accepted multivariate techniques, it can be replicated for other geographical contexts, different temporal horizons or alternative thematic domains without substantial methodological modifications. Future applications could incorporate regional statistics, port-level indi-

cators or additional sustainability dimensions while preserving the same analytical logic. Such flexibility increases the usefulness of the framework as a monitoring tool supporting evidence-based policymaking under evolving European sustainability strategies.

5.4. Policy Implications

The differentiated transition pathways identified in this study suggest that European sustainability policies should move beyond uniform implementation strategies towards approaches that recognise the structural diversity of national logistics systems. Although the European Green Deal establishes common objectives for climate neutrality, the empirical evidence indicates that countries progress through distinct combinations of transport, energy and socioeconomic conditions. Consequently, identical policy instruments may produce heterogeneous outcomes depending on the structural characteristics of individual countries. This observation reinforces recent European policy documents emphasising the need for adaptive implementation mechanisms capable of accommodating territorial diversity while maintaining common strategic objectives [1–3].

The identification of four transition profiles provides a comparative benchmarking framework that may support the interpretation of national sustainability contexts and inform strategic reflection at both European and national levels.

Countries belonging to the Maritime Sustainability Leaders profile may offer useful reference cases for comparative analysis, while the remaining profiles illustrate different structural contexts associated with sustainable maritime logistics. Intermediate and Advanced Transition Systems occupy positions where incremental improvements in renewable energy deployment, modal integration or circular economy performance may accelerate progression towards higher transition profiles. Such differentiated strategies are more consistent with the empirical evidence than universal policy prescriptions based exclusively on final rankings.

The results also highlight the importance of integrating maritime transport within broader energy and logistics policies. The strongest transition profiles are not characterised solely by maritime performance but by favourable interactions among renewable energy deployment, freight transport organisation, labour-market conditions and environmental sustainability.

This systemic interpretation is consistent with recent sustainability frameworks proposed for port systems [24].

Previous systematic reviews likewise conclude that environmental, operational and governance dimensions should be assessed jointly when evaluating sustainable port performance [25].

This finding supports policy approaches that promote coordination across transport, energy and industrial sectors rather than treating maritime decarbonisation as an isolated objective. Similar conclusions have recently emerged in studies emphasising the growing role of ports as energy hubs and multimodal logistics platforms supporting the transition towards climate-neutral supply chains [4–6].

Similar conclusions have been reported regarding the growing importance of energy efficiency measures within European ports [26].

Recent research has also highlighted the growing contribution of advanced analytical techniques, including machine learning and forecasting models, to support maritime decarbonisation strategies and improve the prediction of clean-energy shipbuilding trends and shipping emissions. These complementary approaches reinforce the importance of combining robust statistical methodologies with data-driven decision support for the sustainable transition of the maritime sector [27–29].

From a monitoring perspective, the proposed framework offers a structured approach for monitoring the evolution of national sustainability contexts using harmonised official statistics. Its results may complement other sources of evidence when assessing the implementation of European sustainability policies. Because the methodology relies exclusively on Eurostat indicators, it can be updated periodically as new data become available, allowing policymakers to monitor structural evolution without modifying the analytical framework. The combination of transition scores and cluster membership enables progress to be assessed through changes in structural position rather than through isolated indicator values, providing a richer understanding of long-term sustainability dynamics.

5.5. Limitations and Future Research

Several limitations should be considered when interpreting the findings of this study. First, the analysis is constrained by the availability of harmonised Eurostat indicators. Although the selected variables capture key dimensions of sustainable maritime logistics, they cannot fully represent the operational complexity of port systems, shipping technologies or national logistics governance. Incorporating more detailed port-level indicators would provide additional insights into the interaction between national transition pathways and local operational performance.

Second, the country-level perspective adopted in this study is appropriate for analysing European transition patterns based on harmonised official statistics. However, national averages cannot capture the operational diversity that exists among individual ports, logistics corridors or regional freight systems. Port-level or corridor-level analyses should therefore be regarded as complementary approaches capable of providing greater operational detail while addressing different research questions.

A further limitation concerns the temporal horizon. The study covers the period 2015–2023, which includes the implementation of several major European sustainability initiatives but does not yet capture the long-term effects of recently adopted regulations such as FuelEU Maritime. As additional statistical information becomes available, longitudinal analyses covering subsequent years will provide valuable evidence regarding the effectiveness of these policy instruments and the persistence of the transition pathways identified in the present research.

Future investigations could also expand the methodological framework through the integration of complementary analytical techniques. Machine learning algorithms, network analysis and spatial statistics may provide additional perspectives on the relationships among transport systems, energy transition and environmental performance. Similarly, combining official statistical information with operational port indicators, digitalisation metrics or supply-chain resilience measures would enable more comprehensive assessments of sustainable maritime logistics under rapidly evolving technological and regulatory conditions.

The incorporation of detailed operational energy indicators would also allow future studies to capture the interaction between port efficiency and sustainability transition more accurately [30].

These priorities are closely aligned with the objectives defined in the latest European Blue Economy policy framework [31].

Overall, the proposed framework demonstrates that sustainable maritime logistics should be understood as a multidimensional and dynamic transition process rather than as a static performance outcome.

By combining harmonised European statistics with data-driven multivariate methods, the proposed framework provides a transparent and potentially transferable analytical framework that may support scientific research, strategic planning and evidence-based

policymaking in the transition towards more sustainable and resilient European maritime logistics systems.

Continuous monitoring through harmonised European indicators will therefore remain essential for evaluating progress towards climate-neutral transport systems [32].

6. Conclusions

This study developed a multivariate analytical framework to characterise the national structural conditions associated with sustainable maritime logistics transition across European countries using harmonised Eurostat indicators covering the period 2015–2023.

Rather than constructing a conventional composite index based on predefined weighting schemes, the proposed methodology combined Principal Component Analysis and cluster analysis to reveal latent sustainability structures and classify countries according to statistically derived transition profiles. This approach responds directly to the research objective of providing a reproducible framework capable of supporting the comparative assessment of heterogeneous transition patterns of sustainable maritime logistics systems under the objectives established by the European Green Deal.

The empirical results reveal different patterns of structural variation across European countries during the study period, highlighting that progress towards sustainable maritime logistics is heterogeneous and multidimensional. Four distinct structural profiles emerged from the analysis, reflecting different combinations of maritime activity, modal integration, renewable energy deployment, environmental performance and socioeconomic readiness. The longitudinal assessment further revealed that changes occurred at different rates across countries during the study period.

The analysis indicates that most European countries exhibited positive changes in their relative transition profiles throughout the study period, although these changes occurred at different rates and reflected different structural configurations. Progress therefore appears to depend not only on regulatory commitments but also on the interaction among transport systems, energy policies and national socioeconomic characteristics.

These findings reinforce the view that sustainability should be interpreted as a multidimensional transition process rather than as a static performance outcome. Countries occupying similar positions in overall sustainability rankings frequently display different structural configurations, demonstrating that alternative development pathways may lead to comparable transition levels. Consequently, benchmarking exercises based exclusively on final rankings may overlook important differences in the mechanisms driving sustainability transformation. The identification of transition profiles provides a richer representation of European logistics evolution by incorporating both structural diversity and temporal dynamics.

From a methodological perspective, the proposed PCA–Cluster framework represents one of the principal contributions of this research. By replacing subjective weighting procedures with statistically derived latent dimensions, the methodology improves transparency, reproducibility and interpretability while preserving the multidimensional nature of sustainable maritime logistics.

The Maritime Sustainable Transition Score is included as a complementary descriptive measure that facilitates longitudinal comparison and supports the interpretation of the transition profiles identified through PCA and cluster analysis. The principal contribution of the proposed framework remains the identification of multidimensional transition profiles rather than the construction of a composite sustainability index.

The results provide a comparative analytical perspective that may support the interpretation of European transport policy within the context of sustainable maritime logistics. However, the identified transition profiles should be interpreted as benchmarking insights

rather than evidence of causal relationships or the effectiveness of specific policy measures. The existence of differentiated empirical transition profiles suggests that common sustainability objectives require flexible implementation strategies adapted to national structural conditions. The identified transition profiles illustrate different structural contexts that may assist comparative assessments of national sustainability strategies. Such differentiated approaches appear more consistent with the empirical evidence than uniform policy instruments applied across highly heterogeneous logistics systems.

Several limitations should nevertheless be acknowledged. The analysis is constrained by the availability of harmonised Eurostat indicators and therefore cannot fully capture operational characteristics specific to individual ports or maritime corridors. Similarly, the country-level perspective masks regional differences that may become relevant when evaluating local transition strategies. These limitations should be considered when interpreting the results but do not affect the internal consistency of the proposed analytical framework.

Although the retained component structure proved suitable for the objectives of this study, future research could further assess its robustness through alternative indicator specifications, rotated PCA solutions or complementary multivariate techniques such as exploratory factor analysis or bootstrap-based stability analyses.

The longitudinal analysis presented in this study describes changes in transition profiles over time but does not aim to establish causal mechanisms or dynamic transition processes. Future studies applying panel data techniques, Markov transition models or other longitudinal approaches could provide a deeper understanding of the mechanisms underlying these observed temporal changes.

Future research should expand the proposed framework through the incorporation of port-level indicators, regional datasets and additional sustainability dimensions associated with digitalisation, resilience and supply-chain performance. Extending the temporal horizon beyond 2023 will also enable the long-term effects of recent European initiatives, including FuelEU Maritime and other Green Deal instruments, to be evaluated empirically. The integration of multivariate statistics with machine learning techniques and spatial analytical methods represents another promising avenue for improving the understanding of sustainable maritime logistics transitions.

Overall, this research suggests that sustainable maritime logistics may be more comprehensively characterised through transition profiles than through conventional benchmarking alone. By combining harmonised European statistics with objective multivariate methods, the proposed framework offers a transparent and reproducible analytical framework that may support future scientific research, strategic planning and evidence-informed policymaking related to sustainable maritime logistics.

Consequently, the proposed transition profiles should be interpreted as analytical categories derived from the observed statistical structure of the data rather than as universal stages of maritime logistics development.

Author Contributions: Conceptualization, N.G.-C.; Methodology, N.G.-C. and J.V.-C.; Validation, N.G.-C. and F.S.-F.; Formal analysis, N.G.-C., B.M.-S. and F.S.-F.; Investigation, N.G.-C., B.M.-S. and J.V.-C.; Data curation, N.G.-C. and F.S.-F.; Writing—original draft, N.G.-C., B.M.-S., F.S.-F. and J.V.-C.; Writing—review & editing, N.G.-C., B.M.-S., F.S.-F. and J.V.-C.; Visualization, N.G.-C.; Supervision, N.G.-C. and B.M.-S.; Project administration, N.G.-C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data used in this study were obtained from publicly available Eurostat databases. The manuscript provides the complete list of indicators, their official Eurostat codes and the methodological workflow required to reproduce the analytical dataset and the statistical analyses.

Acknowledgments: The authors would like to acknowledge Eurostat for providing the harmonised statistical data used in this research.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

Abbreviation	Definition
EU	European Union
PCA	Principal Component Analysis
MSTS	Maritime Sustainable Transition Score
KNN	k-Nearest Neighbours
GDP	Gross Domestic Product
GHG	Greenhouse Gas
SDG	Sustainable Development Goal
TEN-T	Trans-European Transport Network

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