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Exploring the EU sustainability divide: Analyzing disparities in climate investments

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A B S T R A C T

Given the undeniable climate crisis, understanding how the European Union (EU) is investing in fighting against climate change is of critical importance. It is therefore essential to explore whether these efforts and investments reflect a unified strategy or disparities among member states. To achieve this, a factor and cluster analysis is conducted on seven key dimensions of current EU climate change investments, identifying two focus areas: renewable energy and electric mobility (e-mobility). The cluster analysis categorizes EU countries into five distinct groups, ranging from sustainability leaders to laggards. Additionally, the evolution of these disparities is analyzed over time (2018–2020). Findings reveal that Denmark, Luxembourg, and Sweden, emerge as sustainability leaders, in both renewables and e-mobility, showing great capacity e expanding HRES investment and contributing significantly to national load balancing and GHG reductions. In contrast, other nations prioritize one area while neglecting the other, hindering balanced sustainability progress. Additionally, while the variation in the renewables decreased over time, indicating a narrowing asymmetry in this dimension, the variation in the e-mobility increased significantly, reflecting a widening gap. Though progress is evident, achieving a more unified and balanced sustainability strategy across the EU requires further investment in both renewables, including HRES, and e-mobility, alongside policy initiatives that promote holistic climate action and reduction of emissions. Strengthening national implementation plans, financial incentives, and public awareness, together with a cross-country knowledge-sharing initiatives, are suggested to improve the fair and sustained progress of all countries toward the EU's green transition goals.

1. Introduction

The world is currently facing the highest temperatures ever recorded, with far-reaching consequences on ecosystems and human life (Symonds, 2023). This concerning pattern is associated with the frequent occurrence of extreme weather events, including intensive heat, heavy precipitation, drought, storms, fires, and floods (Rocha et al., 2022). In addition, Europe is warming at a faster rate than the global average (Limb and Yanatma, 2023). The tendency to raise temperature levels and the increasing of severe weather episodes have resulted in significant environmental damage and have profound impacts on communities worldwide. Thus, the imperative shift from the traditional sources of energy to sustainable alternatives is gaining force (Bölük and Mert, 2014).

The investment trends in combating climate change have been directed at renewable energy (RE) and the transportation sector, both globally (Buchner et al., 2023) and within the European Union (EU) (Cox et al., 2023). In 2021, 70 % of global climate investments were held on RE and greenfield projects aimed at slowing down pollutant gas emissions. In fact, in 2023, the main sources of CO2 emissions were electricity and heat production, followed by transportation and manufacturing (Nassar et al., 2025). Europe led the way, contributing almost half of the total international climate investment. Greenfield investment concerns sectors such as energy, buildings, water, and transport (United Nations Conference on Trade and Development, 2022). As the urgency to mitigate the effects of global heating augments, experts anticipate a boosting investment in the future in energy, transport alternatives, and other green initiatives (Chandler et al., 2022).

RE arises as a key factor in diminishing the reliance on fossil fuels, offering a viable solution to achieve low-carbon energy and combat global warming (White, 2021). Evidence has proved that the adoption of RE sources and sustainable technologies brings benefits such as air quality, lower electricity prices, new jobs, reduced greenhouse gas (GHG) emissions and carbon footprint, and enhanced public health

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(Long and Steinberger, 2016; Xie et al., 2023). In 2022, RE has "*generated more electricity on the continent than polluting fossil gas*" (Jacobo and Manzo, 2023), a signal of hope. Worldwide, the renewable energy capacity grew by 50 % in 2023, reaching around 3372 GW. This includes solar, wind, hydropower, geothermal, and other sources. The market is expected to keep growing at an annual rate of 4.22 %, reflecting a global shift toward sustainable energy. China and the U.S. lead with 760 GW and 265 GW respectively, while Africa's 221 GW capacity is mainly from hydropower, solar, and biomass (Nassar, El-Khozondar, Alatrash et al., 2024; Nassar, El-Khozondar, Elnaggar et al., 2024).

The transportation sector stands out as one of the biggest contributors to carbon dioxide (CO_2) emissions (Fan et al., 2023). Hence, it is urgent to decarbonize motorized transportation and despite one of the most effective ways to accomplish this is by switching to electric vehicles (EVs) (Charetee, 2023), electric mobility (e-mobility) goes beyond cars. Embracing e-mobility represents the best strategy for decarbonizing transportation processes, aligning with the goals of the Paris Agreement and contributing to carbon neutrality (Logan et al., 2020). By transitioning away from fossil fuels, e−mobility reduces toxic gas emissions, improving air quality and reducing noise pollution, thereby enhancing societal well-being and paving the way for a sustainable transportation sector (Tsoi et al., 2022).

While previous research has profiled EU countries based on sustainability indicators, exploring their position on each SDG individually (e.g. Çağlar and Gürler, 2022; Ricciolini et al., 2022; Walesiak and Dehnel, 2024), they have not systematically examined how climate investments are distributed, balanced, and evolving over time. This gap is particularly relevant given the EU's ambitious climate targets and the need for coordinated policy efforts across member states. Our study addresses this by analyzing investment patterns in relation to sustainability transitions, highlighting disparities in funding allocation and the extent of national commitments. By doing so, we offer a deeper understanding of how financial priorities align with climate goals, shedding light on both collective EU strategies and individual country-level efforts to accelerate decarbonization and green innovation. Therefore, this study seeks to answer the following research questions (RQs).

RQ1. Which EU countries are leading in sustainable energy practices, and what are the implications for climate change mitigation?
RQ2. Are there significant differences in the EU countries regarding the environmental indicators found?
RQ3. What explains the disparities between EU countries?
RQ4. Is the EU united against climate change? Through the years, are the countries becoming more cohesive or more divergent on this matter?
RQ5. In what ways did the countries progress in terms of those factors?

To better understand the disparities in climate investments among EU member states, this study is grounded in two main theoretical perspectives: (1) the environmental Kuznets curve (EKC), which posits an inverted U-shaped relationship between economic development and environmental degradation (Grossman, 1995). Based on this framework, the study examines whether more economically developed EU countries allocate higher green investments, reinforcing their role as sustainability leaders; (2) the institutional theory, which provides another critical lens by emphasizing the role of policies, governance structures, and regulatory frameworks in shaping environmental actions (Scott, 2004). Within the EU, disparities in climate investments can be examined through the influence of institutional arrangements, where policy-driven incentives, national funding mechanisms, and the historical context of EU membership impact sustainability trajectories. This study also explores for example whether older EU members—benefiting from more established regulatory frameworks and long-standing climate commitments—demonstrate stronger institutional support for sustainability compared to newer member states.

The analytical approach comprehends two stages: factor and cluster analysis. Factor analysis is used to identify underlying patterns in investment data, reducing dimensionality and revealing latent structures that drive sustainability transitions. Given the complexity of climate investments, FA helps consolidate numerous correlated indicators into a smaller set of meaningful factors, allowing for a more structured understanding of financial priorities across EU countries. Existing composite indices help simplify and track sustainability-related developments but often oversimplify complex realities, use outdated variables, and reflect biased indicator weights. These limitations make them less reliable for assessing nuanced sustainability divides, especially in dynamic contexts like the EU. Instead, multivariate methods offer a more accurate way to uncover latent sustainability patterns and group countries using harmonized Eurostat data. This approach enables us to move beyond isolated SDG assessments and instead capture broader investment trends that shape national sustainability strategies. Building on the factor structure identified, cluster analysis is applied to classify EU countries into distinct clusters based on their investment profiles. This allows us to analyze disparities in climate funding, distinguishing between frontrunners, moderate performers, and lagging nations. By grouping countries with similar investment patterns, CA provides valuable insights into the alignment of financial priorities with decarbonization goals, highlighting areas of divergence and potential policy coordination. This methodology has also been used in several prior studies, allowing it to effectively characterize European divides in several contexts (e.g. Cruz-Jesus et al., 2012; Elena-Bucea et al., 2021).

Based on the above, this research presents the following contributions. First, our research seeks to profile sustainability levels across EU countries through a comprehensive, multivariate approach. We highlight that this research is the first to focus specifically on climate-related investments, such as renewable energy (RE) and e-mobility adoption, providing a unique comparative perspective that considers both sustainability performance and investment trends. While similar studies may exist, our study fills a gap by focusing explicitly on how EU countries are investing in sustainable investments to combat climate change and identifying the disparities between them in terms of both adoption and progress. Second, by conducting individual analyses of each dimension and exploring the connection between them, we aim to acknowledge both the progress and disparities among EU countries in facing environmental challenges. Thus, our analysis offers a holistic view of the position taken by each country, aiming to identify those who are dedicated to the cause and contributing to the achievement of the goals of the Paris Agreement: limiting global warming to a maximum of 1.5 °C by 2030 (Chatjuthamard et al., 2024). Third, this paper outlines general policies and procedures that have been successfully applied, serving as valuable references for other countries addressing climate issues, and gathering valuable insights for future recommendations aimed at stopping climate change. Note that the suggestions may not be uniform across all nations, considering the disparities and challenges that each country may face in their environmental initiatives. As a final point, we want to comprehend each country's action on environmental issues, evaluate the EU's commitment to averting global warming, and investigate whether countries are becoming more cohesive or more divergent in their efforts on this matter. According to President von der Leyen, the energy transition will be fair, or it will "not be" (Joint Research Centre, 2024). Therefore, a set of policy recommendations that can improve EU's sustained and equitable progress across all countries, focusing on EU's funding mechanisms and national implementation plans, are suggested.

The structure of the paper is as follows. In the following section, we provide the theoretical background. Within this section, a set of studies related to the topic is presented, highlighting the ongoing debates and the conclusions drawn from these discussions. Section 3 describes the methodology used to handle the data, including a brief description of the data itself. Section 4 presents the multivariate approach employed, factor and cluster analysis, alongside the results, while section 5 presents the discussion, implications, and limitations of our work. At last, section 6 includes the conclusions.

2. Literature review

2.1. Climate change investments trends

Year after year, the highest temperatures continue to break records. In 2024, the World Meteorological Organization announced 2023 as the warmest year ever recorded, with the average temperature hitting 1.45 °C. This was followed by alarming levels of GHG, ocean heat, sea level rise, and glacier retreat ("Climate change indicators reached record levels in 2023: WMO", 2024). Our daily lives are experiencing increasingly frequent extreme weather episodes such as floods, droughts, and heatwaves, which are worsening each year and impacting both health and economies (Chatjuthamard et al., 2024). Urgent action is needed to avert these risks before they turn into catastrophe (Shakoor et al., 2023).

The widespread use of electricity generation based on fossil fuels, including coal, oil, and gas, combined with an exponential population increase in the latest decades, has induced a quick raise in global challenges associated with CO2 emissions (Asumadu-Sarkodie and Owusu, 2016). Moreover, the release of pollutants and chemicals from fossil fuel combustion contributes not only to environmental issues, including air and water pollution but also has economic and social consequences. One in six deaths worldwide is attributed to this pollution (Fuller et al., 2019), underscoring the critical need to develop and apply effective solutions to this pressing issue. GHG emissions are influenced by a variety of factors covering various topics, including economic, environmental, social, and technological, collectively contributing to the increase of the environmental footprint (Li et al., 2021).

Table 1 presents the factors affecting pollutant gas emissions.

The energy sector is the biggest source of GHG emissions, contributing approximately 76 %, which corresponds to 37.6 gigatons of CO2 emissions (Ge et al., 2022). Within this sector, the area that transportation sector is responsible for about a quarter of the total global GHG emissions (Bakker,2024). Particularly, it is responsible for 24 % of direct GHG releases, with three-quarters of this total generated by road vehicles (Ritchie, 2020; Jones, 2021).

Investment trends in fighting climate change are primarily focused on green technologies, driving low carbon emissions. Research from "Trade and investment trends in a decarbonising world' (2021) and Dahlqvist et al. (2023) show that most contributions are attributed to electric mobility and renewable energies. Notably, these sectors play a crucial role in combating the environmental impacts of transportation and energy, which are among the most prejudicial to the environment. Renewable energies are the primary focus for transitioning the energy system, while electric mobility is gaining increasing relevance as an enabling technology (International Renewable Energy Agency, 2023a, b).

This alerts the urgent need to adopt efficient and accessible transportation solutions, such as promoting zero-carbon vehicles and automated mobility, lessening the levels of pollution. However, these measures alone are insufficient. The public transport system must be remodeled, namely in urban areas, to achieve global decarbonization (Ribeiro et al., 2024). In urban areas, where congestion and pollution are significant challenges, the adoption of EVs extends beyond personal cars to include other types of urban transport, including e-buses and e-scooters (Zhang and Fujimori, 2020; Dias et al., 2021). This shift towards electrified transport is a needed step in addressing climate disaster promoting better quality of life and a decline in air and noise pollution (Icaza-Alvarez et al., 2023).

The experts stated that "*The penetration of electric vehicles in an ambitious scenario could reduce emissions by 8.4 million tons of CO2 in 2030 and 49.5 million tons of CO2 in 2050*" (Sudjoko et al., 2021), confirming the pivotal role of electric transport in drastically reducing pollutant gas emissions and lessening dependence on fossil fuels (Pal et al., 2023). A noteworthy aspect to focus on is the cleanliness of the charging process. Despite emissions related to battery generation, EVs still emit less overall than fossil-fuel-powered cars (Veza et al., 2023). However, with the growing utilization of RE sources in this process, such as solar or wind, emissions can be effectively lowered to zero, paving the way for a greener transportation ecosystem (Barman et al., 2023). Additionally, the accessibility of e−mobility transport options is expanding thanks to the introduction of lower-priced options and the expansion of charging infrastructure (Alanazi, 2023).

Therefore, enhancing energy efficiency and transitioning to renewable energy technologies (RETs) - including hydropower, solar, wind turbines, and biogas - are key factors in significantly reducing toxic emissions, thereby contributing to the reduction of carbon footprint and its far-reaching impacts (Asumadu-Sarkodie and Owusu, 2016; Edenhofer et al., 2011; Suman, 2021). The switch to a sustainable energy system offers a chance to cut off carbon intensity, limit environmental effects, minimize environmental and health complications, and solve market failures in the energy sector (Foster and Elzinga, 2015; Jaiswal et al., 2022). Moreover, the RE sector has become a significant driver of economic growth and job creation, stimulating local economies, innovation, and employment opportunities (Paraschiv and Paraschiv, 2023). The transition to renewables also opens doors for green finance and sustainable economic development (Center for Climate Strategies, 2013).

2.2. PRIOR research

Fossil fuels account for over 75 % of such emissions, making it imperative to reduce emissions by nearly half by 2030 and reach net zero by 2050 (Dell, 2023). Making the shift away from fossil fuels and toward clean and RE sources, it is crucial to meet these vital targets (de Lange, 2024).

To comprehend the potential impact of embracing RE, researchers have undertaken empirical and practical studies, using different approaches and offering valuable insights into the complex relationship between RE adoption, carbon emissions, and broader economic and environmental considerations. The predominant research methodology involves the development of regression models to test the theoretical ideas underlying each study. Specifically, researchers aim not only to identify which indicators raise pollutant gas releases, but also to examine the relationships among them, discovering what drives gas emissions into the atmosphere and exploring strategies for their mitigation. From another perspective, some investigators have applied CA to compare countries concerning renewable features. This method helps to understand the position of each country, uncovering their progress in renewables. Additionally, Appendix Asummarizes prior research on optimization techniques.

Table 2 presents the studies found regarding RE impact on climate change.

To sum up, the studies reviewed underscore the significant role of RE sources in diminishing the use of fossil fuels, thereby reducing the

Table 1
Factors impacting GHG emissions.

Economic	Environmental	Social	Technological
Population	Energy sources	Individual consumption patterns/lifestyles	Advances in cleaner technologies
Research and Investment	Adoption of environmentally practices	Public perception of environmental issues	
GDP per capita	Land use and deforestation		
Government policies			
Energy consumption			

Table 2
Studies on RE use and climate change mitigation.

Author	Theory/Objective	Variables	Method	Limitations/Suggestions
(Longa & Zwaan, 2017)	Kenya's climate goals rely on robust investment in renewables, emphasizing power sector expansion and low-carbon technologies.	CO2 emissions by sector; Energy consumption by sector; Electricity production capacity per technology; GHG emissions by sector.	TIAM-ECN model, a linear optimization model that minimizes energy system costs in each time-period with perfect foresight	Level of detail is not sufficient to capture all traces that exist; Better understanding of the impact on society
Wałachowska and Ignasiak- Szulc (2021)	Comparison of Renewable Energy Sources in 'New' EU Member States.	%energy production from RE sources in the total energy production	Cluster analysis (k- means, wards' method)	–
Suman (2021)	RE crucial for climate mitigation and adaptation, offering socio-economic benefits and emissions reduction.	Energy consumption/generation by energy source	Based on other studies' findings + analysis of the variables using graphs	Focus on the challenges, and barriers of RETs promotion in different political regimes
Acaroğlu and Güllü (2022)	Climate change analysis links energy consumption, revealing renewables decrease temperature, offering mitigation through incentives.	Temperature; Precipitation; Energy types; GDP per capita.	Autoregressive Distributed Lag and Toda- Yamamoto causality analysis	Gathering data for all variables for the same period
Jahanger et al. (2022)	RE consistently reduces CO2 emissions, while globalization amplifies them.	Carbon emission is the dependent variable. GDP per capita, RE (share in total energy) and globalization (KOF index) are the independent variables.	Quantile Autoregressive Lagged model + spectral causality analysis	Include other relevant factors (e. g. load capacity); For a robustness analysis use KRLS models; Study countries with advanced technological infrastructure
Paraschiv and Paraschiv (2023)	Decarbonizing energy relies on boosting renewable share, reducing fossil fuels, and managing variability for sustainable transformation.	RE production (wind, solar, biomass and hydro energy)	Bar and line charts	–
Kwakwa (2023)	RE and institutional quality impact carbon emissions; institutions also moderate renewable energy effects.	Urbanization; Population pressure; Income; RE consumption; Institutional Quality (Corruption, law, political stability, regulation, etc.); Trade openness.	Regressions: STIRPAT model; EKC model	Limited to the African region for 2002–2021. Do not consider CO2 emissions by sector
Syed et al. (2023)	Climate policy uncertainty impedes RE consumption, necessitating reduced uncertainty for enhanced utilization strategies.	CPU (climate policy uncertainty), IPL (industrial production index), oil prices; CO2 emissions; Consumer price index (CPI).	Augmented ARDL model (regression); unit root tests	CPU data not available for other countries
Jaworski et al. (2023)	Poland's pursuit of sustainable energy involves analyzing EU trends, local dynamics, and overcoming implementation challenges.	Photovoltaics (PV), wind turbine generators (WTG), and aquatic base flow (ABF, hydropower).	Cluster analysis + PCA + multiple regression	Do not consider relevant variables: public perception, social barriers, community-based projects, RETs
Cevik (2024)	Increasing the use of renewables enhances both climate resilience and energy security, reducing carbon emissions.	Share of alternative sources of energy including nuclear, renewable, and other non-hydrocarbons; GDP per capita; Trade openness; Energy efficiency.	Time series regression	–

environmental footprint of the energy sector. Besides, based on conclusions drawn from the studies, it is notable that CO2 emissions are driven by urbanization, economic growth, transportation, and industrialization sectors. On the other hand, it is cut off by technological innovations, energy efficiency, institutional quality, and RE production/consumption. The latter one, on its hand, can be motivated by the increase in oil prices, carbon taxes, green bons, and climate policy uncertainty.

Therefore, although there is a great set of prior research on understanding the impact of RE against climate change, there is still not a clear picture of EU countries in capturing what they are doing in terms of sustainable investments and technologies. Thus, it becomes evident that analyzing the current investment trends and enabling technologies against climate change in EU countries is imperative. Some researchers have opted for constructing regression models, while others have used CA to categorize countries based on their characteristics. In this study, we adopted the latter approach, complemented by FA to enhance the interpretability of the chosen variables. Particularly, the study addresses a significant gap in the literature by providing a holistic view of EU members' profiles regarding the main tendencies in combating environmental degradation. In addition, the paper underscores the potential unity within the EU in this regard and reveals disparities among EU members, thereby suggesting that environmental policies and strategies may not be uniform across all countries.

3. Methodology

3.1. Data

In line with our theoretical background, we want to measure the main tendencies against climate change. Therefore, the data used to perform this study emphasis seven variables collected on "OurWorldInData", "Statista", "WorldBank", "EEA", and "Climatedata" websites and refer to the year 2020. The focus region is the EU countries since they are recognized as the drivers of formulating and implementing policies to combat global warming (Cifuentes-Faura, 2022). Simultaneously, the evolution of CO2 emissions shows Europe's substantial developments when compared to the rest of the world (Cevik, 2024).

To measure the drivers of climate change two variables were collected: the generation of energy by fossil fuels due to their impact on environmental deterioration, including air and water pollution (Denchak,2022) and the CO2 emissions generated by new cars, as higher levels of gas releases promote environmental degradation (Syed et al., 2023).

Additionally, to measure energy production and consumption from clean sources, aligning with the multidimensional trends in terms of sustainable investment (International Renewable Energy Agency, 2023a,b) other variables were considered. The first variable, RE production evaluates energy generation using green sources of energy such as solar, wind, hydro, and biomass. Paraschiv and Paraschiv (2022) confirm that the utilization of eco-friendly energy sources induces a decarbonized energy system, serving as a tool to mitigate climate disaster and promote sustainable development. Next, RE consumption, calculates energy consumption from renewable sources, assessing which is the primary source of energy used. Kwakwa (2023) states that the consumption of RE holds the potential to lower CO2 emissions, thereby ensuring environmental quality.

At last, variables related to enabling technologies for sustainability were collected to capture these trends (International Renewable Energy Agency, 2023a,b). We use the number of sold eco-cars, both plug-in and 100 % electric, to measure the adoption rate of sustainable transportation. As zero gas pollutant emissions are a desired outcome for environmental preservation, the higher number of electric cars sold indicates lower GHG emissions (Zhao et al., 2023), therefore a greater commitment to reverse climate disaster. Not only cars need to switch to zero emissions, other types of transport, like e−scooters, can be used to replace short car trips, thereby reducing CO2 emissions (Dias et al., 2021; Gebhardt et al., 2022). Thus, the number of e-scooter users is also considered as a metric to the adoption rate of sustainable transportation. This provides a full understanding of the environmental impact of transportation choices.

This new perspective aims to contribute valuable insights to the ongoing discourse about the EU's actions to address global heating while also identifying the disparities among EU members.

Table 3 presents the variables under study along with a short description of each.

3.2. Data pre-processing

To gain a visual representation of the dataset and to ascertain the presence of missing values and outliers, a preliminary data preprocessing phase was conducted prior to embarking on in-depth analyses. An important issue to reflect on is that some variables were "normalized per capita" to ensure that the country's size did not skew the analysis. This normalization process was employed to account for factors such as population size, as its reasonable to expect that a larger population would lead to higher numbers of, for example, cars sold. Therefore, the variables were adjusted per capita by dividing them by the population size. We believe that normalizing per capita is appropriate in the context of this research to ensure that each country is evaluated relative to its population size, allowing us to capture sustainability efforts and outcomes in a way that is comparable across countries of varying sizes and populations. This approach has been used in similar studies (Cruz-Jesus et al., 2012; Elena-Bucea et al., 2021). Based on summary statistics output, it is possible to anticipate the existence of outliers, by comparing the values of the quantiles of each variable with its mean. These outliers, which are observations with extreme values, have the potential to significantly impact data analysis. To further isolate those observations, an individual analysis of each variable was conducted, using box plots as a visual aid to help with outliers' identification. Regarding missing values, three variables presented some gaps, ranging from 2 to 3 missing values. However, taking into consideration the total of 27 observations, these instances of missing data represent a relatively small proportion. The KNN Imputer was the technique chosen to handle missing values. We believe this is the most suitable method for our dataset, as it effectively handles missing values by leveraging the relationships between data points in a way that preserves the overall structure of the dataset. We have also tested other imputation methods such as decision trees, which provided similar results. Additionally, the imputed values were verified to ensure that they were aligned with the overall patterns in the dataset. Moreover, as previously mentioned, box plots were generated for each variable, revealing the presence of outliers in all cases. To prevent any potential distortion of the results, analysis with and without the outliers was performed and the results were compared, reaching the conclusion that they did not influence the other observations (the factor scores were very similar). Therefore, we kept the outliers.

After data preparation steps were completed, the dataset was normalized using standardized scaling. This data transformation technique is commonly used when data are not on the same scale. It operates by centering each variable at mean zero and variance equal to one (Amorim et al., 2023).

Table 3
Variables' description.

Category	Variable name	Description	Support
Climate change drivers	Fossil fuels	Energy production by fossil fuels per capita	(Denchak, 2022; Geet al., 2022)
	CO2 cars	Average CO2 emissions per km from new passenger cars	(Syed et al., 2023)
Climate change mitigation investment trends and enabling technologies	RE production (more details in Appendix B)	% Renewable energy production, as a proportion of a total	(Edenhofer et al., 2011; Paraschiv and Paraschiv, 2022)
	RE consumption	% Renewable energy consumption, as a proportion of a total	(Edenhofer et al., 2011; Kwakwa, 2023)
	Battery EVs	Number of EVs sales per capita	(Zhao et al., 2023)
	Plug-in Hybrid EVs	Number of sales of Plug-in Hybrid EVs per capita	(Zhao et al., 2023)
	E-scooters users	Number of e-scooter users per capita	(Dias et al., 2021; Gebhardt et al., 2022)

4. Methods & results

4.1. Factor analysis

After treating the missing values and the outliers, a dimensional reduction technique - FA – was employed to enhance the interpretability of the data. FA aims to uncover the unobservable and latent dimensions that explain the correlation among variables. Factor analysis is a statistical technique used to identify underlying latent variables (factors) that explain the variance in observed variables. The mathematical formulation is as follows: $X = \Lambda F + \varepsilon X$, where X is the vector of observed standardized variables (Table 3) ($n \times p$ matrix), Λ is the factor loading matrix ($p \times k$), F is the vector of common factors ($n \times k$ matrix), ε is the vector of unique variance ($n \times p$ matrix), where n represents the number of observations, p the number of variables, and k the number of factors.

Some assumptions must be verified, before running into the execution of FA. First, it is necessary that the variables present a relationship among them, otherwise, FA may give weak results (Schuster and Yuan, 2005). To access this, the correlation matrix was developed. The matrix (see Table C.1Appendix) shows that there are pairs of variables that present moderate levels of correlation (Nickolas et al., 2023) indicating a good fit for FA.

The second step was to check the Kaiser-Meyer-Olkin (KMO) of each variable individual. KMO is a method to assess the suitability of data for FA namely, to determine whether the data has sufficient common variance to justify the extraction of underlying factors. A KMO value of 0.5 or higher is acceptable for FA, indicating that the variables have enough commonality to proceed with the analysis (Statistics How To, n. d.). It is evident that all variables (see Table C.2in Appendix), except for "Battery EVs", present values above the threshold. Despite this variable falling below 0.489, the value is close to the threshold, so the variable was not removed, as it was also relevant for the analysis. Moreover, the overall KMO value is favorable at 0.648, which suggests a good fit for FA.

Once these conditions were met, FA was employed using varimax rotation, a technique that minimizes the number of variables with high loadings on each factor and makes factor interpretation easier

(Sarmento & Costa). Although there are several methods to estimate communalities, principal component factor was chosen for this analysis because it assumes that all variance from the original variables is the communality. This method is adequate in this case as the data is count-based, minimizing subjectivity (Sharma, 1996). Therefore, the eigen decomposition of the correlation matrix is performed such as $\Sigma = \Lambda\Lambda\hat{}T+\Psi$, where Ψ is the diagonal matrix of unique variances. The eigenvalues are presented in Table C.3 in Appendix.

Although there are no absolute criteria to decide on the number of dimensions to retrieve, the choice can be relied on three main criteria, while always keeping in mind the context of the analysis: Pearson's, Kaiser's, and the Scree Plot. For Pearson's criteria, the decision is to retain factors until they collectively account for at least 80 % of the total variance (Jolliffe and Cadima, 2016), which resulted in selecting three factors (see Table C.3in Appendix). According to Kaiser's criteria, the factors that have an eigenvalue higher than one (as the data was standardized) should be chosen, which corresponds to the selection of two factors (see Table C.3 in Appendix). Finally, the Scree Plot indicated two factors (Auerswald and Moshagen, 2019).

Having all the criteria considered and comparing the different tests conducted, the optimal number of factors to be extracted is two. The variance explained by two factors was pointed out to 74 % (Table 4). Nevertheless, opting for three factors resulted in a third additional factor represented by only one variable. To avoid this from happening, the analysis was continued with two factors.

To measure the reliability of each variable, the final communalities were calculated (see Table C.4in Appendix), and all variables presented a value above 0.69 (see Table C.4in Appendix) which means that the variables are very well explained (Eaton et al., 2019).

4.1.1. *Interpretation of the factors*

Moving on to the interpretation of the two factors based on the loading values. The loadings represent the correlation between each original variable and the identified factors. Statistically, only the strongly correlated variables are used to interpret the factors. Regarding factor interpretation, several rotations were performed, always achieving a similar variance distribution among the factors and therefore confirming the reliability of the variable's distribution.

Factor 1 addresses the **RE dimension** as it contains variables related to RE (namely production and consumption) vs the generation of energy using fossil fuels. While the first two variables are positively correlated to this factor, a higher value of fossil fuel-powered energy leads to a low RE index as they are negatively related. This fact was expected given that fossil fuels are a non-renewable energy source. All correlation values are above 0.8 in absolute terms.

Factor 2 can be interpreted as the **e-mobility dimension** since it includes variables related to e-mobility, positively correlated, and on the other hand, negatively related, the emissions released from new cars. This conclusion was expected given that electrified transport does not release CO_2. All correlation values are above 0.6 in absolute terms.

Notably, the variable "E-scooter users' is correlated with both dimensions. This suggests that E-scooter users are not only aware of environmental issues but also motivated to adopt sustainable practices.

Table 4
– Factor loadings with varimax rotation.

Variable Name	RE index	E-mobility index
Battery EVs	0.057	**0.858**
E-scooter users	0.498	**0.665**
Plug-in Hybrid EVs	0.451	**0.763**
CO2 cars	0.023	**−0.832**
RE production	**0.820**	0.287
RE consumption	**0.864**	0.164
Fossil fuels	**−0.863**	0.035
Variance explained (%)	37.42 %	36.62 %
Cumulative variance (%)	37.42 %	**74.04 %**

E−scooters offer a practical solution for these individuals as they are affordable, sustainable, and easy to use.

Additionally, these results were compared with existing indexes on similar topics for external validation purposes. Namely the European environment agency (EEA) renewable energy progress report was analyzed (European Environment Agency, 2024a,b). This report tracks renewable energy developments and GHG emissions in EU countries. Accordingly, the results point out that countries like Sweden and Luxembourg as best performers, while the Netherlands, Ireland and Cyprus show a lowest performance. These findings are aligned with the found scores in factor 1 and therefore suggest the suitability of the RE dimension label. Regarding factor 2, factor scores were compared with the results of the European alternative fuels observatory (European Commission, 2024). Accordingly, results suggest the Netherlands, Germany, France and Sweden as the countries with greatest alternative fuel transport, showing the greatest growth rates in terms of battery electric, plug-in hybrid, and hydrogen transports. These align with the factor 2 scores and therefore suggest an adequate labeling of factor 2 as e-mobility dimension.

Table 4 presents the factor loadings for each variable, regarding each dimension.

To ensure the robustness of both the factor and cluster analysis, we conducted the segmentation using both the factor scores and the original variables, confirming that the cluster composition remained largely consistent across approaches. Additionally, we validated our results by comparing them with findings from previous literature and external benchmarks, such as the climate change performance index (CCPI). This cross-validation reinforces the reliability of our clustering approach and provides further confidence in the identified patterns of sustainability investment across EU countries. Several studies have assessed the progress of European countries on sustainable development goals (SDGs), highlighting significant disparities across regions. Stanujkic et al. (2020) identified Sweden, Denmark, Germany, France, and Finland as the top performers, while Bulgaria and Romania showed the least progress. Similarly, Rocchi (2022) using the SDG achievement index, confirmed that Nordic EU countries lead in SDG performance, whereas Baltic and former Eastern nations lag. These results are also aligned with the found clusters, especially the sustainable leaders and laggards' composition. Over the last years, Sweden consistently led in SDG advancements, with other Nordic countries following closely behind (Ricciolini et al., 2022), which also aligns with the found results. Additionally, the climate change performance index (CCPI) was also analyzed. This metric uses a standardized framework to compare the climate performance of several EU and non-EU countries, being assessed in four main dimensions – emissions, renewable energy, energy use and climate policy (Germanwatch, 2025). According to this, Denmark and the Netherlands lead the rank, with Poland and Bulgaria being the worst performing countries, also being aligned with our results.

4.2. *Cluster analysis*

The next step is CA, which involves classifying the countries based on their similarity, to obtain homogenous groups with heterogeneity between them. The approach was conducted first for the two dimensions obtained in FA, and second using the seven original variables. The results obtained for clustering based on factors and the original variables were similar, with only Denmark changing cluster, which proves the representativeness of the two extracted dimensions in explaining the entire dataset. The similarity measure was defined as the Euclidean distance between points, such as $d\,(xi,xj) = \sqrt{\sum (x_{ik} - x_{jk})^2}$. Later, both hierarchical and non-hierarchical methods were applied. The application of CA comprehends two methods: hierarchical and non-hierarchical. In this study, the hierarchical methods are used to decide the number of clusters to be extracted, as this method does not require a prior definition of it (Shetty and Singh, 2021). Here, all five hierarchical methods were compared (Single, Complete, Average, Centroid and Ward's) and the one with best performance was used. The performance is measured using R-Square, defined as $R^2 = \frac{ss_B}{ss_T}$, being the ratio of the between-clusters sum of squares (ss_B) and the total sum of squares (ss_T), and therefore varying between 0 and 1. The R^2 is a measure of explained variance (information) as it is the ratio of the between.-cluster distances (that we keep) over the total distances between observations in the original dataset. It thus measures the extent to which groups or clusters are different from each other or, in alternative, how much the groups are homogeneous. Then, we ran the k-means non-hierarchical algorithm to form the groups, having as initial seeds the centroids of the clusters obtained with the hierarchical method, a strategy to yield better results (Sharma, 1996). Lastly, to verify whether each dimension was statistically different across clusters, the Kruskal-Wallis test was conducted, at a significant level of 5 %. After forming the clusters, we categorized them using "profiling analysis", based on each cluster's average for each factor (Cruz-Jesus et al., 2012).

4.2.1. Cluster analysis using factor scores

All considered and after testing similar solutions, results were better using Ward's algorithm, with the highest scores of R-squared, showing a five-cluster solution (see Figure C.2in Appendix) and dendrogram (see Figure C.1in Appendix). The Wards method creates clusters by minimizing the error sum of squares (ESS) of each cluster solution, being defined as $\sum_{j=1}^{k}\sum_{i=1}^{n_j}\left(x_{i_j}-\overline{x}_j\right)^2$ for each observation i of each cluster j. The Kruskal-Wallis test confirmed significant statistical differences between the clusters concerning both dimensions, as suggested by Cruz-Jesus et al. (2012). The Krustal-Wallis test confirmed significant statistical differences between the clusters concerning both dimensions. The final five-cluster solution, achieved with k-means, is drawn in Fig. 1. Each country is plotted respecting its values on both indexes and is bordered according to its cluster.

Table 5 presents the average of each factor for each cluster.

Based on "profiling analysis" (Table 5) we noted that: Bulgaria, Cyprus, Czech Republic, Greece, Hungary, Ireland, Italy, Malta, Poland, Slovakia, Slovenia, and Spain have the lowest values on the average of both axes, therefore these countries form the "**sustainable laggards**" cluster. A second cluster includes Croatia, Estonia, Lithuania, Latvia, and Romania where the renewables factor is much higher than the average but, in turn, low values of e-mobility describing an unbalanced sustainability index, labelled as "**green energy-focused**". In the opposite unbalanced direction, forming a third cluster, the Netherlands shows the highest level regarding e-mobility and on the other hand, the lowest level for RE, describing a severely unbalanced sustainability index. Therefore, it is called "**green mobility-focused**". Belgium, France, Germany, and Portugal with moderate values for both dimensions, around the average, integrate a fourth cluster, called "**sustainable balanced**". The rest of the countries, Austria, Denmark, Finland, Luxembourg, and Sweden form the last cluster, "**sustainable leaders**", presenting high levels for both dimensions, above the average.

4.2.2. Sustainability evolution

To enhance the comparison not only among all EU countries but also within the country itself over time, the movement of each country between 2018 and 2020 is plotted in Fig. 2. To accomplish this, and therefore understand how those countries progressed in the sustainable dimensions identified, the data reported before 2020 was normalized using the average and standard deviation of 2020, to allow the comparison across years. Subsequently, factor scores were calculated using the standardized coefficients obtained from FA (Cruz-Jesus et al., 2012).

The general trend is the considerable progress in the e-mobility domain, particularly evident among both the leaders and the green mobility-focused countries. However, EU members face challenges in the renewables dimension, with many of them showing only minor progress or a decrease. Curiously, despite the bad performance in green mobility, Estonia presents substantial growth in the RE dimension, moving from the worst quadrant to a more favorable position in the first quadrant, indicating a positive shift from being a laggard to a green energy-focused country.

Back to the e-mobility dimension, countries belonging to sustainable leaders, green mobility-focused, and sustainable balanced clusters present a huge gain, moving in a vertical way, from the bottom to the top position. In contrast, many of them show poor performance or even a decrease in the other dimension, suggesting that increased allocation in one dimension may negatively impact investment in another dimension.

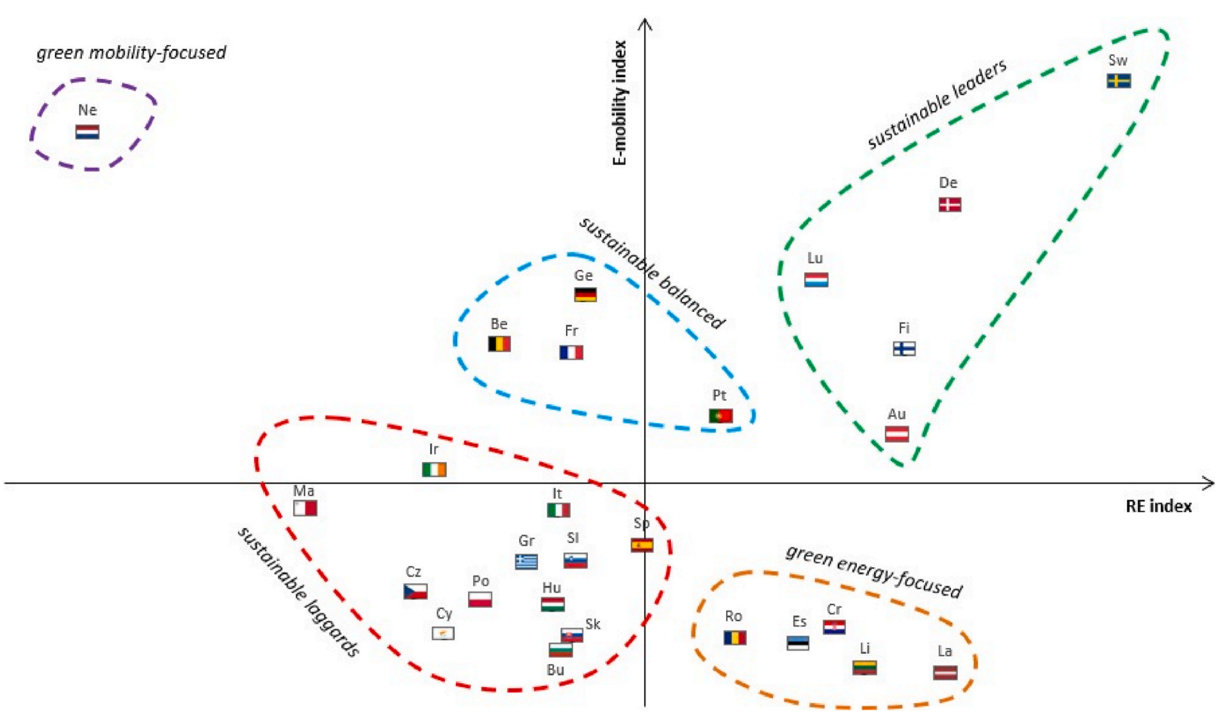

Fig. 1. CA using the factor scores for 2020.

Table 5
Average for the identified clusters.

	Sustainable laggards	Green energy- focused	Sustainable balanced	Sustainable leaders	Green mobility- focused	Overall AVG
RE index	−0.61	0.84	−0.22	1.28	−2.44	−0.23
E-mobility index	−0.53	−0.97	0.75	1.23	2.03	0.50

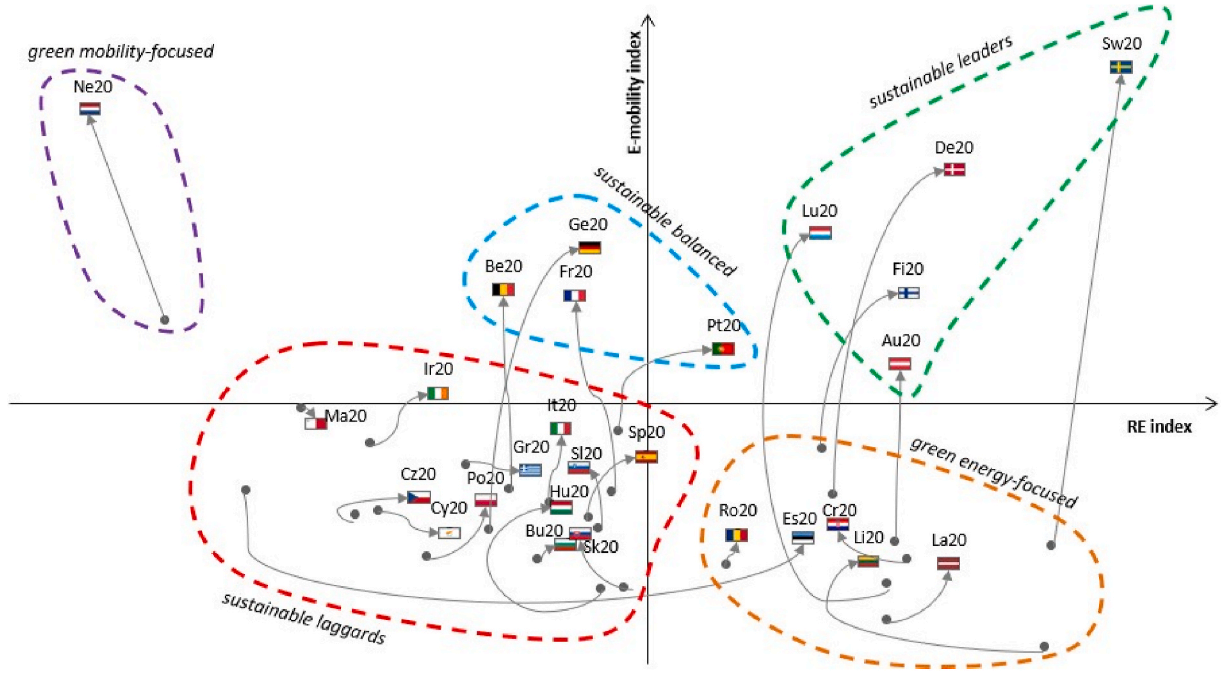

Fig. 2. Movement of the EU-27 countries in the two dimensions between 2018 and 2020.

Notably, Denmark, Finland, Germany, Ireland, Latvia, Poland, Portugal, Spain, and Sweden achieved significant advancements in both dimensions simultaneously, moving diagonally from the bottom-left to the top-right, demonstrating a balanced development strategy.

One interesting thing to point out is the fact that the number of laggard countries suffered a considerable decrease between 2018 and 2020, confirming the concern and commitment of EU members in facing the climate crisis, with the adoption of regulations and policies. Thus, this number is expected to continue to drop as the countries will continue to boost their innovation in environmental aspects and international agreements will be yielded. Also, supporting this idea is the fact that no country worsened both dimensions. EU members that have joined sustainable leaders and sustainable balanced clusters did so because of the positive shift demonstrated.

Estonia was the only one that did not improve in the e-mobility dimension while improving in the RE dimension the most. In contrast, all the other countries concentrated on green mobility, with the Netherlands and Luxembourg presenting one of the biggest

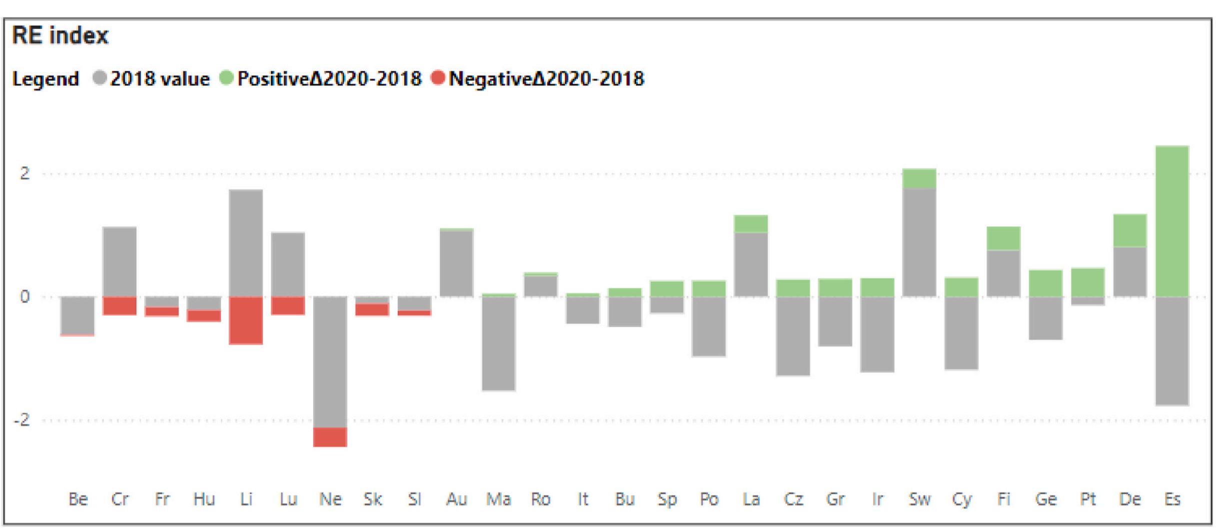

Fig. 3. Evolution of EU members in RE dimension.

developments on this index and neglecting the RE topic. This fact leads us to consider that, generally, when one country focuses on one dimension, it tends to overlook the other. Figs. 3 and 4 provide a more detailed analysis of the evolution of EU members, primarily aiming to detect whether imbalances among EU nations respecting each factor are narrowing or widening. The base value of zero, as factor scores are standardized, represents the average for each dimension in 2020.

In 2018, most countries fell short of the 2020 average in RE dimension. However, the progress between 2020 and 2018 was evenly distributed across nations, suggesting EU-wide policies could be effective. Notably, Estonia improved the most, moving from a poor performer to a leader in this dimension. Meanwhile, Sweden, Finland, and Denmark, already above average in 2018, reenforced their lead, indicating they were ahead by two years due to early adoption of incentivizing renewable energy policies.

Fig. 4 shows uneven progress in e-mobility across EU countries. While some nations made notable advances, these advancements weren't uniformly distributed, alerting for an unbalanced approach. In 2018, apart from the Netherlands, all EU members were below average, indicating poor performance. The Netherlands' two-year lead indicates effective early adoption of e-mobility strategies. Curiously, while Luxembourg and the Netherlands showed significant improvements in e-mobility, their performance in renewable energy worsened. In contrast, Estonia presented the opposite trend, underscoring the challenge of achieving balanced progress across both dimensions.

One interesting fact is that the majority of the best-ranked countries in terms of progress in both indexes belong to the sustainable leaders and sustainable balanced clusters, indicating a strong commitment to employ sustainable practices.

Table 6 shows the variability for each dimension for the years 2018 and 2020.

Table 6 shows that the variation in the RE index decreased from 2018 to 2020, indicating a narrowing asymmetry in this dimension. In contrast, the variation in the e-mobility index increased significantly, reflecting a widening asymmetry in e-mobility adoption. Figs. 3 and 4 support these results as described above.

5. Discussion

5.1. Discussion of the findings

The analysis assents on two latent dimensions related to environmental indicators, "RE index" and "e−mobility index". The first factor describes the utilization of RE, while the second dimension expresses the adoption of electric transportation.

Table 6
Standard deviation for each dimension in 2018 and 2020.

	RE index	E-mobility index
Std18	1.11	0.23
Std20	1	1
ΔStd20-Std18	**−0.11**	**0.77**

Answering the first RQ, the factor scores of EU countries reveal that Denmark, Luxembourg, and Sweden followed by Austria and Finland have the highest levels in both dimensions. As a result, those nations are labelled as "sustainable leaders". This classification aligns with findings from prior studies that recognized those nations as the top-ranked in sustainability indicators (Šoja et al., 2016; Cucchiella et al., 2017; Cheba et al., 2022; Starostka-Patyk et al., 2024). Moreover, as mentioned in the literature review section, boosting RE and e-mobility fosters the growth of low-carbon emissions (Dixon et al., 2023). Therefore, being placed in the best quadrant, those countries are mitigating climate change.

To answer the second RQ, through CA, we group the countries into five homogenous profiles within them, but heterogenous between them. This allows a simple and improved analysis rather than considering the EU countries individually, providing interesting insights on the environment development stage of each profile – sustainable leaders, sustainable balanced, green mobility-focused, green energy-focused, and sustainable laggards. Evidence proves there are significant inequalities between EU countries regarding the dimensions found. Leading the evolution, we have the "sustainable leaders" countries whose behavior must be followed by the laggards' countries, creating ways to foster both factors at the same time. Furthermore, these findings find support in various articles. Limb (2023), King (2023), van Halm (2023), and Jaworski et al. (2023) defined the same countries as frontrunners in RE, aligning with the results of this study. This consistency indicates the ongoing commitment of these countries to increasing their share of RE sources. In the same direction, the LeasePlan (2022) article supports the leadership of the countries in EVs. Also, the authors call attention to the necessity for diversified actions in clean energy projects and express hope for a cleaner world in the upcoming years.

Simultaneously, CA points out the groups of countries facing challenges in one or the two dimensions, revealing that some EU countries put their effort into a single dimension, neglecting the other. For instance, countries belonging to the green energy-focused cluster must focus on vertical advancement, going from bottom to top position, by motivating the adoption of EVs, to complement RE effort. In contrast,

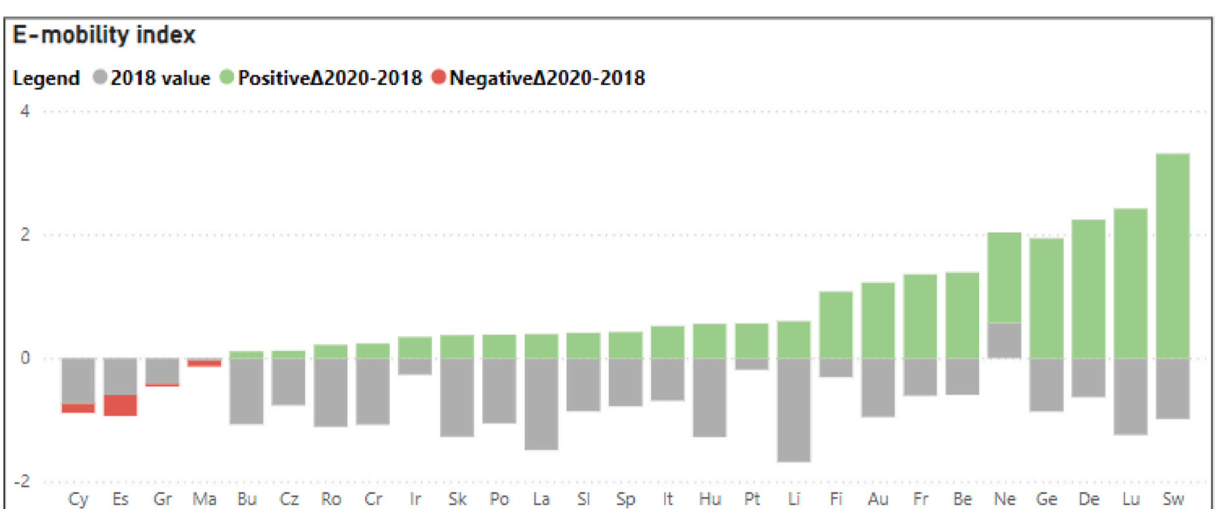

Fig. 4. Evolution of EU members in e-mobility dimension.

the green mobility-focused country must prioritize horizontal direction, going from left to right position, putting their effort into RE infrastructure. These countries are performing well in one dimension, so contrary to laggards, they only need to concentrate on one dimension. To overcome this gap, they can learn from sustainable leaders and implement some of their policies, fostering environmental sustainability.

Although CA offers an effective way of grouping countries based on their characteristics, it does not provide any insight into the reasons behind these disparities. To better understand what causes the level of inequality between the profiles found, answering the third RQ of this paper, we conducted an analysis to discover the factors contributing to this. In particular, we investigated countries' environmental programs, year of entry into the EU, and education level as higher literacy is associated with a greater understanding of the urgency and necessity to combat climate change (Filho et al., 2023).

Most of the sustainability laggards' countries (apart from Greece and Ireland) joined the EU in 2004 or later (European Commission, n.d.), a statistic that may be reflected in the disparities observed across the region. However, with the introduction of EU funds, social programs, agreements, and innovation initiatives, we anticipate a positive shift towards sustainability. Notably, between 2018 and 2020, significant improvements have already been registered, indicating the effectiveness of these policies. In addition, the sustainable leaders have implemented a set of policies aimed at motivating commitment to fight global warming, and as the results demonstrate, those environmental strategies applied by the leaders' countries, individually, have played a crucial role in shaping this division and contributing to the disparities found.

Thus, it is important to understand what strategies can be employed to motivate the citizens to opt for sustainability choices. These initiatives include public investments in charging infrastructure to increase the availability of fast charging stations and offering free parking for EV users (Arora and Gargava, 2023). Additionally, measures such as government incentives - which involve subsidies for home charging infrastructure, increased fees for fossil-fuel-powered vehicles, registration fee reductions, and increased consumer awareness of incentives - can significantly motivate the adoption of zero-emission vehicles (Jenn et al., 2018; Liu et al., 2023). The biggest obstacle in encouraging European consumers to purchase EVs lies in their affordability. Nonetheless, with technological advancement they will become economically viable options, with more powerful batteries, opening doors for lower-income countries to embrace this sustainable transportation solution (Jaeger, 2023).

To stimulate the transition to RE sources, countries provide financial incentives such as subsidies, tax credits, feed-in tariffs, and green certificate schemes (Johansson and Turkenburg, 2004; Scha ffer et al., 2014). Looking ahead, in the future, strategies may involve the installation of photovoltaic systems, and EV chargers in supermarkets, parks, malls, and hotels. (Thebault and Gaillard, 2021; Mastoi et al., 2022; Şirin et al., 2023), and adoption of RE systems for a green transport structure (Mathiesen et al., 2008). These measures are seen as a powerful step towards a sustainable future. Evidence shows that if governments are willing to spend trillions of euros, countries will be able to power themselves using their own RE sources by 20230 (Katanich, 2023).

Despite the financial boost, promoting public awareness and education on clean energy is also essential to alert citizens to the climate's consequences (Almulhim, 2022; Keller et al., 2022). Piao and Managi (2023) suggested that higher education levels demonstrate more awareness and environmentally friendly attitudes. Therefore, investing in education contributes to drawing a path to a sustainable outcome. Our findings reveal a clear correlation between the education choices of EU members and their positions in sustainable development within the EU. Particularly, the countries with top education systems belong to the clusters of sustainable balanced and sustainable leaders (Zia, 2023; "These Are the Countries With a Well-Developed Public Education System", n. d.).

To answer both the fourth and last QR, EU countries' paths were plotted between 2018 and 2020 (Fig. 2). This movement is reflected in the two dimensions identified, as the final cluster solution is similar to the clustering based on the original variables. This similarity guarantees the extracted factors accurately represent the original dataset.

The tendency within the EU provides insight into the degree of unity among EU nations in the fight against climate change. Between 2018 and 2020, there was a notable decline in the number of laggards, suggesting a shift in favor of sustainable practices within the EU. This trend implies a collective effort towards addressing environmental challenges, as countries demonstrate cooperation to adopt more environmental policies and initiatives. Moreover, the continuous decrease in the laggards' number indicates a positive trajectory and reinforces the idea of EU nation's collaboration.

Over the three-year period, the already mentioned leaders have distinguished themselves as frontrunners, due to their continuous advancements in sustainable practices, primarily in e-mobility. Notably, Denmark, Finland, Germany, Ireland, Latvia, Poland, Portugal, Spain, and Sweden have demonstrated growth in both e-mobility and RE. Curiously, in 2018, no country held a leadership position. Moreover, the leaders had a higher evolution on the e-mobility index, together with the Netherlands, emerging from laggards to sustainable leaders and a green mobility-focused country, respectively. Also, Belgium, France, Germany, and Portugal have made the jump, progressing from laggards to achieving a balanced sustainability position. Overall, the narrowing asymmetries between the RE index and the e-mobility index emphasize the collective progress made by EU nations, with significant improvements observed in at least one index, particularly in e-mobility.

Overall, all countries show positive advancements in at least one index. This indicates a growing awareness, perception, and motivation to drive into environmentally friendly practices, underscoring a collective commitment to combat the ongoing climate disaster. However, the fact that some countries present disparities in the two dimensions, with high levels in one dimension while displaying low levels in the other, alerts the environmental imbalances as there are countries that just prioritize one dimension, ignoring the other. This evidence compromises the collective efforts of the EU toward achieving Sustainable Development Goals as RE and e-mobility adoption must be balanced. Hence, all countries must adopt strategies that promote balanced and identical environmental development. This involves prioritizing the use of renewables as the primary sources of energy while shifting to electrically powered transport.

5.2. Limitations and future research

One of the limitations of this paper is its focus only on EU countries. To enhance future research, it is recommended to extend the analysis by including countries outside the EU, with a focus on comparing North America and the EU, considering their predominance as major economies. Additionally, variables were normalized by population size and not taking into account economic measures. We recognize that this can also be seen as a limitation, and we acknowledge this possibility for future research. Moreover, the number of variables used might be considered restricted given the enormous area of sustainability. So, future studies should consider other features such as the number of charging stations (providing a more detailed investigation of the infrastructure supporting RETs), challenges and barriers to RETs promotion, and countries policies against global warming (fiscal benefits, for example). Lastly, the period of the analysis, from 2018 to 2020, may be outdated. Since then, international climate conferences, such as Conference of Parties, have taken place, intensifying efforts in addressing this crisis – new measures and initiatives may have been implemented. The study focuses on the 2018–2020 period to capture key EU climate investments in renewable energy and e-mobility, aligning with major policy milestones like the EU Green Deal and Just Transition Fund. While the timeframe is short, it provides valuable insight into EU countries' progress toward sustainability amid significant policy changes. As one of the first studies of its kind, it offers an initial snapshot of member states' sustainability efforts during a crucial transition period.

6. Conclusions and policy implications

This paper's aim is to describe the sustainable levels of each EU country based on a multivariate statistical approach. First, FA was performed to identify two key dimensions: the RE index and the e−mobility index. The first concentrates on the utilization of RE, while the second evaluates the adoption of e-mobility. Second, CA was conducted to compare the 27 EU members based on these dimensions and group them into five distinct profiles according to their similarities. Evidence revealed a considerable distance between countries concerning their sustainable levels. The exploration of each country's path between 2018 and 2020 indicates that nations are building the right path towards sustainability collectively, working as a unit towards a common goal of reversing climate change. The objective for the upcoming years should be to manage efforts to ensure consistent growth in both indexes. At least, while the gap in e-mobility is widening, the gap in the other dimension is narrowing. While many EU countries have made significant advancements in one of the two dimensions, a coordinated strategy is needed to ensure equitable progress in both dimensions. This study therefore suggests that while the EU is making progress towards sustainability goals, disparities among member states must be actively addressed to achieve collective climate objectives. Therefore, several policy implications can be recommended.

First, a key policy implication of this study is the need for targeted policies that support lagging countries in closing the sustainability gap. Closing the sustainability gap between EU nations requires recognizing that each country's profile is shaped by a combination of industry structure, geographical location, and political priorities. A sector-specific approach can enhance policy effectiveness. For instance, in countries with high renewable energy adoption, such as Sweden and Denmark, as found in the results, the focus should shift toward improving grid efficiency and energy storage capacity. For example, Germany was one of the countries showing greatest improvement on the RE dimension. This country has strong energy programs such as the KfW Renewable Energy Program (European Directorate-General for Energy, 2025b) providing financial incentives for grid modernization and energy storage, setting an example for other EU nations. Meanwhile, in countries like Cyprus or Malta, where coal-based energy still dominates, targeted policies should prioritize financial support for renewable energy infrastructure development and just transition strategies to support workers in fossil fuel-dependent industries. This is especially relevant in the case of Malta that totally relies on fossil fuel imports and is the country with the lowest share of renewables in gross inland energy consumption. The EU's Just Transition Fund plays a crucial role here, but further investment is needed to ensure an equitable energy transition. It is therefore important to enhance financial and regulatory support mechanisms, such as increased funding of the Green Deal, the Just Transition Fund (European Commission, 2021), and the New European Bauhaus initiatives (European Commission, 2024a), among others. Additionally, most of the countries with lower scores on these dimensions are also considered widening countries. Therefore, although specific EU commissioned projects exist to support these countries, it is important for future research to assess the success of such widening initiatives. According to the EU Commission, the widening measures under the Horizon 2020 programme have initiated several changes and advancements in the research and innovation fields of these countries (European Commission, 2024b). However, it is important to make sure that these advancements are continued, guaranteeing that the funding is well implemented, and that this is reflected in both long-term research collaborations and implementation actions that go beyond the projects. Regarding e-mobility, policy priorities must align with national economic and industrial contexts. In France and Italy, where strong automotive industries exist, policy recommendations should focus on integrating EVs into public transport systems and incentivizing private sector investments in green mobility solutions. For example, the France's Bonus-Malus system rewards EV adoption while penalizing high-emission vehicles, encouraging a shift toward cleaner transportation (International Energy Agency, 2024).

Secondly, given countries' disparities, it is important to continue establishing and redefining national implementation plans together with specific milestones and performance indicators (Malah-Kuete and Messie-Pondie, 2025). Prior research suggests that countries can adopt a phased approach, focusing on strengthening carbon pricing mechanisms, enforcing emission reduction targets, and offering financial incentives to increase investments in RE and e-mobility infrastructure. Policymakers should also work closely with private industries to encourage the development of sustainable technologies and solutions (Wunderlich et al., 2019). On this topic, prior studies also suggest that the cultural and economic differences highlight the need for policymakers to perform local analysis when developing pricing mechanisms in different regions (Man and Thuy, 2025). Additionally, these plans should also consider the implementation of national-level incentives, such as subsidies and tax incentives to improve citizens investments in green technologies, especially in e-mobility. This is especially relevant for countries that are still lacking infrastructure or flexibility to effectively adjust their consumption patterns (Viadere, 2025). While EU-wide policies provide a common framework for achieving shared climate goals, the unique economic, infrastructural, and institutional contexts of each member state must be carefully considered to ensure that sustainability efforts are both effective and equitable. Given the varying levels of economic development and resource availability across the EU, a one-size-fits-all policy approach is insufficient. Instead, localized interventions tailored to each country's specific strengths and challenges are essential. For example, as results suggested, countries like Sweden, Denmark or Germany, which already have well-developed renewable energy infrastructures, are increasingly focusing on integrating renewable sources into the energy grid and expanding investment in green hydrogen technologies to further decarbonize their energy systems. Germany, for example, introduced large-scale hydrogen strategies (Directorate-General for Energy, 2025a), including substantial public funding to support the production, transportation, and storage of green hydrogen. The EU's hydrogen strategy plan has developed a comprehensive framework to support the uptake of renewable and low-carbon hydrogen. Similarly, Denmark is advancing its Energy Islands initiative (European Commission, 2025), which aims to establish offshore wind hubs that will supply green electricity to surrounding nations. This initiative covers 14 EU countries with large island populations, including the identified sustainable laggards such as Croatia, Cyprus, Greece, Ireland, Italy, Spain, being therefore a positive initiative to change their position regarding clean energies. In contrast, countries where fossil fuel dependency remains high, require targeted investments in e-mobility infrastructure and renewable energy expansion. Governments in Poland, Hungary, and Romania have introduced tax incentives and direct subsidies for electric vehicle (EV) adoption, alongside funding programs for the expansion of charging networks, translating in vertical shifts as results suggested. For example, in Poland, the National Fund for Environmental Protection and Water Management has been created to support and finance environmental projects (International Energy Agency, 2021). On the other side, the Netherlands stands out in the e-mobility dimension, suggesting being a reflection of the Dutch Government's ambition of achieving only zero emission passenger cars by 2030 (The Netherlands - EV Adoption, 2023).

Thirdly, one should consider that technology is needed but not enough without citizen acceptance. Therefore, education and public awareness play a crucial role. Countries with well-developed education systems tend to perform better in both RE and e-mobility dimensions, suggesting that increasing environmental literacy can significantly influence sustainability progress. Beyond financial support, disparities in knowledge and technology adoption present a significant challenge. To address this, the EU should strengthen knowledge-sharing platforms and capacity-building programs aimed at fostering technology transfer and best practices between countries. Partnerships between top and lower performance countries could be expanded through joint projects that facilitate expertise exchange. Policymakers should integrate sustainability-focused curricula in educational institutions and promote public awareness campaigns to foster behavioral change towards greener consumption and mobility patterns. Additionally, knowledge-sharing initiatives between leading and lagging countries could speed up the adoption of the best practices towards climate change mitigation and adaptation. Thus, a stronger collaboration among EU countries through coordinated policies and shared investments is key to closing the sustainability gap. Aligning national policies with EU climate goals is the only way to ensure fair contributions to the green transition. Finally, it is relevant to note that although this study is based on 2018–2020 data, the policy implications and recommendations are framed in a way that is forward-looking. The gaps identified in RE and e-mobility adoption, as well as the disparities between countries, are expected to remain relevant in the coming years. Thus, we believe that the proposed strategies for bridging these gaps through targeted financial support, tailored policies, and increased collaboration remain important.

CRediT authorship contribution statement

Catarina Coelho: Writing – original draft, Visualization, Software, Resources, Investigation, Formal analysis, Conceptualization. **Catarina Neves:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Frederico Cruz-Jesus:** Writing – review & editing, Validation, Supervision, Methodology.

Contribution statement

Our study makes a significant contribution by identifying two key dimensions of the current climate investment trends—electric mobility (e-mobility) and renewable energy (RE)—using factor analysis, and subsequently classifying EU countries into five distinct sustainability profiles through cluster analysis. These insights highlight both the progress and the disparities in sustainability efforts across the EU. Our research underscores the importance of balanced progress in both e-mobility and RE to achieve collective environmental goals. We also explore the impact of government strategies, education, and EU membership on driving sustainable practices. By highlighting these factors, our study provides valuable implications for policymakers, researchers, and sustainability advocates. To the best of our knowledge, our paper is one of the few that provides such a detailed look at sustainability efforts within the EU, using robust statistical methods focused on the two key dimensions of sustainability. We believe this paper will connect with your journal's readers and add valuable insights to the ongoing conversation on sustainable development.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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APPENDIX A. – Literature review on optimization techniques

While this study focuses on EU-level investment patterns in renewable energy and e-mobility, it's pertinent to acknowledge related research employing iterative and optimization-based approaches in hybrid renewable energy systems (Ali et al., 2021). For instance, Nassar et al. (2023) explored a topography-based hybrid renewable electrical power system, emphasizing the significance of site-specific factors in system design. Similarly, Nassar et al. (2022) analyzed the reliability and economic aspects of isolated hybrid power systems incorporating pumped hydropower storage. These studies, though centered on localized system configurations, underscore the broader applicability of iterative methodologies in renewable energy planning and optimization. Additionally, HOMER software has been widely applied in modeling and optimizing hybrid renewable energy systems, particularly in isolated and site-specific contexts. For example, Nassar et al. (2022) designed a standalone hybrid PV/wind/diesel generator system to support energy needs during the COVID-19 pandemic, demonstrating the tool's utility for emergency infrastructure planning. Similarly, El-Khozondar et al. (2023) conducted a feasibility study using HOMER to design an isolated hybrid system, emphasizing cost-effectiveness and system reliability in off-grid scenarios. In addition to the use of iterative and scenario-based tools like HOMER, recent research has employed a variety of advanced optimization techniques to enhance the design and performance of hybrid renewable energy systems. For instance, the Whale Optimization Algorithm (WOA) has been applied for renewable energy integration and solar-to-vehicle planning, while Monte Carlo Simulation (MCS) has proven effective in evaluating power flow uncertainty in vehicle-to-grid (V2G) operations. Other studies have focused on multi-objective optimization strategies for isolated systems, balancing reliability and cost under region-specific weather conditions (Alsharif et al., 2023), and leveraging feature selection techniques for hybrid system sizing and energy management (Ahmed et al., 2023)). Although these methods are beyond the scope of the current policy-level analysis, they demonstrate the diversity of tools available for techno-economic optimization and system planning in renewable energy contexts. Each optimization method used in renewable energy system planning involves specific limitations and uncertainties. For example, HOMER's outcomes can be constrained by predefined load profiles, cost assumptions, and lack of dynamic control modeling, which may limit its realism in complex, real-time systems. Algorithms like WOA are sensitive to parameter tuning and may converge prematurely to local optima if not carefully calibrated. In general, uncertainties in weather data, cost fluctuations, and system behavior under real-world conditions can affect the robustness and generalizability of results across these methods. Therefore, while such tools are valuable for scenario exploration and design, their outputs should be interpreted within the context of these limitations.

APPENDIX B. – Renewable energy production details

The SHARES Manual[1] outlines the methodology employed to determine the proportion of energy derived from renewable sources.

In this methodology, hydroelectric power is averaged over several years to reduce the impact of weather-related fluctuations and does not include pumped-storage hydro. Wind energy is also averaged, with data from 2021 onward distinguishing between onshore and offshore wind in accordance with the RED II directive. Solar energy figures encompass both photovoltaic systems and solar thermal power.

Other renewable electricity sources include energy produced from gaseous and liquid biofuels, renewable municipal waste, geothermal sources, and marine energy such as tides, waves, and ocean currents. However, only electricity generated using certified compliant liquid biofuels is eligible for inclusion. From 2021 onwards, as mandated by RED II, solid and gaseous biofuels used in larger installations must also meet sustainability standards and greenhouse gas (GHG) emission reduction criteria.

In the heating and cooling sector, renewable sources include solar thermal systems, geothermal energy, ambient heat captured through heat pumps, and from 2021 onwards, renewable cooling technologies in line with RED II. This category also includes solid, liquid, and gaseous biofuels, as well as the renewable portion of waste. Similar to electricity, only heat produced using compliant liquid biofuels is counted. Solid and gaseous biofuels used in large-scale systems must also comply with sustainability and GHG savings requirements starting in 2021 under RED II.

Additionally, RED II has revised the weighting factors for renewable electricity used in various modes of transportation, influencing how contributions from renewables in this sector are calculated.

The SHARES tool ensures consistency across EU Member States by providing a standardized approach to calculating the share of energy from renewable sources. This harmonized methodology minimizes discrepancies that could result from using different calculation techniques or assumptions, promoting reliable and comparable reporting across the EU.

[1]https://ec.europa.eu/eurostat/web/energy/database/additional-data#Short%20assessment%20of%20renewable%20energy%20sources%20(SHARES).

APPENDIX C

Table C.1
Correlation Matrix

	RE consumption	RE production	CO2 cars	Battery EVs	E-scooter users	Plug-in Hybrid EVs	Fossil fuels
RE consumption	1,0	0,8	-0,07	0,03	0,3	-0,04	-0,06
RE production		1,0	-0,3	0,4	0,4	0,3	-0,6
CO2 cars			1,0	-0,6	-0,4	-0,6	0,06
Battery EVs				1,0	0,5	0,8	-0,1
E-scooter users					1,0	0,6	-0,3
Plug-in Hybrid EVs						1,0	-0,1
Fossil fuels							1,0

Table C.2
KMO value for each variable

Variable Name	KMO
Battery EVs	0.489
E-scooter users	0.742
Plug-in Hybrid EVs	0.653
CO2 cars	0.687
RE production	0.640
RE consumption	0.661
Fossil fuels	0.713
Overall KMO	**0.648**

Table C.3
Eigenvalues and Cumulative Variance for each factor

Factor	Eigenvalue	Cumulative Variance
1	3.639	0.374
2	1.543	0.740
3	0.693	0.839
4	0.499	0.910
5	0.350	0.961
6	0.175	0.986
7	0.101	1.000

Table C.4
Communality for each variable

Variable Name	Communalities
Battery EVs	0.740
E-scooter users	0.691
Plug-in Hybrid EVs	0.785
CO2 cars	0.692
RE production	0.753
RE consumption	0.774
Fossil fuels	0.747

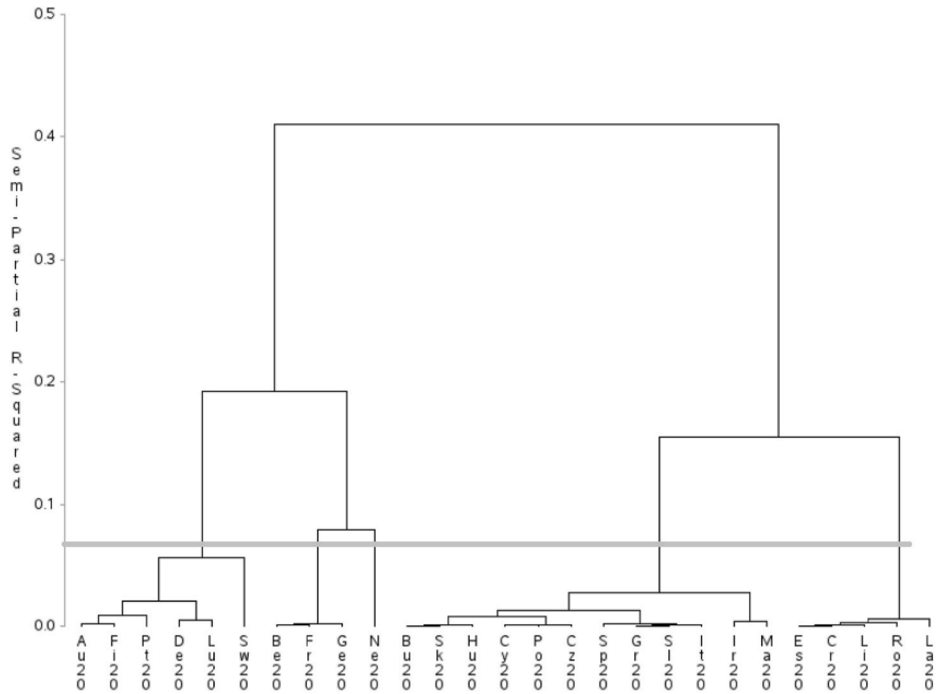

Fig. C.1. Dendrogram using Wards.

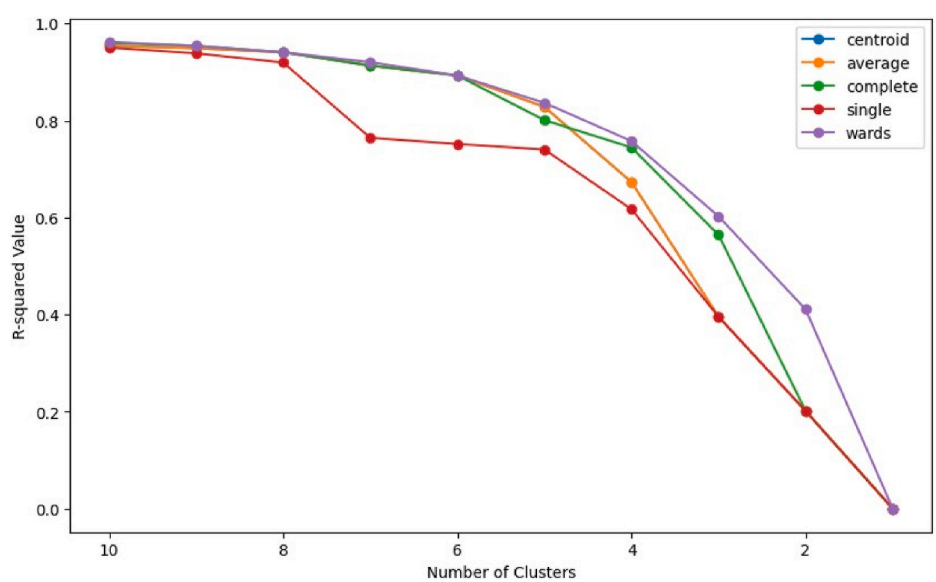

Fig. C.2. R-squared Values for Hierarchical Clustering with Different Linkage Methods.

Data availability

Data will be made available on request.

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