FULFILL

Fundamental decarbonisation
through sufficiency by lifestyle changes

Quantitative evaluation of the macroeconomic impacts of up-scaled sufficiency action at the European level

FULFILL Deliverable D 6.2

Place: Bolzano

Fundamental decarbonisation through sufficiency by lifestyle changes

GA#: 101003656

Deliverable number (relative in WP)	**D 6.2**
Deliverable name:	**Quantitative evaluation of the macroeconomic impacts of up-scaled sufficiency action at the European level**
WP / WP number:	N° 6
Delivery due date:	31.05.2024
Actual date of submission:	17.06.2024 Version 2: 07.08.2024
Place	Bolzano
Status	Final
Dissemination level:	Public
Lead beneficiary:	Eurac Research, Politecnico di Milano
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FULFILL has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003656.

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Acknowledgement

FULFILL has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003656.
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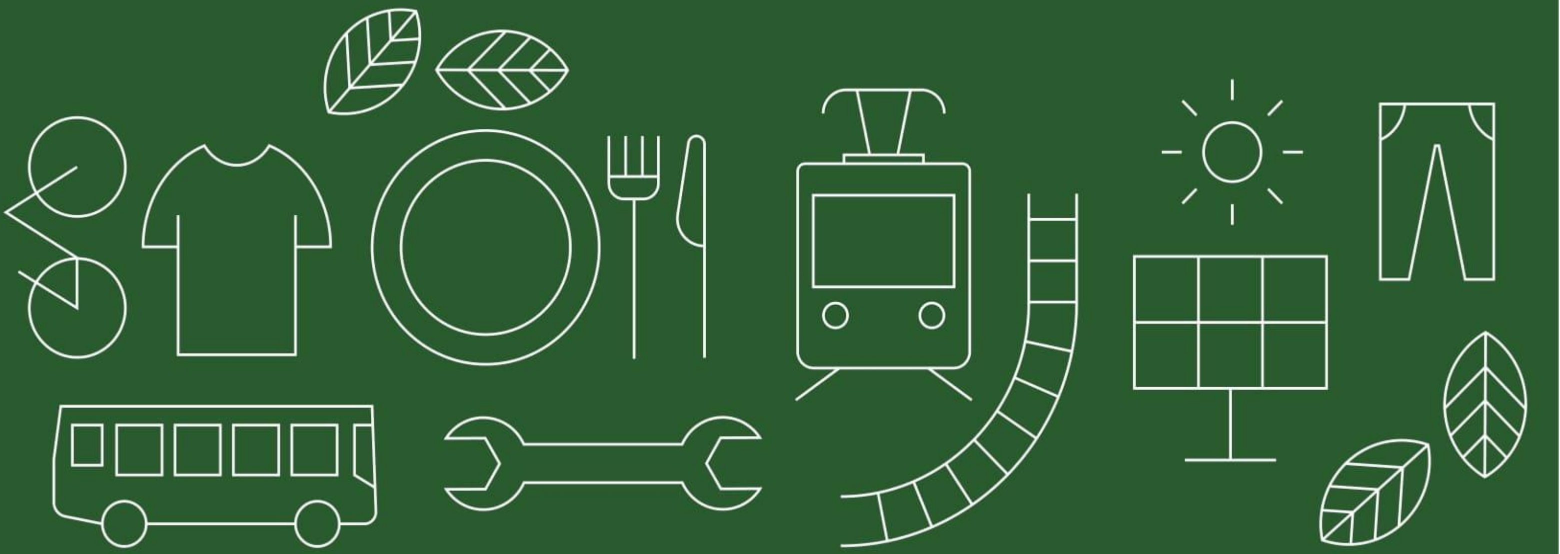

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List of Abbreviations

AIC	Akaike Information Criterion
ARIMA	Auto Regressive Integrated Moving Average
BEV	Battery Electric Vehicles
EU	European Union
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GWP100	Global Warming Potential at 100 years
HH	Households
ICEV	Internal Combustion Engine Vehicle
IO	Input-Output
MARIO	Multi-Regional Analysis of Regions through Input-Output
MS	Microsoft
NECP	National Energy and Climate Plan
RoW	Rest of the World
SSH	Social Sciences and Humanities
SUT	supply-use input-output table
t	tonnes
vkm	vehicle-km
WCSS	within-cluster sum of squares

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Abstract / Summary

This deliverable presents the method and results of assessing the potential impacts of a selection of sufficiency scenario measures on greenhouse gas emissions, Gross domestic product (GDP), and employment in the European Union (EU) and the rest of the world (RoW). An input-output model based on the Exiobase v3.3.18 database was employed, with adjustments made to represent the sufficiency scenario assumptions and background changes up to 2050. The input data from five FULFILL countries (Italy, France, Germany, Latvia, and Denmark) was extended to all EU countries using a clustering approach.

Six sufficiency scenario assumptions were modelled: diets, moderate car sizing, cycling more, flying less, sharing spaces in housing, and sharing products. The results show that dietary changes and reduced air travel have a large potential for reducing greenhouse gas emissions. By 2050, the sufficiency scenario assumptions could lead to a 13% reduction in emissions within the EU compared to a scenario without these measures. However, the measures also result in a ~4% reduction in GDP and a decrease of ~20 million jobs within the EU by 2050, with even more significant job losses in the RoW.

The deliverable discusses the limitations of the study, such as the exclusion of rebound effects and the assumptions made in extending the input data to all EU countries. Despite these limitations, the findings highlight the potential of sufficiency scenario assumptions to complement technological solutions in achieving decarbonization targets, while also emphasizing the need to manage the economic and social implications of these measures carefully.

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Introduction and Overview

Purpose of this Document

The purpose of this document is to clarify the method employed in translating the results from Task 6.1 (explained in detail in Deliverable 6.1), which estimated and quantified sufficiency scenario assumptions, into inputs for a global input-output model. This document details the adjustments made to the underlying database of the model and describes the clustering method used to extend the inputs from only five countries to all European countries. Furthermore, it presents the results of the potential socio-economic impacts and, with particular detail, the reductions in greenhouse gas emissions achievable through these sufficiency scenario assumptions.

Project Summary

The project FULFILL takes up the concept of sufficiency to study the contribution of lifestyle changes and citizen engagement in decarbonising Europe and fulfilling the goals of the Paris Agreement. FULFILL understands the sufficiency principle as creating the social, infrastructural, and regulatory conditions for changing individual and collective lifestyles in a way that reduces energy demand and greenhouse gas emissions to an extent that they are within planetary boundaries, and simultaneously contributes to societal well-being. The choice of the sufficiency principle is justified by the increasing discussion around it, underlining it as a potentially powerful opportunity to actually achieve progress in climate change mitigation. Furthermore, it enables us to go beyond strategies that focus on single behaviours or certain domains and instead to look into life-styles in the socio-technical transition as a whole. The critical and systemic application of the sufficiency principle to lifestyle changes and the assessment of its potential contributions to decarbonisation as well as its further intended or unintended consequences are therefore at the heart of this project. The sufficiency principle and sufficient lifestyles lie at the heart of FULFILL, and thus constitute the guiding principle of all work packages and deliverables.

Project Aim and Objectives

- To achieve this overarching project aim, FULFILL has the following objectives:
- Characterise the concept of lifestyle change based on the current literature and extend this characterisation by combining it with the sufficiency concept.
- Develop a measurable and quantifiable definition of sufficiency to make it applicable as a concept to study lifestyle changes in relation to decarbonisation strategies.
- Generate a multidisciplinary systemic research approach that integrates micro-, meso-, and macro-level perspectives on lifestyle changes building on latest achievements from research into social science and humanities (SSH), i.e. psychological, sociological, economic, and political sciences, for the empirical work as well as Prospective Studies, i.e. techno-economic energy and climate research.
- Study lifestyle change mechanisms empirically through SSH research methods on the micro- (individual, household) and the meso-level (community, municipal):
  - achieve an in-depth analysis of existing and potential sufficiency lifestyles, their intended and unintended consequences (incl. rebound and spillover effects), enablers and barriers (incl. incentives and existing structures) as well as impacts (incl. on health and gender) on the micro level across diverse cultural, political, and economic conditions in Europe and in comparison to India as a country with a wide range of economic conditions and lifestyles, an history which encompasses simple-living movements, and a large potential growth of emissions.

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    - assess the dynamics of lifestyle change mechanisms towards sufficiency on the meso-level by looking into current activities of municipalities, selected intentional communities and initiatives as well as analysing their level of success and persisting limitations in contributing to decarbonisation.
- Integrate the findings from the micro and meso-level into a macro, i.e. national and European, level assessment of the systemic implications of sufficiency lifestyles and explore potential pathways for the further diffusion of promising sufficiency lifestyles.
- Implement a qualitative and quantitative assessment of the systemic impact of sufficiency lifestyles which in addition to a contribution to decarbonisation and economic impacts includes the analysis of further intended and unintended consequences (incl. rebound and spillover effects), enablers and barriers (incl. incentives and existing structures) as well as impacts (incl. on health and gender).
- Combine the research findings with citizen science activities to develop sound and valid policy recommendations contributing to the development of promising pathways towards positive lifestyle change
- Generate findings that are relevant to the preparation of countries' and the EU's next NDCs and NDC updates to be submitted in 2025 and validate and disseminate these findings to the relevant stakeholders and institutions for exploitation.
- Consider the relevance and potential impacts of sufficiency lifestyles beyond the EU.

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1. Methodology

To assess the impact of the sufficiency scenario assumptions using the data provided by Task 6.1, an input-output (IO) model is employed. To accurately capture these measures, the IO model must possess certain characteristics that are not inherent to any existing database. One database closely meets these requirements and was extended within this project through the endogenization of specific final consumption sectors that are typically not explicitly represented in such models. The process is explained in detail in this chapter.

Additionally, the input data from Task 6.1 only covers five European countries, necessitating a clustering approach to extend the analysis to all European countries. This method is also explained in this chapter.

1.1. Impact assessment as comparison between *Sufficiency* and *Reference* scenarios

A *Sufficiency* scenario is a set of inputs that represents at least one sufficiency scenario assumption. The difference between the *Reference* and *Sufficiency* scenarios lies in the changes in final consumption based on the input-output database, "where the reference scenario already includes a transition process which does not take into account sufficiency measures. Also contained within the reference scenario is the decarbonization of power and electrification of some final uses.

On top of these background variations, sufficiency scenario assumptions can be either included or excluded. The *Sufficiency* scenarios model the changes taking place in presence of the measures in addition to the existing background changes, while the *Reference* scenario only include the background changes (see Figure 1).

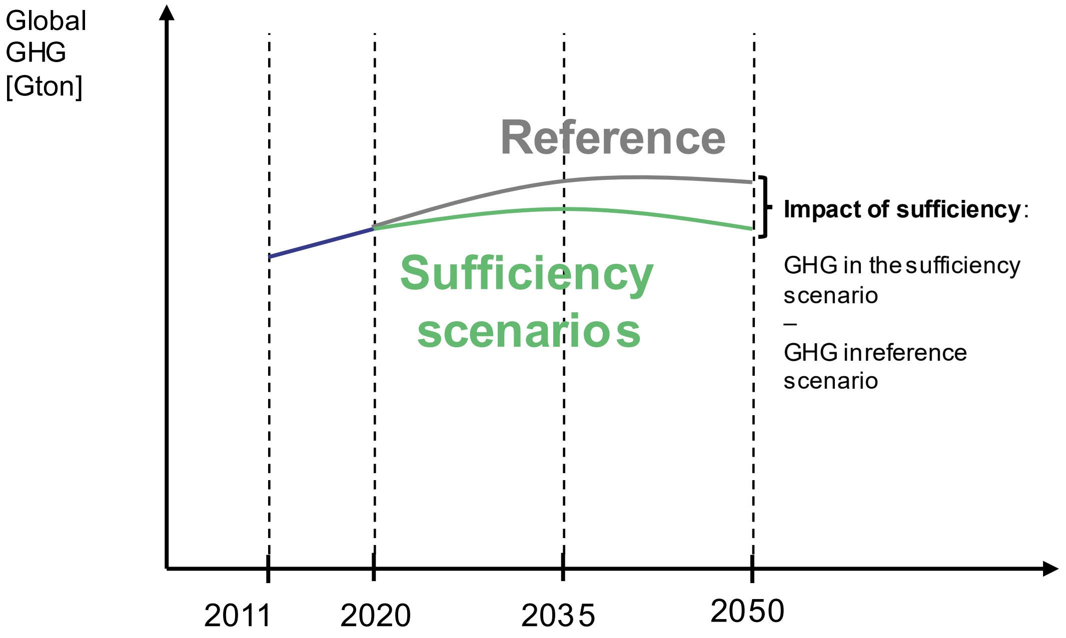

Figure 1 – Qualitative representation of how impact assessment results are reported for each sufficiency scenario assumption

The subsequent chapters explain why and how these changes occur. This approach allows to isolate and evaluate the specific impact of the sufficiency scenario assumptions against the backdrop of the ongoing transitions. Essentially, one set of scenarios where sufficiency scenario assumptions are present (*Sufficiency* scenarios) and one where they are absent (*Reference* scenario). As shown in Figure 31, the impact of each measure is determined by the net variation in the input-output model's results,

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comparing the emissions of Greenhouse Gases (GHG), resource use, and socio-economic indicators between the reference scenario and the corresponding sufficiency scenario. The difference between these two impacts indicates the effect of the sufficiency scenario assumption.

However, there are limitations to this approach. Many sufficiency scenario assumptions lead to cost savings, which in reality could be reinvested in other sectors. For instance, savings on utility bills might be used by a household for additional travel. This rebound effect is considered beyond the scope of the project, as accounting for it would require numerous additional assumptions, complicating the interpretation of the results.

1.2. Assessing the impact of sufficiency scenario assumptions through Input-Output

In this chapter, we elucidate the methodology employed to evaluate the sufficiency scenario assumptions, as integrated from Task 6.1, which has quantified the nature of these measures. This evaluation has been conducted using a meso-economic input-output model.

1.2.1. Mathematical background of input-output models

Input-output tables are widely used for scenario analyses, allowing the assessment of impacts by comparing baseline and modified tables. This approach is applicable across various fields. The model used in this study is a supply-use input-output table (SUT), which distinguishes between commodities supplied and consumed by industrial activities in each country.

A SUT model allocates data about the production of commodities by industrial activities in the supply (**S**) matrix, while the use (**U**) matrix traces the commodity inputs required by each industry to produce its output(s). The final demand of commodities by households and other economic agents is represented in the **Y** matrix. The total demand of commodities vector (**Q**) is derived by summing intermediate transactions traced in **U** and **Y** (Eq. 1). The total supply of industrial activities, on the other hand, can be calculated by summing all the outputs of each activity (Eq. 2, where **i** is a vector of 1s). From this, the intermediate technical coefficients matrix is calculated, expressing intermediate transactions per unit of total production (Eq. 3) and the market shares (matrix **s**)of the activities supplying each product (Eq. 4).

$$\mathbf{Q} = \mathbf{U}\,\mathbf{i} + \mathbf{Y} \qquad \textit{Eq. 1}$$

$$\mathbf{X} = \mathbf{S}\,\mathbf{i} \qquad \textit{Eq. 2}$$

$$\mathbf{u} = \mathbf{U}\,\widehat{\mathbf{X}}^{-1} \qquad \textit{Eq. 3}$$

$$\mathbf{s} = \mathbf{S}\,\widehat{\mathbf{Q}}^{-1} \qquad \textit{Eq. 4}$$

In input-output models used for scenarios impact evaluation, environmental extensions are included to evaluate the environmental and social impacts of policies and technological interventions that acts upon the economic structure of industrial activities. The environmental transactions each industry is responsible for are captured in the **E** matrix. Other production factors, such as employee compensation and taxes, are included in the **V** matrix. Both **V** and **E** can be normalized per unit of total production to create matrices **v** and **e**, as it is shown for **u** (Eq. 5 and Eq. 6).

$$\mathbf{v} = \mathbf{V}\,\widehat{\mathbf{X}}^{-1} \qquad \textit{Eq. 5}$$

$$\mathbf{e} = \mathbf{E}\,\widehat{\mathbf{X}}^{-1} \qquad \textit{Eq. 6}$$

$$\mathbf{w} = (\mathbf{I} - \mathbf{us})^{-1} \qquad \textit{Eq. 7}$$

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To transition from direct to embedded environmental impact accounting, the direct impacts ($\mathbf{e}$) are multiplied by the Leontief inverse matrix ($\mathbf{w}$, Eq. 7) to obtain the specific footprint matrix $\mathbf{f}$ (Eq. 8). This matrix can be further detailed to attribute the footprint to upstream activities and regions $\mathbf{f_{ex}}$.

$$\mathbf{f} = \mathbf{e}\,\mathbf{s}\,\mathbf{w} \qquad \textit{Eq. 8}$$

1.2.2. Adding new activities and commodities

It is possible to extend an input-output table by adding new activities and/or commodities that are not originally traced within its sectoral granularity, following the matrix augmentation method described by (Miller & Blair, 2009). These new activities and commodities needs to be integrated within the macroeconomic picture captured by the original table, therefore the commodity inputs they require need to be mapped to the commodities traced by the table.

Operationally, the new activities and commodities are added to the hybrid Exiobase SUT by extending its matrices with:

- new columns in matrix **u**, representing the inputs to the new activities
- new rows in matrix **u** to indicate how new commodities are consumed by the activities, included the new ones
- new columns in matrix **s** to indicate how new commodities are produced by the various activities
- new rows of matrix **s** to show the outputs of the new activities
- new columns of matrix **v** to indicate the factors of production employed by each new activity
- new columns of matrix **e** representing the environmental transactions of the new activities.

1.2.3. Taxonomy of modellable interventions

An input-output (IO) model can simulate a wide range of interventions by manipulating different matrices. Each type of intervention targets specific aspects of economic activities and environmental impacts:

- Final Consumption: changes in household consumption of goods and services can be simulated by adjusting the Y matrix. This allows the model to assess the impact of varying demand patterns on overall production and environmental outcomes.
- Technological Efficiency: the u matrix can be modified to simulate increased efficiency in certain technologies or the substitution of one input for another. This reflects improvements in production processes and the adoption of more efficient technologies, leading to changes in resource use and emissions.
- Direct Inputs of Natural Resources and Emissions: similar to changes in technological efficiency, the e matrix can be adjusted to reflect modifications in the direct inputs of natural resources (such as water, land, or primary energy) to a particular activity or changes in direct emission factors. This helps in evaluating the impact of resource conservation measures and emission reduction strategies.
- Supply Shifts: the s matrix can be altered to simulate shifts in the supply of a given commodity from one technology to another. For instance, changing the electricity production mix to include more renewable sources can be modelled by adjusting the s matrix, thereby assessing the impact on both production and environmental metrics.

These interventions can also be combined to analyse more complex scenarios where multiple changes occur simultaneously. This comprehensive approach enables the assessment of integrated strategies

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for sustainability, considering the interplay between consumption, technological efficiency, resource use, and supply dynamics.

1.2.4. Limitations of input-output models

Input-output models, extensively used for economic and environmental analysis, have several inherent limitations that must be carefully considered when interpreting results for future scenarios (Miller & Blair, 2009). These models assume linear relationships between inputs and outputs, which do not account for economies of scale or technological advancements. The static nature of input-output models means they are based on a snapshot of the economy at a particular point in time, typically a single year, limiting their applicability for long-term projections. The accuracy of these models heavily depends on the quality and timeliness of the input data, which often come with significant uncertainties when projecting future scenarios.

Aggregation issues in input-output models can mask significant intra-sectoral variations, leading to potential inaccuracies, particularly in diverse sectors. The assumption of fixed technological coefficients implies that production technologies remain constant over time, which is unrealistic given the rapid pace of technological change. Furthermore, input-output models typically do not account for changes in prices and relative prices over time, affecting supply and demand dynamics.

Input-output models often exclude critical feedback loops and interdependencies between economic and environmental systems, leading to potential underestimations or overestimations of certain impacts. The simplified treatment of co-products and by-products can lead to inaccurate allocation of environmental impacts across different products and industries. Additionally, these models might not adequately capture regional and sectoral differences, resulting in generalized results that may not be applicable to specific contexts. Lastly, input-output models typically do not incorporate behavioural changes in response to policy measures or economic changes, which can be significant in real-world scenarios.

Despite these limitations, input-output models remain a valuable tool for economic and environmental assessments due to their ability to provide a comprehensive overview of complex inter-sectoral relationships. However, it is essential to complement these models with other dynamic and non-linear modelling approaches to enhance the robustness of long-term projections. By integrating multiple methodologies, researchers can better address the inherent uncertainties and limitations, providing a more accurate and holistic understanding of future economic and environmental impacts.

1.3. Database and impact categories

The study is grounded on the Exiobase v3.3.18 hybrid-units input-output database, adopted in its supply-use (SUT) version (Merciai & Schmidt, 2018). The database has a rich regional and sectoral coverage, encompassing 43 countries (including all the EU member states and their main trade partners) + 5 closing Rest of the World regions (Rest of America, Asia, Middle East, Africa and Europe), 200 commodities and 164 industrial activities, depicting global economy of 2011. It is an environmentally-extended database, covering 1000+ satellite accounts ranging from emissions of GHGs and other local pollutants, to water, primary energy and land consumption, to other social dimensions such as employed people.

Several indicators for each dimension have been analysed. For the sake of this work, the most representing indicator for each dimension of sustainability has been reported namely:

- Greenhouse Gas Emissions (GHG) in Global Warming Potential at 100 years (GWP100) in tonnes (t) of CO_2 equivalent;
- total employment in thousands of workers;
- Gross Domestic Product (GDP) in millions of euros constant values (2011)

for the environmental, social and economic dimension respectively. In the Results chapter, detailed results for these 3 indicators are reported and commented.

1.4. Overcoming database limitations

The chosen database offers significant advantages for processing the input provided by Task 6.1. In particular, it offers the advantage of using physical units for certain product categories, such as energy products, allowing for a representation that avoids the uncertainties associated with commodities' price determination. The model itself is comprehensive and representative of the economy, despite being based on data from 2011. Its limitations can be resumed as follows:

- It lacks an explicit representation of residential sectors, which are crucial for accurately modelling consumer diets, energy use in homes (particularly for heating), and private car usage. Therefore, it is necessary to introduce (i.e., endogenize) these new sectors within intermediate consumption, making it easier to update significant changes in technology-specific market shares or efficiencies (see chapters 2.3, 2.4 and 2.5).
- The database is a snapshot of the year 2011. While representing all changes from then to the present, as well as those projected up to the end of the study period (2050), is beyond the scope of this work, it is essential to update the following piece of information, for a more accurate representation: electricity mixes, private car stock mixes, heating system mixes, final demand for private transport, housing services, heating system efficiencies, and car efficiencies. Additionally, the demand for all other goods and services was also updated.

Each of these updates is performed for every year and region in the database. This was made possible by Multi-Regional Analysis of Regions through Input-Output (MARIO), an open-source package that allows for the manipulation of input-output tables (Tahavori et al., 2023).

Another limitation addressed is the lack of data availability for all 27 European countries. The analysis provided by the input provider was thorough for only five countries, referred to as FULFILL countries: Italy, France, Germany, Latvia, and Denmark. Subsequently, the data needed to be reprocessed to make it applicable to an input-output database that includes all European countries, with the appropriate proportions tailored to each country's context. This was achieved using a clustering method to identify which countries most closely resemble each of the initial five countries. Each measure has specific indicators, which will be explained further later, allowing us to map each of the non-included European countries to the appropriate cluster based on similarity to the initial five. In this way, the measures were effectively extended to all European countries.

1.5. Reference scenario for sufficiency scenario assumptions

To establish a reference scenario for the six sufficiency scenario assumptions across the five considered countries (Italy, Denmark, France, Latvia, and Germany), a methodology combining two forecasting approaches was employed. This methodology aimed to project future trends based on historical data, providing a baseline against which the impact of sufficiency scenario assumptions could be assessed.

The first approach utilized the Auto Regressive Integrated Moving Average (ARIMA) model, a popular time series forecasting technique. The ARIMA model was chosen for its ability to capture the temporal dependencies and patterns in the historical data. The auto_arima function from the pmdarima library in Python was used to automatically select the best ARIMA model for each country's time series data. This function tests various combinations of model parameters (p, d, q) and selects the optimal model based on the Akaike Information Criterion (AIC), which balances the goodness of fit with model complexity.
p stands for the number of lag observations in the model; it's the "autoregressive" part. A lag is a previous data point in a time series. For example, if p=1, the model predicts the current value based on the immediately preceding value. If p=2, it uses the last two values, and so on. This component captures the relationship between a variable's current value and its past values. d (Integrated - I Term): d refers to the degree of differencing required to make the time series stationary. Stationarity means that the statistical properties of the series (like mean and variance) are constant over time. Many time

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series models, including ARIMA, assume stationarity. Differencing is a transformation applied to the time series. A first difference (d=1) removes trends or seasonal structures by subtracting the current value from the previous value. Higher degrees of differencing (d=2, d=3, etc.) involve differencing the differenced series. q (Moving Average - MA Term): q is the size of the moving average window; it's the "moving average" part. It represents the number of lagged forecast errors that the model uses. This component helps the model to account for any randomness or unexpected shocks in the time series. Selecting the right values for p, d, q can be challenging. They are usually determined based on the autocorrelation and partial autocorrelation plots of the data, or through automated processes like grid search or, as in this case, using the auto_arima function from the pmdarima package, which automatically tests various combinations to find the best fit based on a criterion like the AIC. AIC is a measure used to compare different models. The lower the AIC, the better the model. AIC takes into account the goodness of fit of the model and the number of parameters used (encouraging simplicity).

The second approach involved fitting a logarithmic curve to the historical data. This approach assumes that the growth or change in the sufficiency scenario assumptions follow a logarithmic pattern over time. The logarithmic curve was fitted using linear regression on the log-transformed data. For both the ARIMA model and the logarithmic curve, confidence intervals were calculated to quantify the uncertainty associated with the projections. To obtain the final reference scenario for each sufficiency scenario assumption and country, the projections from the ARIMA model and the logarithmic curve were averaged. This averaging approach aimed to balance the strengths and limitations of each forecasting method and provide a more robust estimate of the future trends. This averaging approach aimed to balance the strengths and limitations of each forecasting method and provide a more robust estimate of the future trends. The ARIMA model excels at capturing short-term dynamics and autocorrelation in the data but may struggle with long-term trends. On the other hand, the logarithmic curve fitting method is more conservative for capturing long-term growth patterns but may not account for short-term fluctuations. By combining both methods, the final reference scenario benefits from the strengths of each approach while mitigating their individual limitations.

1.6. Extending input data through countries clustering

This research introduces a clustering approach to analyse sufficiency scenario assumptions and evaluate their impacts on lifestyle, energy consumption, and climate in EU 27 member states. The clustering methodology is applied at the European level using K-means, elbow, and silhouette score techniques. The objective of implementing the K-means clustering technique is to group data points into clusters such that points within the same cluster are more similar to each other than to those in other clusters. While the elbow method and silhouette score are utilized to determine the optimal number of clusters. Additionally, a constraint can be imposed in the K-means algorithm, known as "seeding," where specific data points are pre-assigned to clusters before clustering begins. For instance, in this study, the constraint that five countries ('Italy', 'Latvia', 'Germany', 'France', 'Denmark') must belong to different clusters sets the initial centroids of the clusters to be the data points corresponding to these countries.

The clustering model is applied to identify EU countries with similar consumption patterns and lifestyles, grouping them into clusters. For instance, in a clustering analysis based on dietary habits, specifically focusing on vegetable and meat consumption across the EU-27 nations, countries exhibiting similar consumption patterns may be aggregated into the same cluster. To gain insights into each EU country's lifestyle and living standards, five clusters (designated as clusters 0-4) are created. This approach aids in identifying similar consumption patterns of sufficiency scenario assumptions across EU member states. The elbow method is a heuristic technique used to identify the optimal number of clusters (k) in a dataset. It involves plotting the within-cluster sum of squares (WCSS) or the distortion for different values of k, typically ranging from 1 to some maximum number of clusters. As the number of clusters increases, the WCSS typically decreases, since smaller clusters lead to smaller distances between data points and their centroids. The silhouette score is a measure of how similar an object is to its own cluster (cohesion) compared to other clusters (separation). For each data point, the silhouette score ranges from -1 to 1. A high silhouette score indicates that the object is well matched to its own cluster and poorly matched to neighbouring clusters.

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To apply the clustering approach to diet sufficiency scenario assumptions, the study considers two widely consumed food items: meat and vegetables. For mobility, bicycles and cars are used as indicators of sufficiency scenario assumptions in EU countries. Similarly, for moderate car size sales, the study considers sales of SUVs and small cars. Furthermore, the Flying less sufficiency scenario assumption is evaluated using the indicator of air passengers carried per capita in European countries. Additionally, for sharing living spaces sufficiency scenario assumption, the average size of houses based on floor area per person and the number of rooms per person are considered. Finally, for product sharing sufficiency scenario assumptions, the study uses proxy indicators annual municipal waste generated per capita in EU countries.

2. Case studies' data and assumptions

In this chapter, the empirical and modelling evaluations undertaken to ensure a consistent representation of sufficiency scenario assumptions and background, within which they develop, is presented. The chapter is structured as follows. Each major category of necessary adjustments, whether for background representation (final demand growth, electricity mix evolution and endogenization and evolution of private consumption sectors) or for modelling the sufficiency scenario assumptions, is addressed in dedicated subchapters. These chapters explicitly reference each of the six sufficiency scenario assumptions discussed.

For each measure, two paragraphs are dedicated. The first paragraph outlines the evaluations conducted to integrate the measure into the Input-Output model. The second chapter elucidates how these evaluations are then utilized to extend the measures beyond the initial five FULFILL countries (i.e., Italy, France, Denmark, Latvia and Germany), for which complete input data were provided, utilizing a clustering approach.

2.1. Final demand growth

Being a hybrid-units database, Exiobase v3.3.18 is particularly suitable for environmental impact evaluation. However, the database is calibrated to year 2011, while the first year of the modelling observation period is 2020, and scenarios envisage projections up to 2050.

The first step of the nowcasting (from 2011 to 2020) and forecasting (2020 to 2050) processes regarded the projection of the final consumption following historical and projected trends of the GDP by country. While final consumption is an exogenous input for IO models, GDP is an endogenous output, however, there is a historical relationship between the former and the latter. The final demand has been simulated to evolve annually, reflecting changes in the economic scenario. This was achieved by running an input-output table shock, while also adjusting the total volumes of final consumption.

This adjustment is implemented in two main ways. Firstly, certain commodities directly or indirectly affected by sufficiency scenario assumptions are identified. For example, the quantity of final demand for vehicle km needed to evaluate sufficiency scenario assumptions, such as *Moderate car sizing*, is considered. These commodities are defined based on data collected for defining sufficiency assumptions and extended to other non-identified countries through the described clustering approach. For all other cases, when a product was not directly impacted by the measures, an increase in final demand in each country for all products linearly to the expected GDP growth for that country was assumed.

The starting point was the OECD database, which projects GDP per capita and population for all countries worldwide until 2050 (OECD, 2023). This projection is essential because the model adopted in this study, being global, also needs to account for the growth of non-European countries for consistency. This is crucial for evaluating the total expected impact at a global level.

2.2. Electricity mix evolution

Exiobase provides 12 different electricity production technologies: for each country, it is possible to calculate the market share of electricity production (i.e. electricity production mix). Such market shares were updated with those of 2020, based on data provided by Ember (Ember, 2024).

In order to include the environmental impact of the electricity sector, it is necessary to consider the annual evolution and trends of each country's electricity mix. Different approaches are used for different groups of countries for data collection. For European countries, the NECP (National Energy and Climate Plan) have been used as reference for the forecast. These documents, from 2019, has been submitted to the European Commission by all EU Member States. Each NECP contains all the information on actual and planned measures, including national energy plans (2021-2030), which aim to address energy efficiency, energy security, decarbonization, renewable energy, greenhouse gas emission reductions, the internal energy market, interconnections and research, innovation and competitiveness. Some of these countries have also included in the document a forecast of the energy mixes up to 2040. According to the information contained in these documents, the electricity mixes have been assessed to represent the stated policies scenario from 2020 to 2050. In many NECPs, data is

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available until 2040, but as not all countries have provided a forecast beyond 2030, a specific extrapolation has been hypothesized for those where data is missing. This consists of taking the trend between the latest available data and projecting it to 2050. In order to check and validate the results, different national policies regarding the phase-out of specific fossil fuel plants and renewable installation targets, such as the penetration of renewable energy, have been taken into account. In addition, for all European countries with imprecise or vague data in the NECP and the remaining extra-EU countries, the National Energy Master Plan and the official national document were used.

The aggregated EU results demonstrate the evolutionary trend shown in the Figure 2. It should be noted that, due to assumptions reflecting current national planning, a fully decarbonized mix is not achieved.

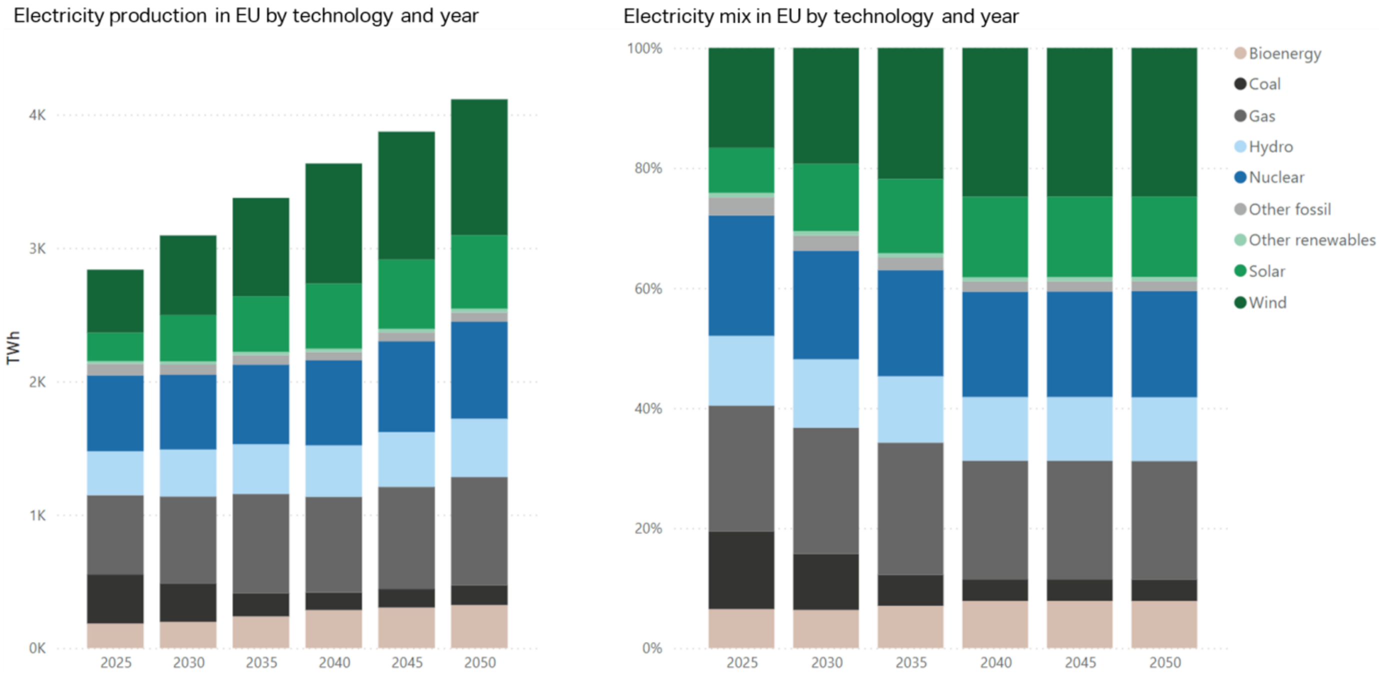

Figure 2 – Electricity production (on the left) and mix (on the right) in EU by year assumed in this study.

2.3. Endogenizing food consumption

Most input-output models obscure the effects of final consumption activities in their databases. While it could be possible, we do not alter the final demand for food item exogenously. Based on clustering results, we instead introduced a new commodity (*meals*). This change helped scale the application to all EU countries.

2.3.1. Diets

Input-output implementation and assumptions

In addition to the 164 industrial activities and 200 commodities traced by the Exiobase dataset, the model has been extended to new activities and commodities following the methodology described in Section 1.2.2.

Each diet has been characterized as a new activity in the database, consuming an inventory of food commodities (which have been properly mapped to the commodities traced in Exiobase considering dry matter conversions) and producing the daily meals consumed per capita. The food consumption by diet is provided in Table 1.

The implementation of the sufficiency scenario assumption related to dietary change (Diets) is modelled by updating the market shares of various diets within the meals commodity (Figure 3). This simulates a gradual and country-specific shift from omnivorous diets to vegetarian, vegan, and pescetarian options. For details, see Deliverable 6.1 (Jacob & Taillard, 2024).

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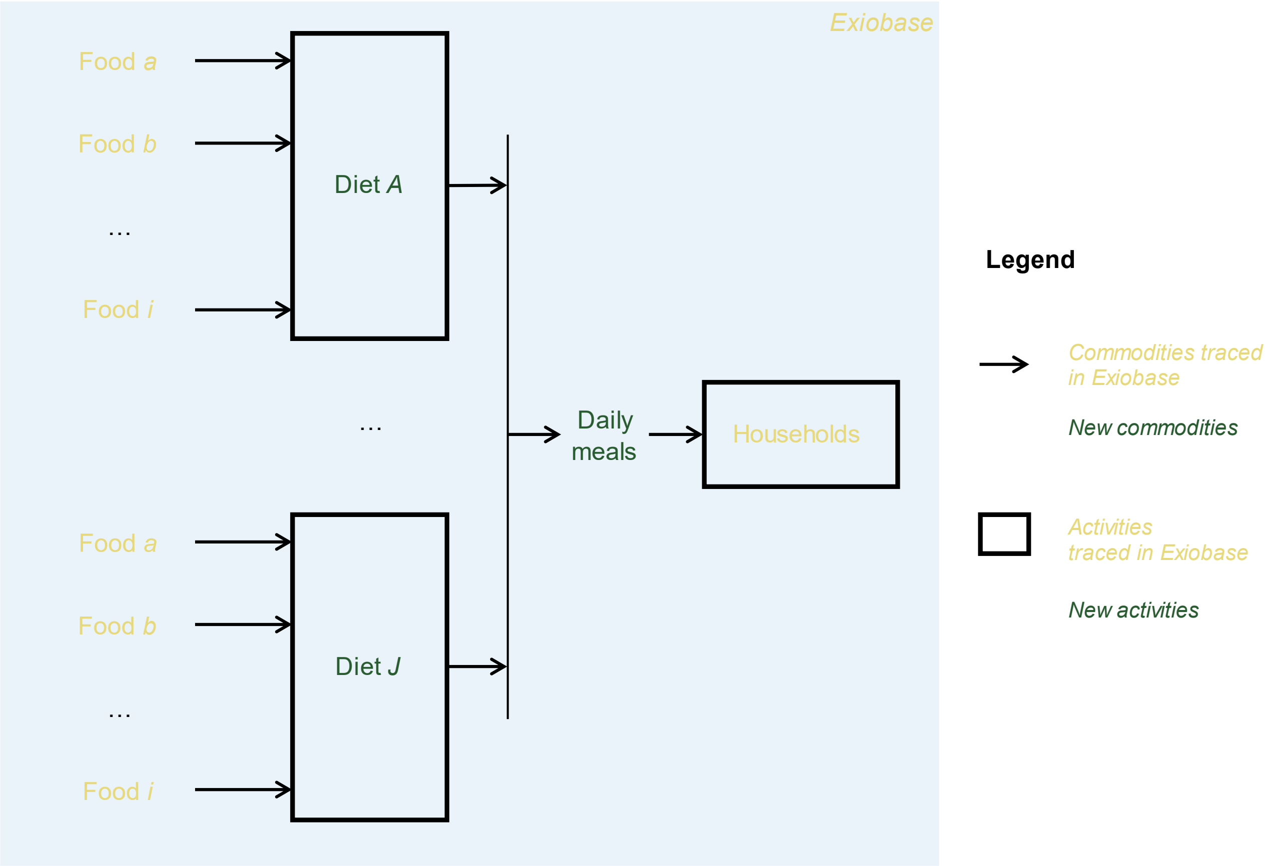

Figure 3. Simplified representation of the implemented diet model for a given country

Table 1. Food requirements (g/day per capita) by diet type. Grams differentiating diets of the same type refer to the amount of meat per day consumed, while (opt) stands for "optimized" diet, as described in Deliverable 6.1(Jacob & Taillard, 2024)

Food requirements	**Diet type**											
	Omnivore				**Flexitarian**		**Vegetarian**		**Pescetarian**		**Vegan**	
	170g	100g (opt)	75g	45g (opt)	30g	20g (opt)		(opt)		(opt)		(opt)
Bovine and ovine meat	62	26	25	10	9	4	0	0	0	0	0	0
Pork, offals and others	73	32	33	14	14	5	0	0	0	0	0	0
Poultry	38	44	18	20	8	9	0	0	0	0	0	0
Dairy	291	136	253	116	222	103	190	78	151	66	4	4
Seafood	52	26	44	23	40	21	48	26	0	0	0	0
Fruits	341	155	336	149	358	149	419	181	404	183	553	299
Vegetables	392	298	350	355	378	393	501	470	483	525	571	283
Legumes	32	72	38	142	66	348	162	536	216	585	370	433
Cereals	210	156	185	197	180	201	211	138	231	204	256	215
Oils	20	24	19	26	20	22	23	27	23	35	26	17
Convenience food	39	16	30	20	24	26	21	28	27	63	23	56
Coffee tea chocolate	800	153	790	164	836	255	919	331	730	210	592	279
Alcohols	118	72	89	67	77	61	70	57	59	51	58	26
Non-alcoholic beverages	98	132	79	93	67	82	70	92	99	66	89	68
Sugar chocolate	11	9	10	7	9	5	9	10	9	10	9	9
Others	59	77	49	85	44	81	49	78	48	92	32	24

The underlying assumptions indicate a trend in diet adoption as shown in the figure.

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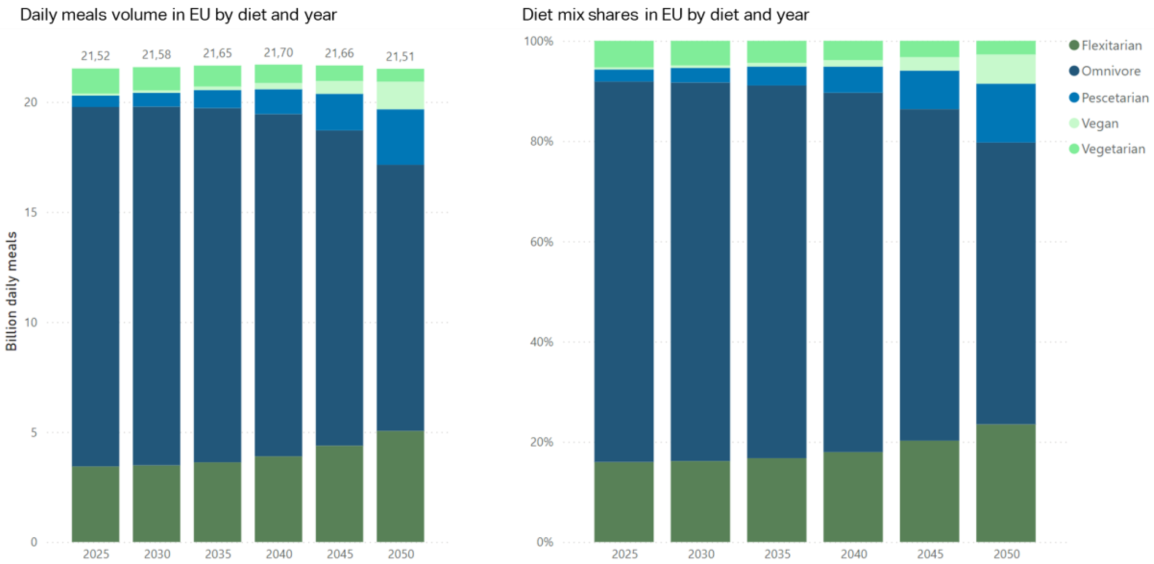

Figure 4 – Daily meals volumes (on the left) and diet mix (on the right) in EU by year assumed in this study.

Reference scenario

Figure 5 presents the historical data of meat consumption per capita for the five selected countries (Italy, Denmark, France, Latvia, and Germany) and the future trends obtained using the ARIMA and logarithmic curve fitting methods, as described in the methodology section (1.4). The historical data shows varying trends in meat consumption across the countries. For France, Denmark, and Latvia, the consumption of meat per capita has remained relatively stable over the historical period. This stability translates into a steady future trend when projected using the ARIMA and logarithmic approaches. On the other hand, Italy and Germany exhibit a decreasing trend in meat consumption per capita in the historical data. This decreasing trend is captured by both the ARIMA and logarithmic models, resulting in a projected decline in future meat consumption for these countries.

As outlined in the methodology section, the final reference scenario for each country is obtained by taking the average between the ARIMA and logarithmic projections. This averaged result is then implemented in the MARIO model to assess the impact of dietary changes on various sustainability indicators in the reference scenario. The reference scenario for meat consumption serves as a baseline against which the effects of the sufficiency scenario assumptions related to dietary changes can be evaluated. By comparing the projected outcomes in the presence of sufficiency scenario assumptions to this reference scenario, the potential environmental, economic, and social impacts of dietary shifts can be quantified and analysed.

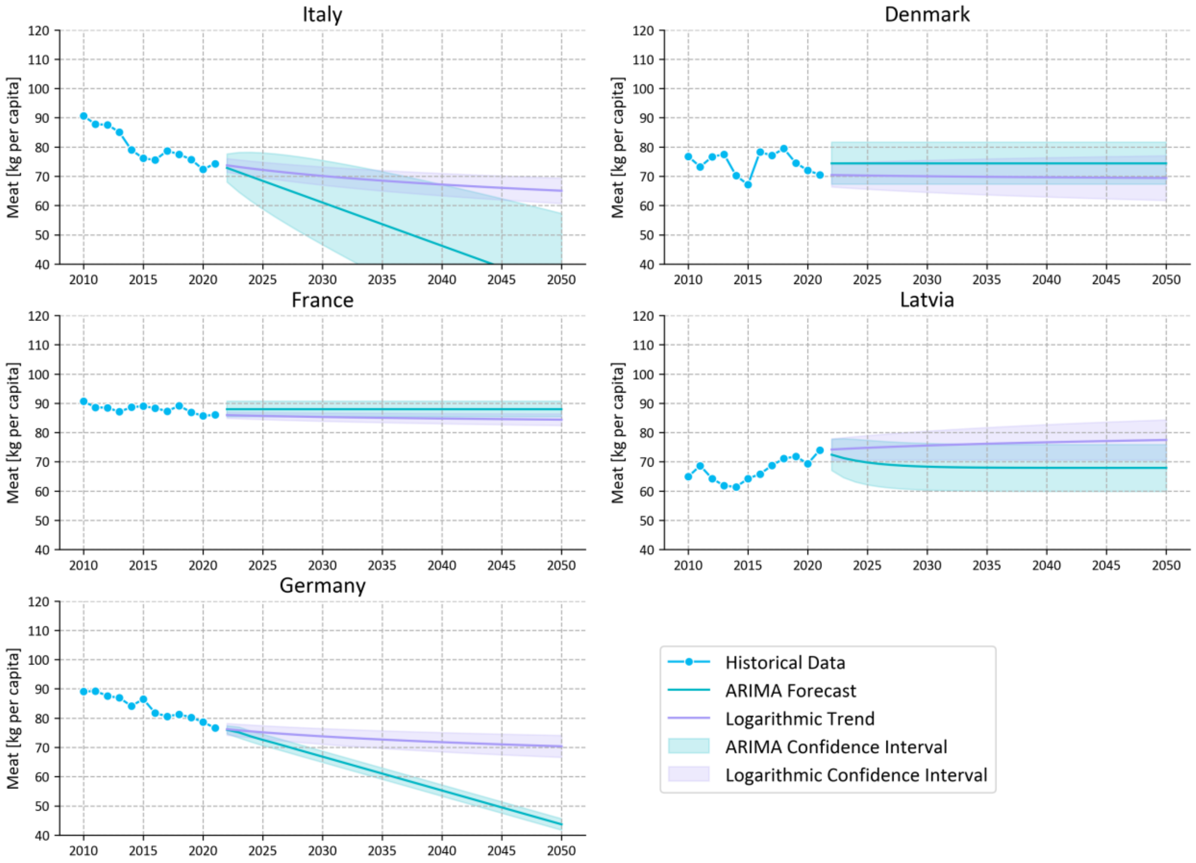

Figure 5 Reference scenario for diets (Data source: FAO, 2021).

Extending input data through countries clustering analysis

Diets and eating habits are crucial part of the sufficiency scenario assumptions, which identify lifestyle of the individuals as well as the community living standard. This sufficiency scenario assumption considers the annual consumption of vegetables and meat per capita.

The data presented in Figures 6 describes the annual consumption of vegetables and meat in European Union countries. The food consumption data is obtained from the World Food and Agriculture Organization (FAO, 2021). The indicator vegetables and meat are selected for the evaluation because they are the highest consumed food items as well as having the high emission levels.

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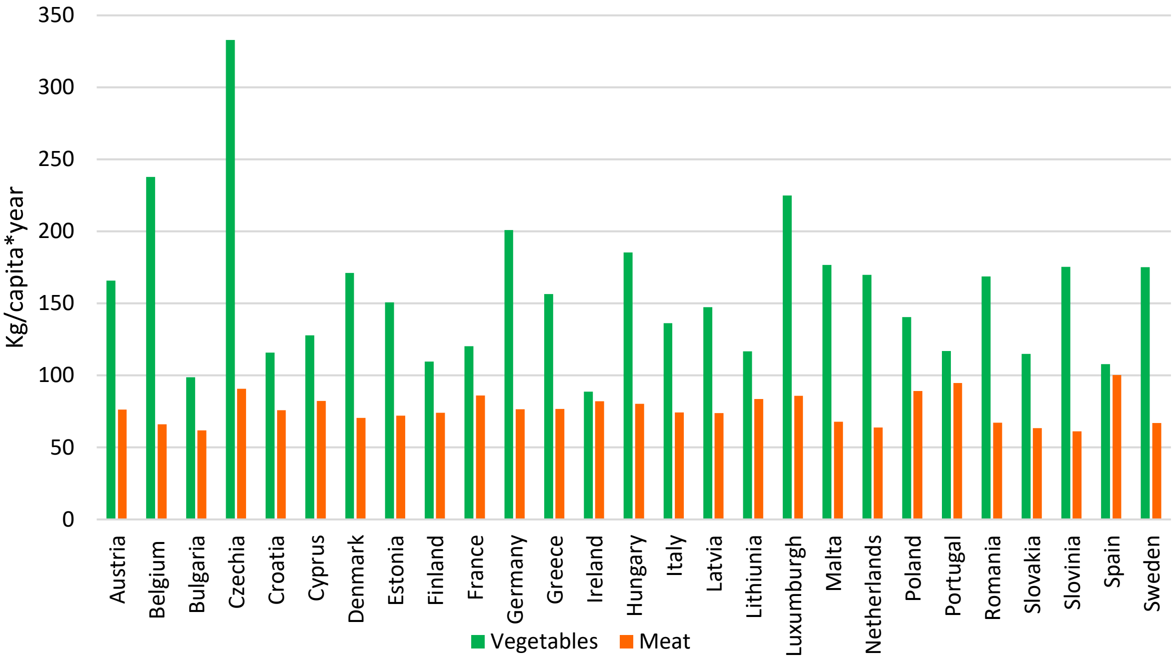
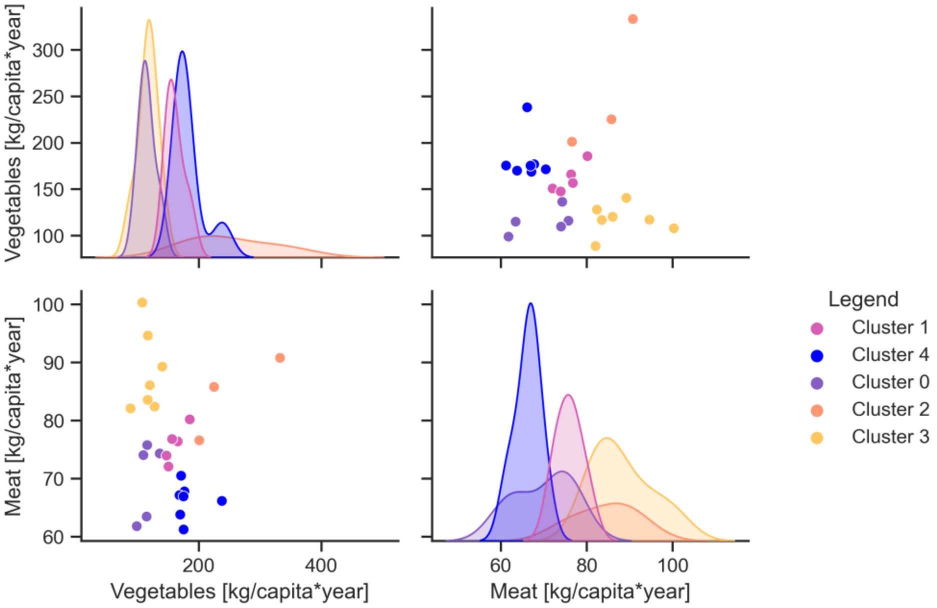


Figure 6. The historical data of vegetables consumption in EU-27 countries (FAO, 2021)

The objective of this sufficiency scenario assumption is to realize the concept of less consumption of meat and dairy products and thus reduce the environmental impacts caused by the meat and dairy industry. The clustering approach used two indicators; meat and vegetables consumption in kg/capita. The results of the clustering modelling for the Diets is shown in figure 7.



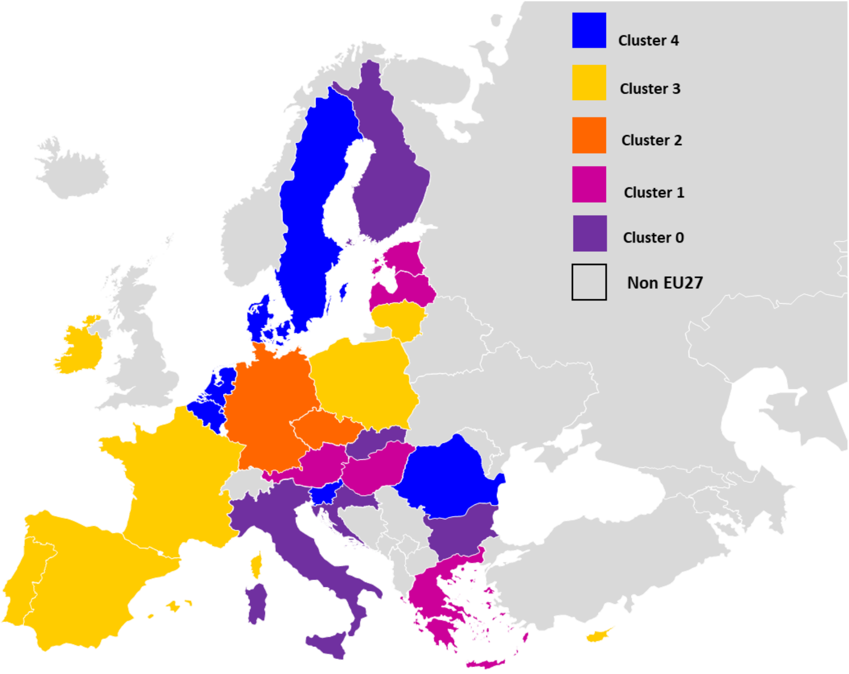


Figure 7 on Top, correlation matrix of meat and vegetables consumption per capita. On the bottom, the resulting clustering classification for EU27 member states.

The countries with similar meat and vegetables consumption patterns were placed into the same clusters. For example, countries with the highest meat consumption per capita fall into cluster 3 (France, Spain, Portugal and Poland and others). In contrast the countries grouped in cluster 4 are the lowest meat consuming countries.

2.4. Endogenizing private car mobility

Private mobility, especially road transport, represents a major contributor to GHG emissions (Lamb et al., 2021). In most of the EU member states, the main mode adopted for private road transport is via passenger cars, as show in in Figure 14.

For these reasons, two sufficiency scenario assumptions, regarding reducing the average car size and to reduce the daily car commuting in favour of cycling, have been implemented in the model.

To accurately model these sufficiency initiatives, it is necessary to represent the penetration of different powertrains in vehicles used for private transportation, as well as their efficiencies, for each year and each country. As with other cases, data provided by Task 6.1 is utilized where possible, and clustering is employed to map the evolution of these factors in other EU countries based on relevant specific indicators.

Similarly to diets, passenger cars have been introduced new activities in Exiobase (Figure 8), specifying fuel economies and direct GHG emission factors for each powertrain.

In parallel to the sufficiency scenario assumption, the penetration of low-carbon vehicles in the fleet of each country was modelled by updating the market share coefficients of the *Car mobility* commodity, expressed in vehicle-km (vim). As for the change in electricity mixes, the update of these market shares is modelled independently on whether the sufficiency scenario assumption is enabled.

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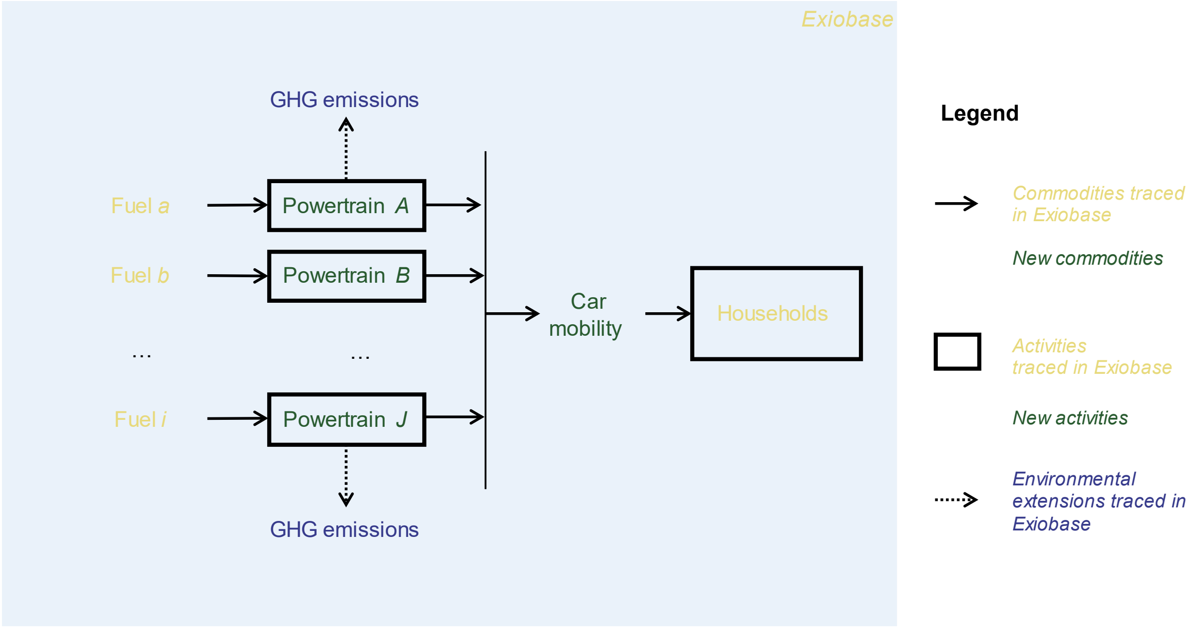

Figure 8. Simplified representation of the implemented passenger cars model for a given country

Another background projection, independent of the update of car efficiency or power-train mix, concerns the total number of driven kilometers in each country. This projection is based on the assumption of starting from (European Commission, 2013).

The evolution of powertrain efficiencies and penetration in each country is extended to all European countries through clustering analysis. Clustering is based on current powertrain penetration data, and each country is associated with the assumed evolution used to determine the input data necessary for the five FULFILL countries.

The total volume of distance travelled by passenger cars and the penetration of different powertrains (notably traditional diesel and gasoline cars, and electric vehicles) assumed for this study – both in the *Reference* scenario and in the sufficiency scenarios – is depicted in the Figure 9.

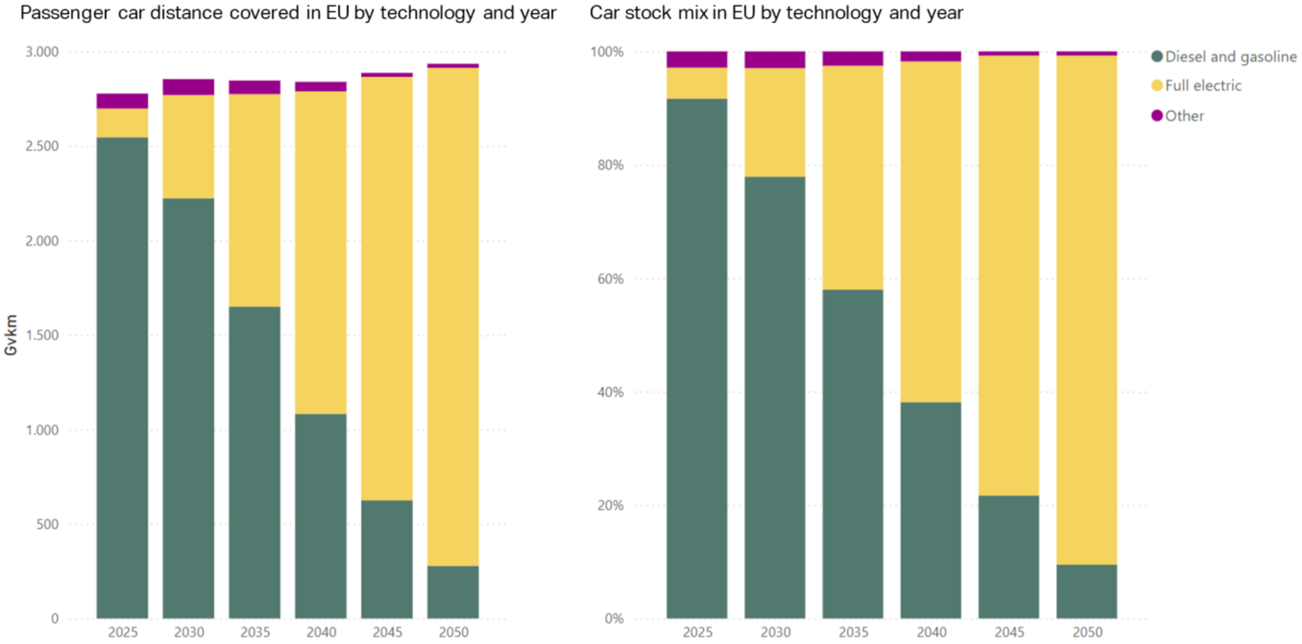

Figure 9 – Passenger car distance covered (on the left) and car stock mix (on the right) in EU by year assumed in this study.

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2.4.1. Moderate car sizing

Modelling implementation and assumptions

The first sufficiency scenario assumption (*Moderate car sizing*) regarding private passenger cars simulates the individual attention to the car efficiency at the moment of the purchase. From the modelling standpoint, this is implemented by updating the fuel economies (and, consequently, emission factors) of each powertrain in each projected year. This is done considering different average weights of cars with and without this measure.

Reference scenario

Figure 10 presents the historical data of car sales per year per person for the five selected countries (Italy, Denmark, France, Latvia, and Germany) and the future trends obtained using the ARIMA and logarithmic curve fitting methods, as described in the methodology section (1.4). The historical data reveals relatively stable trends in car sales per person across all five countries. Italy, France, Germany, and Denmark exhibit similar values, while Latvia shows lower car sales per capita compared to the other four countries. The impact of the Covid-19 pandemic in 2020 is visible in the data for all countries, with a noticeable dip in car sales during that year. This disruption, however, appears to be temporary, as the trends stabilize and resume their pre-pandemic patterns in the subsequent years. The future trends obtained from the ARIMA and logarithmic models reflect the stability observed in the historical data. For all five countries, the projected car sales per person remain relatively constant, aligning with the historical patterns.

As outlined in the methodology section, the final reference scenario for each country is obtained by taking the average of the ARIMA and logarithmic projections. This averaged result is then implemented in the MARIO model to assess the impact of moderate car sizing on various sustainability indicators.

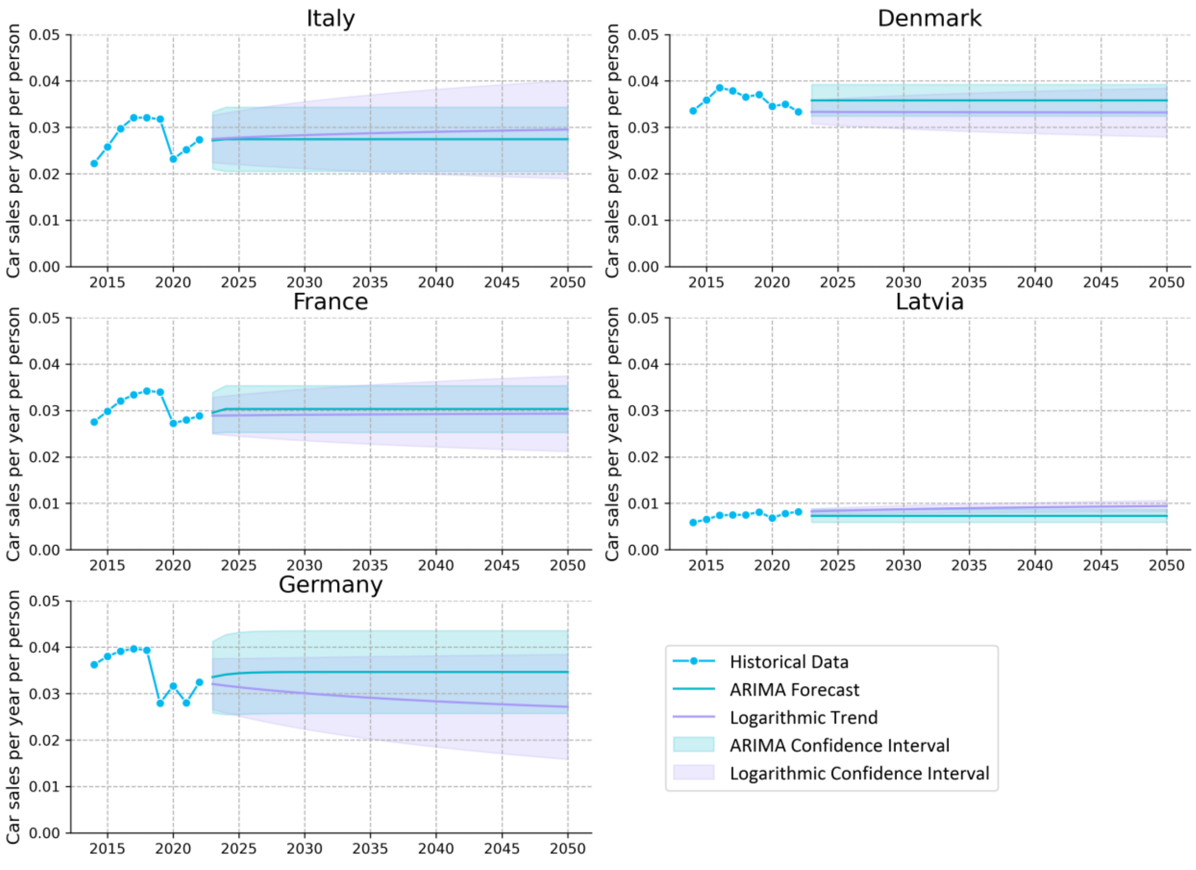

Figure 10 Reference scenario for moderate car sizing. (Datasource: Statista, 2024)

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Extending input data through countries clustering analysis

This sufficiency scenario assumption introduces the a concept of using smaller to moderate size cars instead of large or heavy size cars for mobility. The concept can lead to the reduction of energy demand by the transport sector as well as significantly to reducing the GHG emissions. The clustering approach implemented for the sufficiency scenario assumption uses the indicator annual sales of moderate size cars while for the correlation clustering the indicator used are the annual sale of small cars vs SUV's. The results presented in figure 11 and 12 show the sale difference of small cars and SUV's during the period of 2014-2022 in the 27 EU member states. For this sufficiency scenario assumption a total of 4 clusters were developed and the countries with similar sale patterns fell into the same cluster. For example, figure 13 indicates the countries with the less sale difference of smaller to SUV cars in the period 2014-2022 were grouped in cluster 3. The countries with similar trends of higher sales difference during the 10-year period were placed in cluster 4.

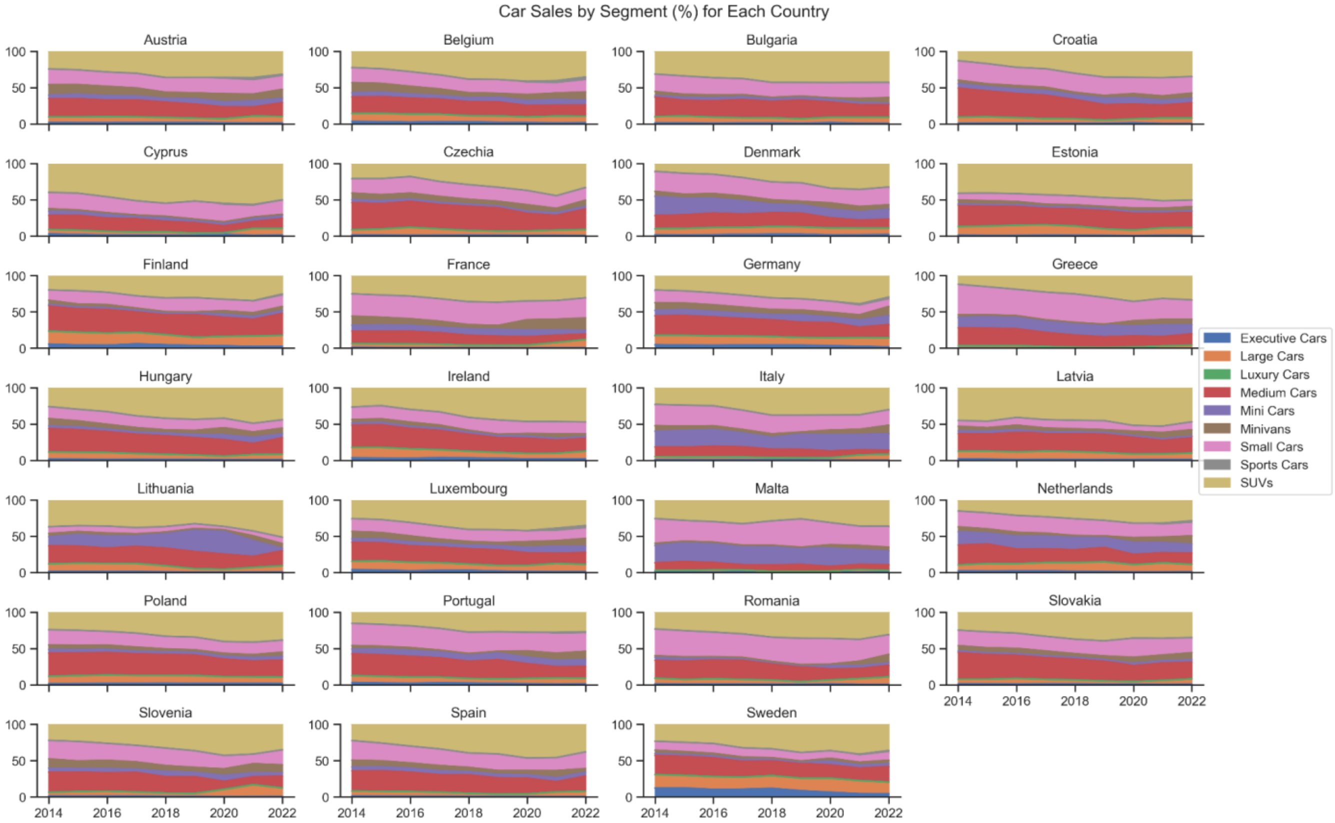

Figure 11 Car sales share by segment for each EU country (Statista, 2024).

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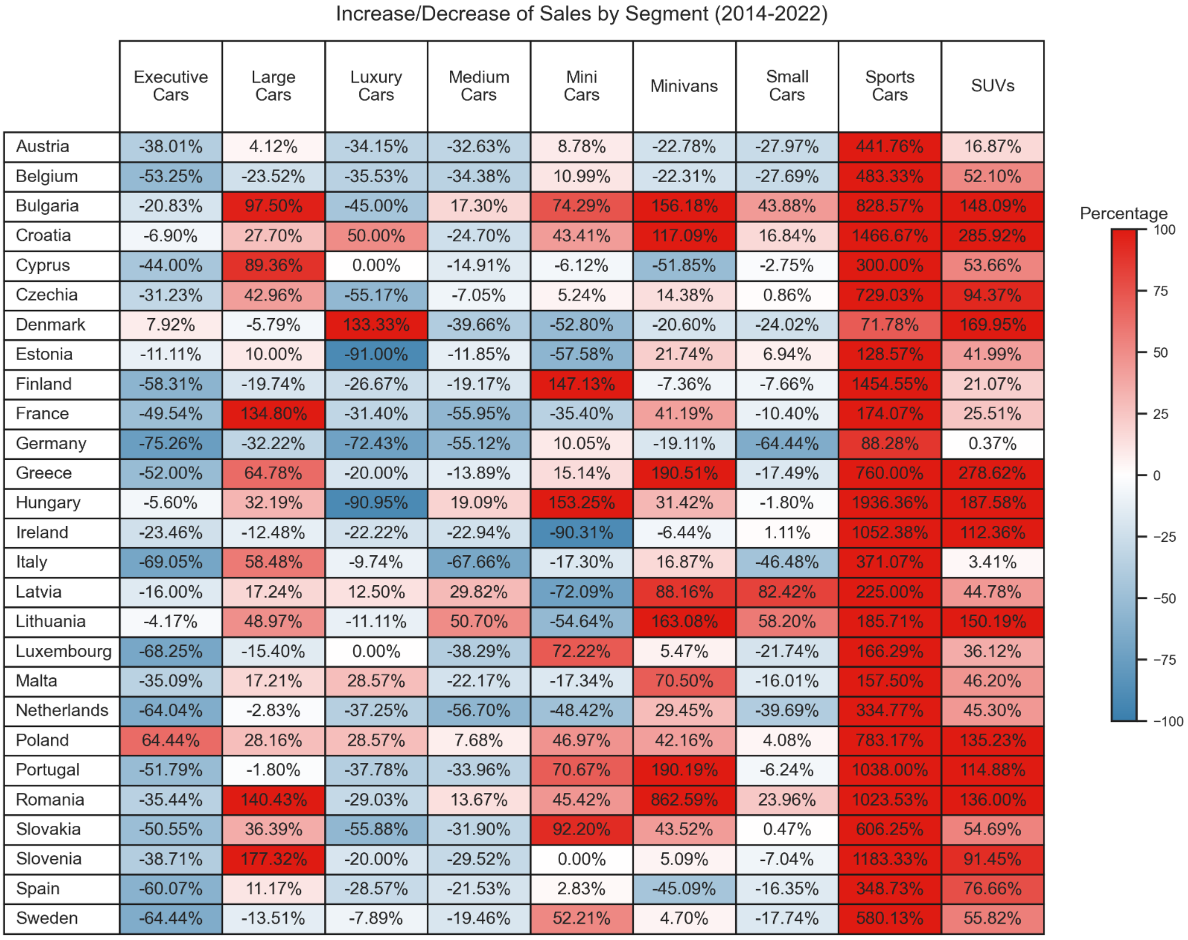
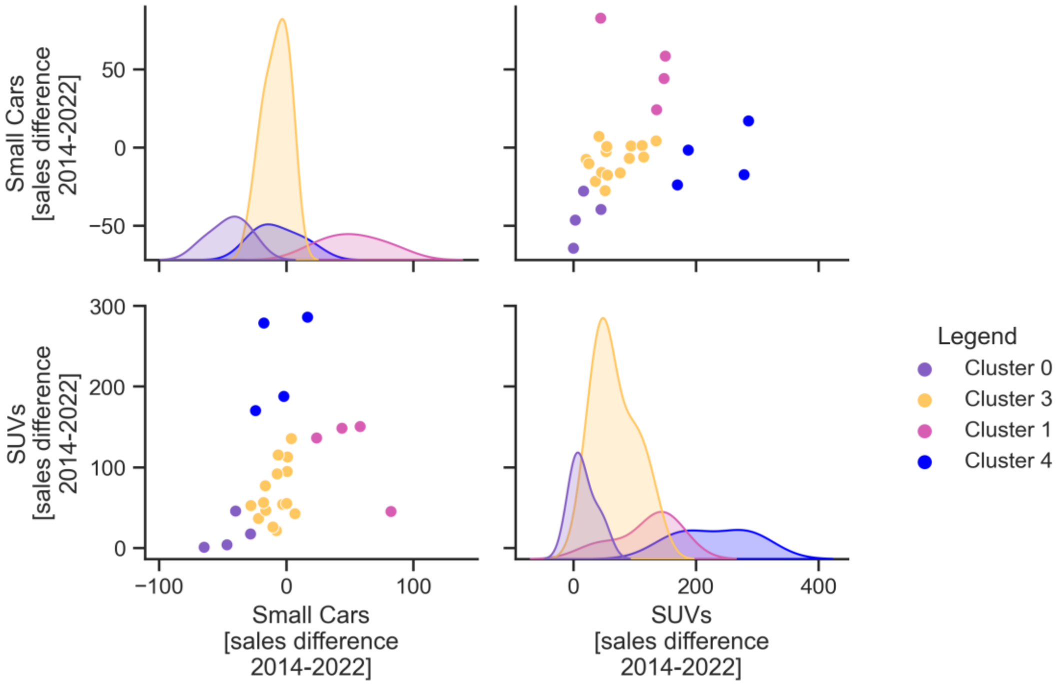


	Executive Cars	Large Cars	Luxury Cars	Medium Cars	Mini Cars	Minivans	Small Cars	Sports Cars	SUVs
Austria	-38.01%	4.12%	-34.15%	-32.63%	8.78%	-22.78%	-27.97%	441.76%	16.87%
Belgium	-53.25%	-23.52%	-35.53%	-34.38%	10.99%	-22.31%	-27.69%	483.33%	52.10%
Bulgaria	-20.83%	97.50%	-45.00%	17.30%	74.29%	156.18%	43.88%	828.57%	148.09%
Croatia	-6.90%	27.70%	50.00%	-24.70%	43.41%	117.09%	16.84%	1466.67%	285.92%
Cyprus	-44.00%	89.36%	0.00%	-14.91%	-6.12%	-51.85%	-2.75%	300.00%	53.66%
Czechia	-31.23%	42.96%	-55.17%	-7.05%	5.24%	14.38%	0.86%	729.03%	94.37%
Denmark	7.92%	-5.79%	133.33%	-39.66%	-52.80%	-20.60%	-24.02%	71.78%	169.95%
Estonia	-11.11%	10.00%	-91.00%	-11.85%	-57.58%	21.74%	6.94%	128.57%	41.99%
Finland	-58.31%	-19.74%	-26.67%	-19.17%	147.13%	-7.36%	-7.66%	1454.55%	21.07%
France	-49.54%	134.80%	-31.40%	-55.95%	-35.40%	41.19%	-10.40%	174.07%	25.51%
Germany	-75.26%	-32.22%	-72.43%	-55.12%	10.05%	-19.11%	-64.44%	88.28%	0.37%
Greece	-52.00%	64.78%	-20.00%	-13.89%	15.14%	190.51%	-17.49%	760.00%	278.62%
Hungary	-5.60%	32.19%	-90.95%	19.09%	153.25%	31.42%	-1.80%	1936.36%	187.58%
Ireland	-23.46%	-12.48%	-22.22%	-22.94%	-90.31%	-6.44%	1.11%	1052.38%	112.36%
Italy	-69.05%	58.48%	-9.74%	-67.66%	-17.30%	16.87%	-46.48%	371.07%	3.41%
Latvia	-16.00%	17.24%	12.50%	29.82%	-72.09%	88.16%	82.42%	225.00%	44.78%
Lithuania	-4.17%	48.97%	-11.11%	50.70%	-54.64%	163.08%	58.20%	185.71%	150.19%
Luxembourg	-68.25%	-15.40%	0.00%	-38.29%	72.22%	5.47%	-21.74%	166.29%	36.12%
Malta	-35.09%	17.21%	28.57%	-22.17%	-17.34%	70.50%	-16.01%	157.50%	46.20%
Netherlands	-64.04%	-2.83%	-37.25%	-56.70%	-48.42%	29.45%	-39.69%	334.77%	45.30%
Poland	64.44%	28.16%	28.57%	7.68%	46.97%	42.16%	4.08%	783.17%	135.23%
Portugal	-51.79%	-1.80%	-37.78%	-33.96%	70.67%	190.19%	-6.24%	1038.00%	114.88%
Romania	-35.44%	140.43%	-29.03%	13.67%	45.42%	862.59%	23.96%	1023.53%	136.00%
Slovakia	-50.55%	36.39%	-55.88%	-31.90%	92.20%	43.52%	0.47%	606.25%	54.69%
Slovenia	-38.71%	177.32%	-20.00%	-29.52%	0.00%	5.09%	-7.04%	1183.33%	91.45%
Spain	-60.07%	11.17%	-28.57%	-21.53%	2.83%	-45.09%	-16.35%	348.73%	76.66%
Sweden	-64.44%	-13.51%	-7.89%	-19.46%	52.21%	4.70%	-17.74%	580.13%	55.82%

Figure 12 relative increase/decrease of sales by segment comparing values of 2014 and 2022 for each EU country.



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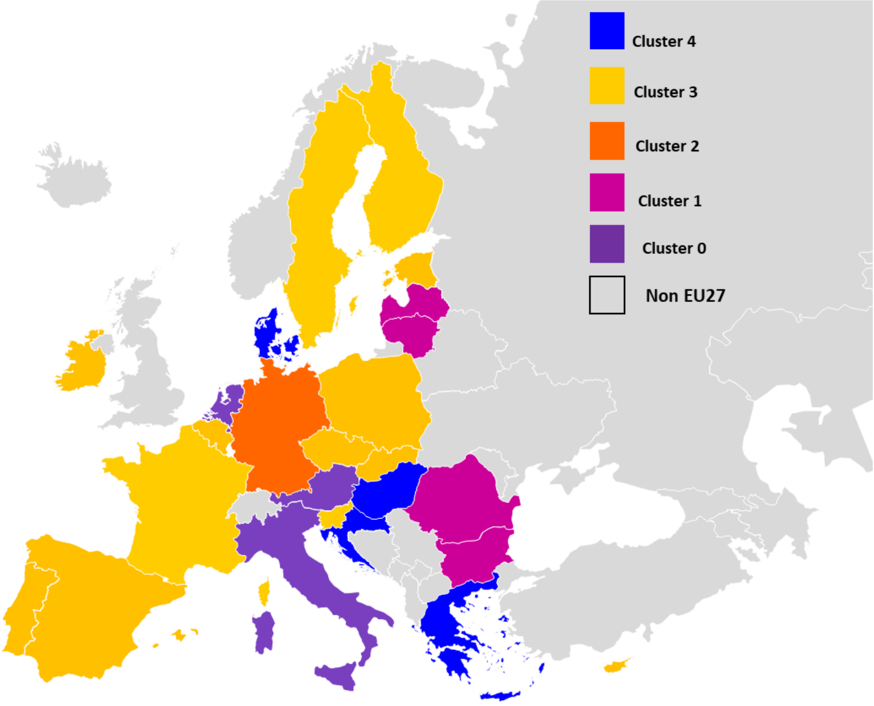

Figure 13 on Top, correlation matrix of small cars and SUVs sales difference 2014-2022. On the bottom, the resulting clustering classification for EU27 member states.

2.4.2. Cycling

Modelling implementation and assumptions

A second scenario for energy sufficiency assumes a shift from private mobility (car use) to biking. This is modelled by reducing the total kilometers driven by car. For each country, we estimated the annual increase in bicycle mileage, and 80% of these new bicycle trips are assumed to replace car trips, reducing the total kilometers driven. Data of the current situation are depicted in Figure 14.

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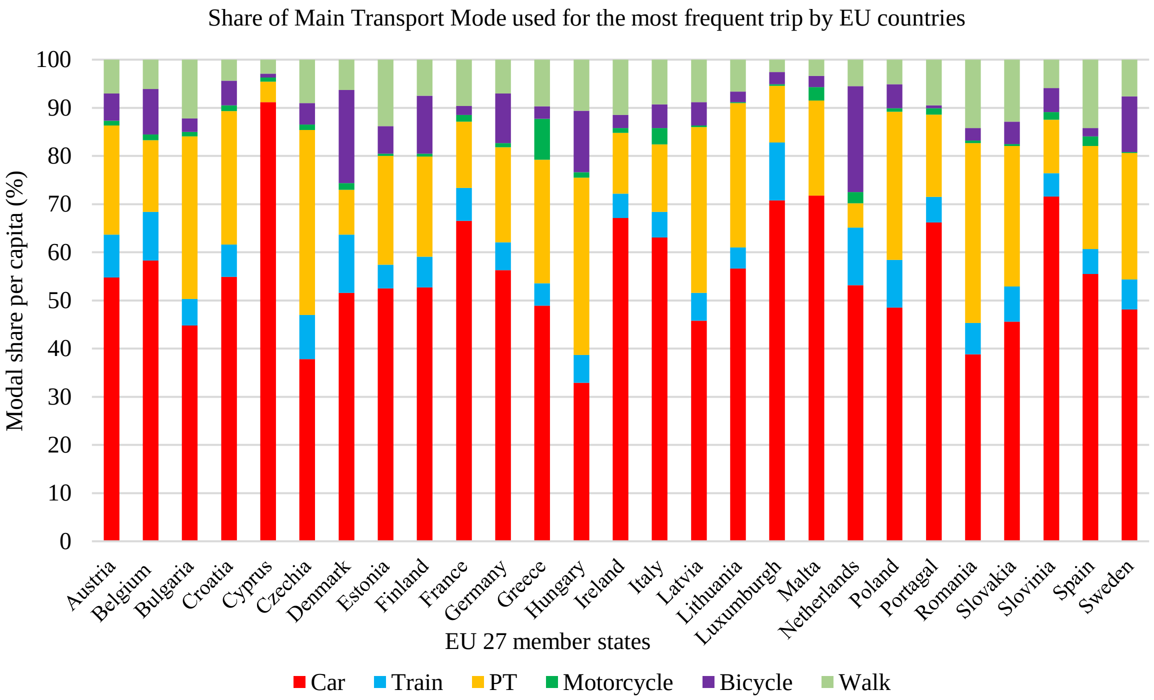

Figure 14. Share of road transport modes in EU-27 countries. (Data source: Fiorello, 2016)

Reference scenario

Figure 15 presents the historical data of the modal share of public transport per person for the five selected countries (Italy, Denmark, France, Latvia, and Germany) and the future trends obtained using the ARIMA and logarithmic curve fitting methods, as described in the methodology section (1.4). In this case, the modal share of public transport per person is used as a proxy for the modal share of cycling, as historical data for cycling are not available. The historical data shows stable trends in the modal share of public transport per person for Italy, France, Germany, and Denmark. These countries exhibit relatively consistent values over the observed period, indicating a steady reliance on public transportation. In contrast, Latvia demonstrates a decreasing trend in the modal share of public transport per person. This suggests a shift away from public transportation in Latvia over the historical period.

The future trends obtained from the ARIMA and logarithmic models reflect the patterns observed in the historical data. For Italy, France, Germany, and Denmark, the projected modal share of public transport per person remains stable, aligning with the historical trends. Latvia, on the other hand, shows a continued decrease in the modal share of public transport per person, following the trajectory seen in the historical data.

As outlined in the methodology section, the final reference scenario for each country is obtained by taking the average of the ARIMA and logarithmic projections. This averaged result is then implemented in the MARIO model to assess the impact of increased cycling on various sustainability indicators.

The reference scenario for the modal share of public transport per person serves as a baseline against which the effects of the sufficiency scenario assumption related to cycling can be evaluated. By comparing the projected outcomes in the presence of increased cycling to this reference scenario, the potential environmental, economic, and social impacts of shifting towards more sustainable modes of transportation can be quantified and analysed. However, it is important to note that using the modal share of public transport as a proxy for cycling may introduce some limitations in the analysis, and further research with direct cycling data would enhance the accuracy of the assessment.

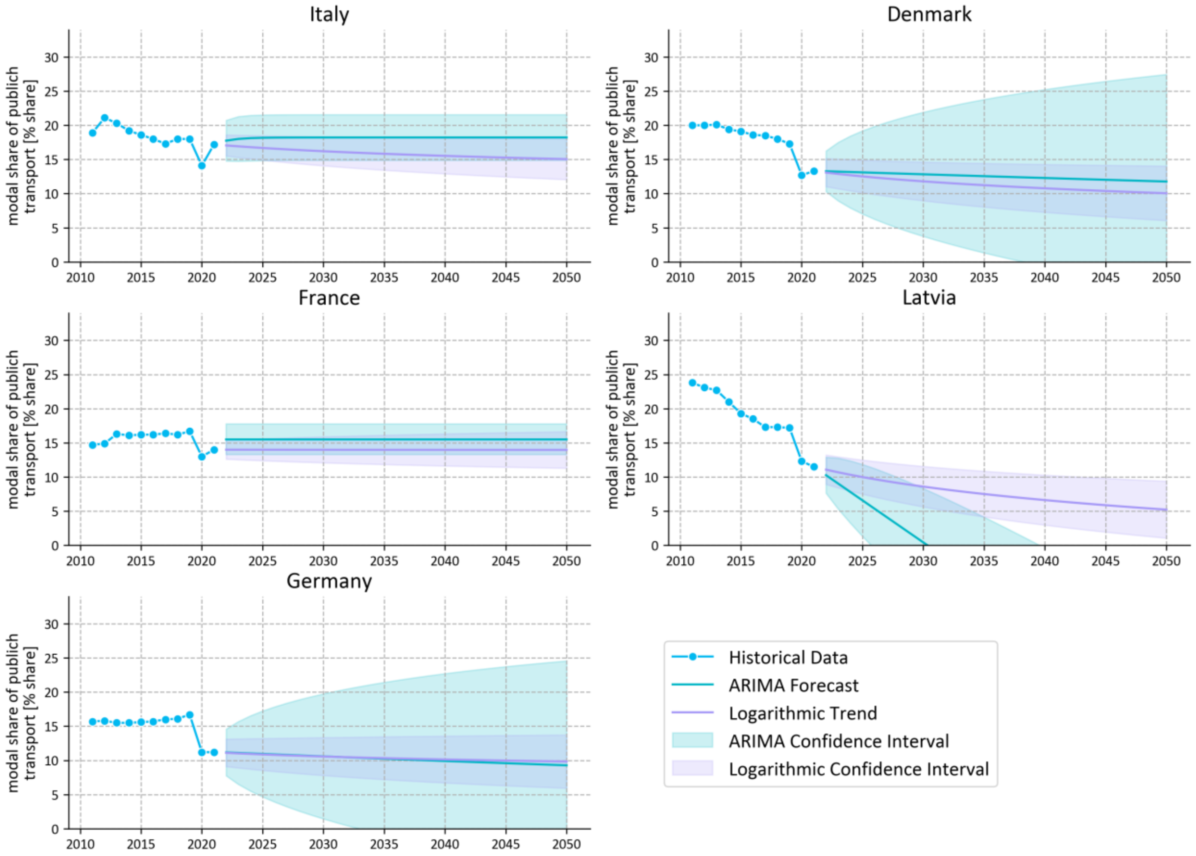

Figure 15 Reference scenario for cycling (Data source: Eurostat, 2023).

Extending input data through countries clustering analysis

The clustering approach employed in the measure used data of main mode of transport per capita in EU countries while the indicator adopted for clustering are the percent usage of bicycle and cars as main mode of transport per capita in EU countries. The results presented in figure 16 show the correlation be-tween usage of cars and bicycles. The results show that the countries falling into cluster 4 (The Netherlands and Denmark) have the highest number of people using bicycles as main transport mode.. While The rest of EU countries fall into the clusters 0, 1, 2 or 3.

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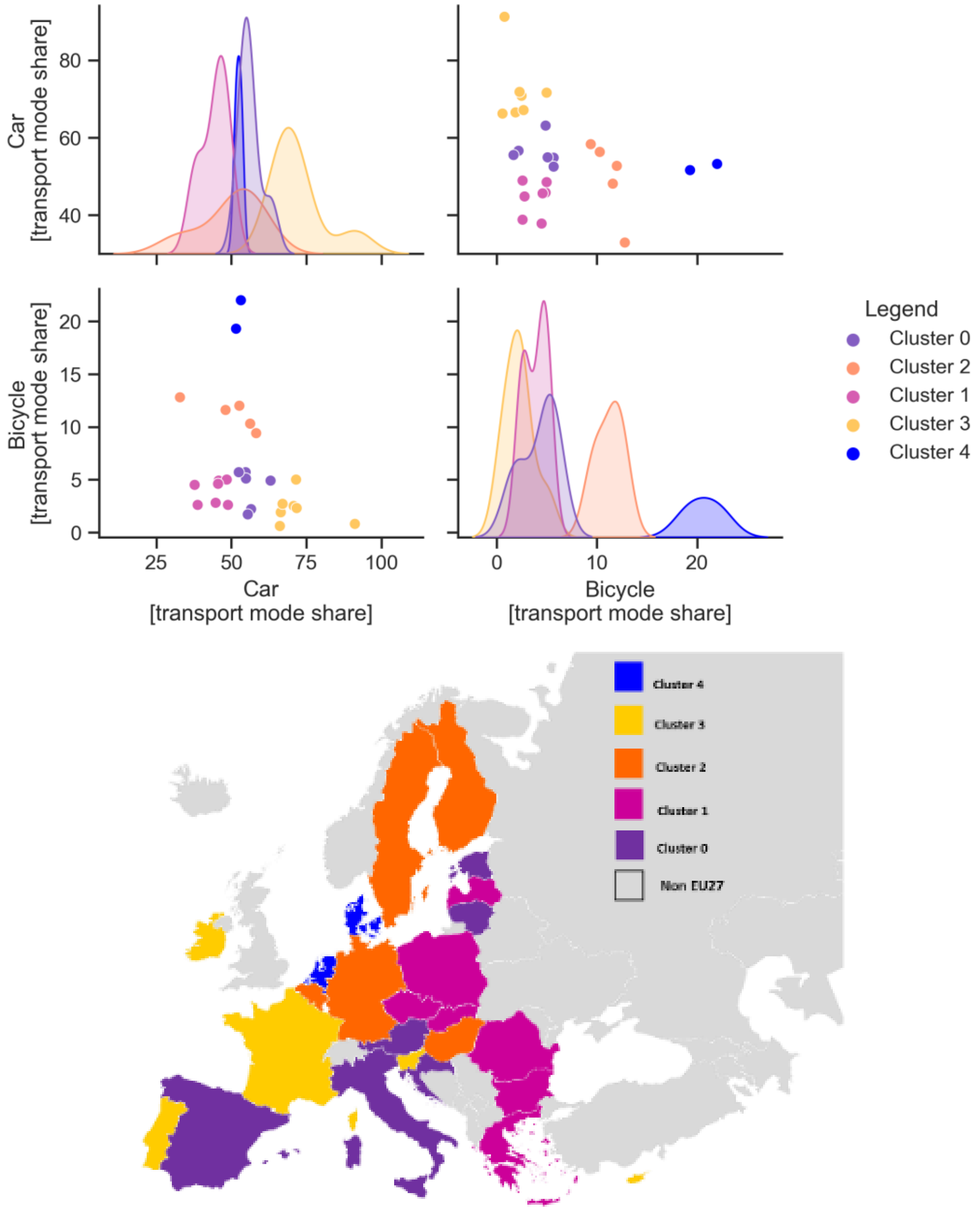

Figure 16 on Top, correlation matrix of cars and bicycle transport mode shares. On the bottom, the resulting clustering classification for EU27 member states.

Figure 16 shows the EU countries categorized into five clusters from 0-4, where every cluster represents a relatively similar mode of transport and mobility trends per capita. The countries with the lowest share of bicycle as main mode of transport per capita are fall into the cluster 0 highlighted in purple colour while the Netherlands and Denmark has the highest users of bicycles placed into cluster 4.

2.5. Endogenizing housing

The residential sector also strongly contributes to GHG emissions, especially due to households' heating and cooling needs. The modelling exercise envisages the implementation of a sufficiency scenario assumption aiming to evaluate the impact of sharing living space in order to reduce the average floor area per capita in the EU member states. This measure will support the reduction of energy required per capita in dwelling as well as reduce the average floor area required per person

Input-output models account for households' consumption of goods and services in the final demand matrix. These consumptions include demand of energy services such as electricity, heating and cooling.

In this modelling exercise, however, it was necessary to define separate technologies for different heating systems in order to manage both their envisaged efficiency enhancements and the progressive switch towards cleaner heating technologies (i.e. heat pumps…). A new activity is added for each heating system in Exiobase, each supplying the *heating service* commodity (expressed in kWh) according to a determined country-specific market share. This commodity, together with electricity (already traced in Exiobase) representing lighting and cooling, is consumed by another new activity named *Housing* supplying, in turn, the *housing service* commodity, expressed in m^2 of floor surface and consumed as final consumption by the households (Figure 17). This approach grants flexibility in implementing the projections regarding the residential sectors, in particular:

- the expected increase in efficiency for each heating system, acting on their fuel consumption and emission factors coefficients
- the update of heating systems market shares, to simulate the penetration of cleaner heating technologies
- the potential reduction of residential heating and electricity consumption by households

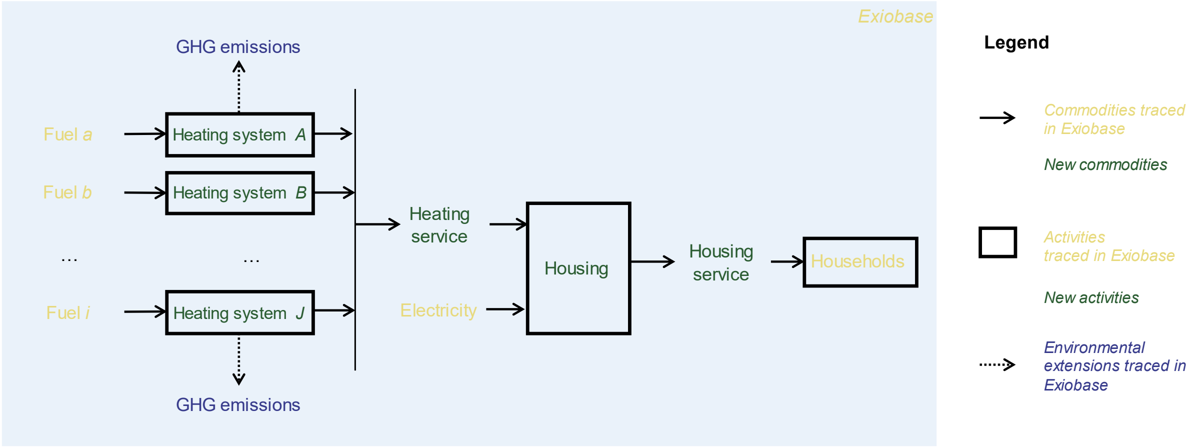

Figure 17. Simplified representation of the implemented housing model for a given country

To extend the housing modelling to the European level, it is necessary to apply the input data obtained from Task 2.1 from the five FULFILL countries to all other countries. This is achieved by obtaining data on heated surfaces from HOTMAPS (www.hotmaps-project.eu), which are then extended based on the current penetration of different heating systems.

The total volume of domestic heating assumed in EU for this study, which will be reduced according to the assumptions of the *Sharing spaces in housing* sufficiency scenario, and the technological mix used to meet this need, is represented for the EU in the Figure 18.

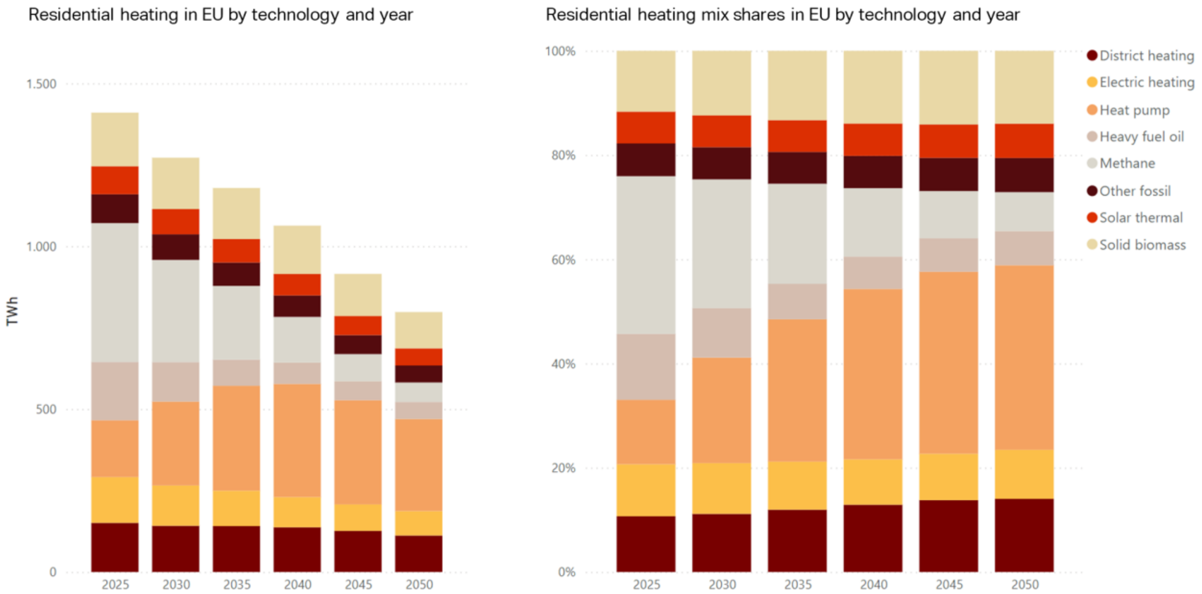

Figure 18 – Residential heating needed (on the left) and technology mix (on the right) in EU by year assumed in this study.

2.5.1. Sharing spaces in housing

Modelling implementation and assumptions

The possibility of sharing the same house among more people (sufficiency scenario assumption indicated as *Sharing spaces in housing*), is implemented by reducing the total consumption of housing service. The assumptions underlying this projection are grounded on estimations on m^2 per capita.

Given that the model already disaggregates the energy consumption of residential buildings, reducing the final demand for residential building heating allows the model to respond accordingly. This response inherently includes the assumptions regarding the amount of each type of energy carrier saved due to the reduced final demand.

Reference scenario

Figure 19 presents the historical data of the number of rooms per person for the five selected countries (Italy, Denmark, France, Latvia, and Germany) and the future trends obtained using the ARIMA and logarithmic curve fitting methods, as described in the methodology section (1.4). In this case, the number of rooms per person is used as a proxy for sharing spaces in housing, as a value close to or lower than 1 could indicate sharing spaces habits. The historical data reveals distinct trends among the countries. Latvia and Italy exhibit stable trends in the number of rooms per person over the observed period. This stability suggests that the level of space sharing in housing has remained relatively constant in these countries. On the other hand, France, Germany, and Denmark show increasing trends in the number of rooms per person. This indicates a gradual shift towards more spacious living arrangements and potentially less sharing of housing spaces in these countries.

The future trends obtained from the ARIMA and logarithmic models reflect the patterns observed in the historical data. For Latvia and Italy, the projected number of rooms per person remains stable, aligning with the historical trends. France, Germany, and Denmark, however, show a continued increase in the number of rooms per person, following the trajectories seen in the historical data.

As outlined in the methodology section, the final reference scenario for each country is obtained by taking the average of the ARIMA and logarithmic projections. This averaged result is then implemented in the MARIO model to assess the impact of sharing spaces in housing on various sustainability indicators.

The reference scenario for the number of rooms per person serves as a baseline against which the effects of the sufficiency scenario assumption related to sharing spaces in housing can be evaluated. By comparing the projected outcomes in the presence of increased space sharing to this reference

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scenario, the potential environmental, economic, and social impacts of optimizing housing utilization can be quantified and analysed. However, it is important to acknowledge that using the number of rooms per person as a proxy for space sharing may have limitations.

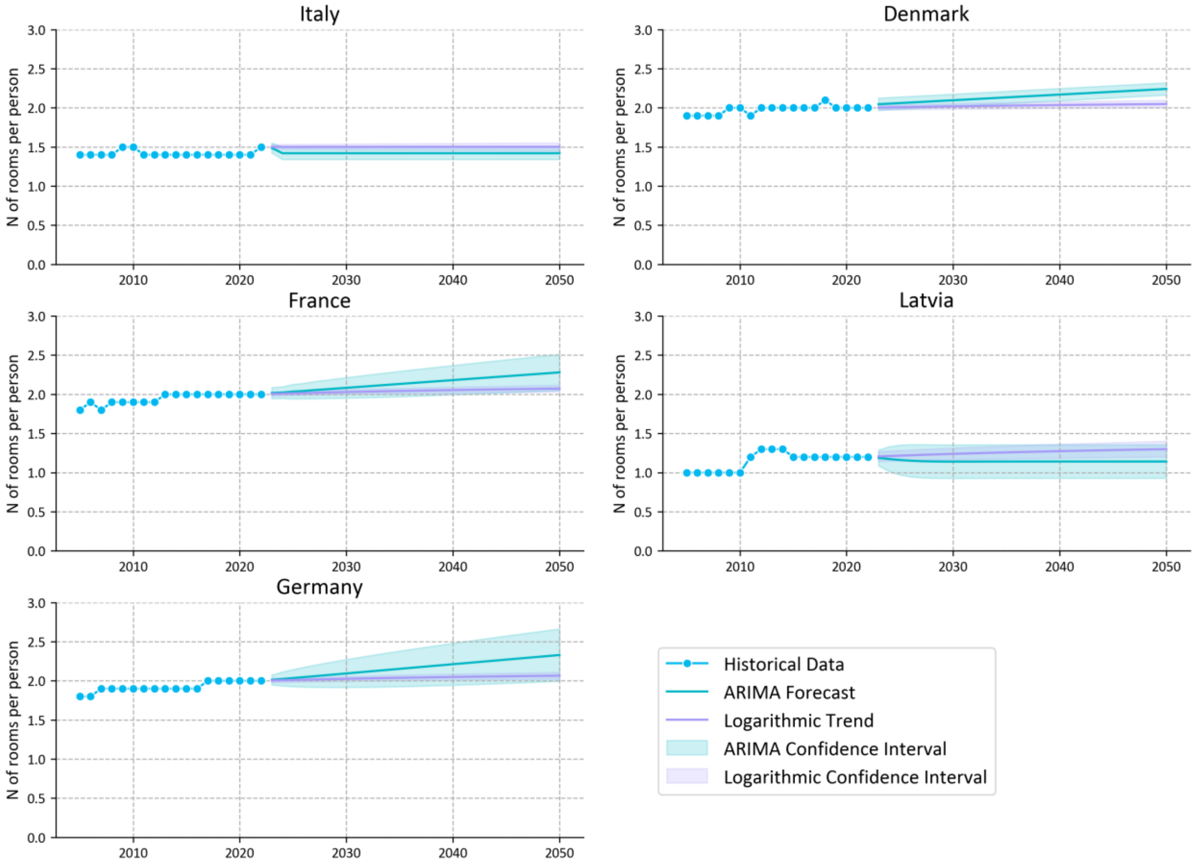

Figure 19 Reference scenario for sharing spaces in housing (Eurostat, 2024).

Extending input data through countries clustering analysis

For the cluster analysis the indicators used are average floor area m^2 per person and average number of rooms available per capita in EU countries (see Figure 20). The data is obtained from the Eurostat website and Odyssee-Mure website[1]-[2].

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[1] Eurostat's Average floor area per person: https://ec.europa.eu/eurostat/databrowser/view/ILC_LVHO03__custom_7139622/bookmark/table?lang=en&bookmarkId=0407f1bd-cf5b-46cf-add6-a1c8454ed251.

[2] Energy sufficiency indicators and policies. https://www.odyssee-mure.eu/publications/policy-brief/energy-sufficiency.html

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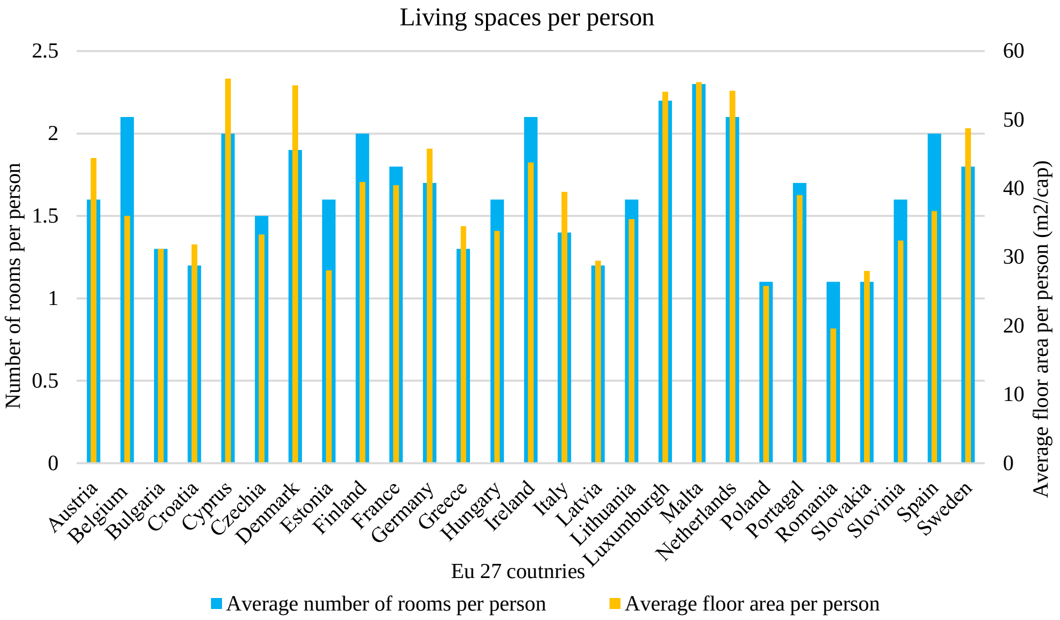

Figure 20. Average size (n. rooms) and floor area per capita in EU27 countries (Data source: ODYSSEE-MURE, 2018)

The concept of this sufficiency scenario assumption is to share spaces in houses with other people, in order to reduce the floor area (m^2) per capita. More shared spaces mean less surface dwellings which could reduce the average floor area per person, as well as per capita energy demand in the buildings. The clustering approach for this sufficiency scenario assumption is applied on 27 EU member states by selecting two indicators; i) average floor area (m^2) per capita and ii) the average number of rooms per person. The EU countries with similar characteristics are grouped into the same cluster. Figure 21 shows the correlation between two indicators and present the countries with similar dynamics of the sharing spaces fall into the same cluster. The countries with more floor area per capita and number of rooms fall in to the fourth cluster such as Denmark and Netherland. Similarly, the countries with lowest floor area and number of room per capita are grouped in the zero cluster.

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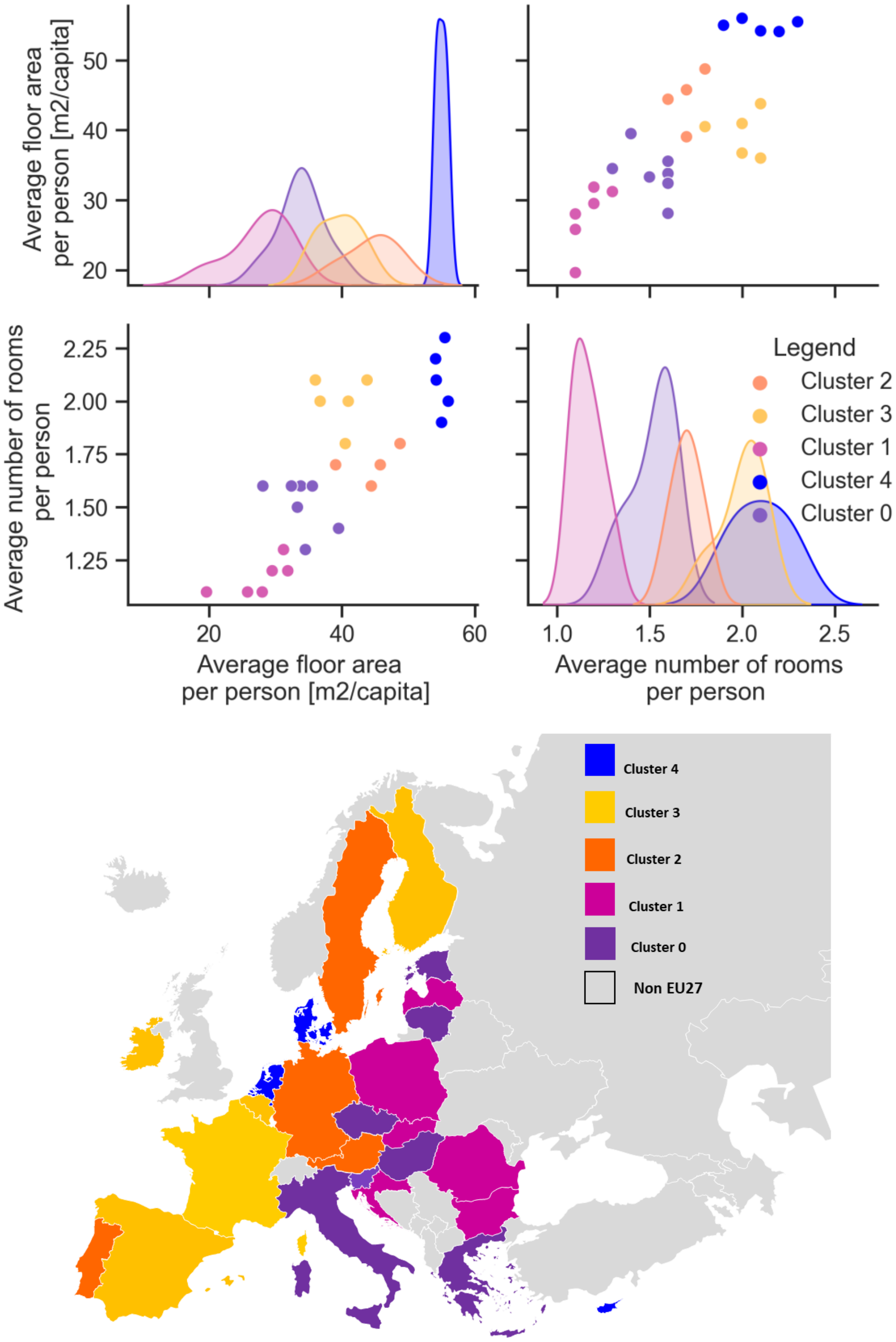

Figure 21 on Top, correlation matrix of average number of rooms per person and average floor area per person. On the bottom, the resulting clustering classification for EU27 member states.

2.6. Modelling final consumption changes

This chapter addresses the sufficiency scenario assumptions that did not require the endogenization of private consumption sectors but could be modelled solely by updating the final demand for products by households directly in the final demand.

2.6.1. Flying less

Modelling implementation and assumptions

Starting from the estimated reduction in fuel consumption due to lower air traffic (see deliverable 6.1 (Jacob & Taillard, 2024)) a proportional reduction in the consumption of the Exiobase commodity "Air transport service" is implemented to model the *Flying less* sufficiency scenario assumption. The fuel consumption reduction encompasses both leisure and business trips, therefore a reduction in "Air transport service" from both households and industrial activities has been modelled: no distinction was implemented among intermediate activities (i.e., the same percentual reduction in the use of "Air transport service" has been assumed for all final and intermediate consumption categories).

No rebound effects have been included in the analysis. The objective here is to understand the potential savings achievable by avoiding flights. While it is acknowledged that avoiding flights may not always be feasible, there are many business trips today that can often be replaced by video calls. Holiday travel destinations can vary widely and may be accessible by different modes of transport; for example, a road or railway trip of a few hundred kilometers can potentially serve as an alternative to a 2-3 hour flight. The uncertainty associated with these assumptions makes it useful to isolate the effect of simply avoiding air travel. This, along with the explanations regarding the uncertainty of some crucial data provided in Deliverable 6.1 (Jacob & Taillard, 2024), led to the decision not to implement rebound effects.

Some authors claim the relevance of water vapor emissions in aviation (Lee et al., 2021). Quantifying this effect is characterised by large uncertainty. To account for this additional climate impact brought by aviation, an environmental extension specifically dedicated to track such impact has been added to complement GHG emissions of the aviation sector. This additional climate impact is estimated to be roughly equal to fossil CO_2 emissions of air transport.

On the supply side, no specific assumptions are put in place regarding technological advancements in the aviation industry. The scenario analysis outline, therefore, a "business as usual" situation from this perspective.

Reference scenario

Figure 22 presents the historical data of the number of annual air passengers carried per capita for the five selected countries (Italy, Denmark, France, Latvia, and Germany) and the future trends obtained using the ARIMA and logarithmic curve fitting methods, as described in the methodology section (1.4). The historical data reveals increasing trends in the number of annual air passengers carried per capita for all five countries. This suggests a growing popularity and reliance on air travel over the observed period.

The future trends obtained from the ARIMA and logarithmic models reflect the patterns observed in the historical data, but with some variations among the countries. Latvia and Denmark show steeper increases in the projected number of annual air passengers carried per capita, indicating a more rapid growth in air travel demand in these countries.

On the other hand, Italy, France, and Germany exhibit slower increases in the future trends compared to their historical patterns. While the number of annual air passengers carried per capita is still projected to rise in these countries, the growth rate appears to be more moderate.

As outlined in the methodology section, the final reference scenario for each country is obtained by taking the average of the ARIMA and logarithmic projections. This averaged result is then implemented in the MARIO model to assess the impact of flying less on various sustainability indicators.

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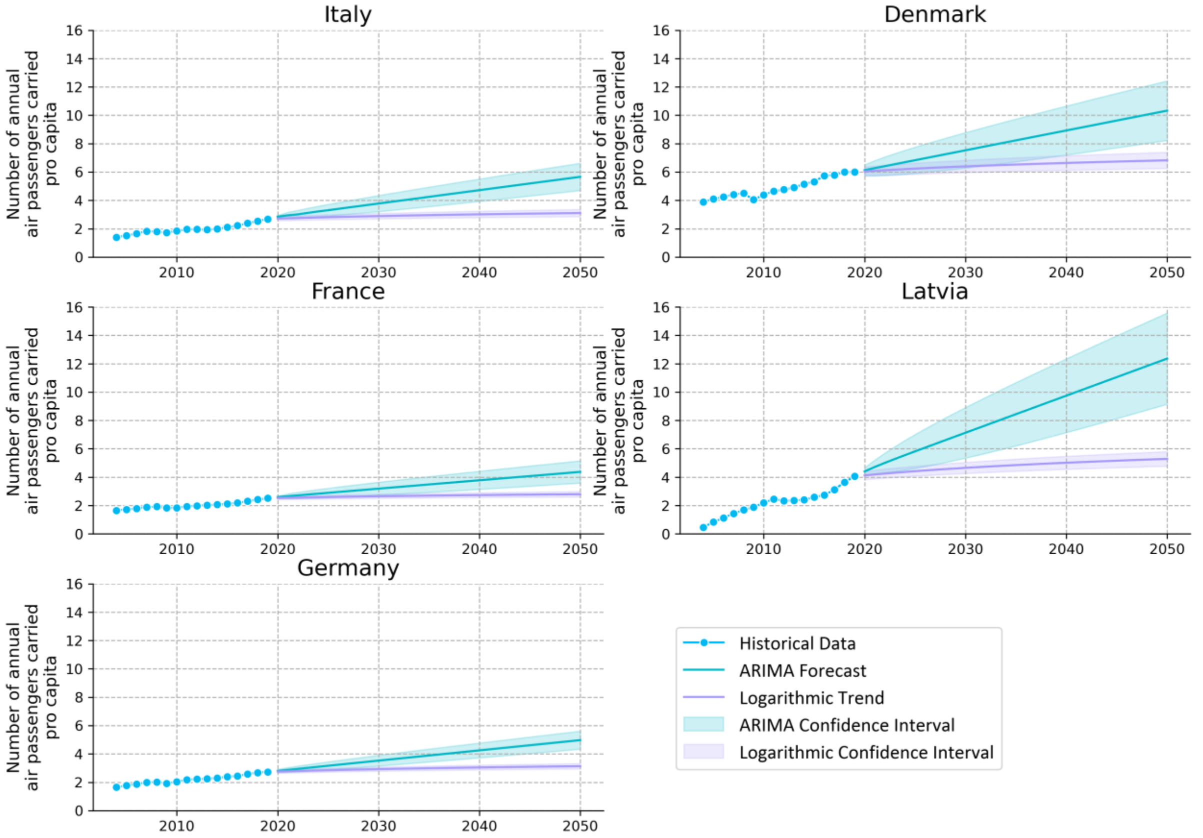

Figure 22 Reference scenario for flying less (Data source: Eurostat (2022) .

Extending input data through countries clustering analysis

Flying less is one of key sufficiency scenario assumptions which account for a large amount of greenhouse gas emission in aviation sector. For the clustering we use annual air passengers carried per capita obtained from (Eurostat, 2022). Data for the GDP per capita is obtained from (WEO, 2023).

For this sufficiency scenario assumption the member states were grouped into 4 clusters stars from cluster 0 to 4. The results shown in figure 23 the highest number of countries fall into the cluster 0, where the travel by air is limited and other modes of transport are being used for long distance travel.

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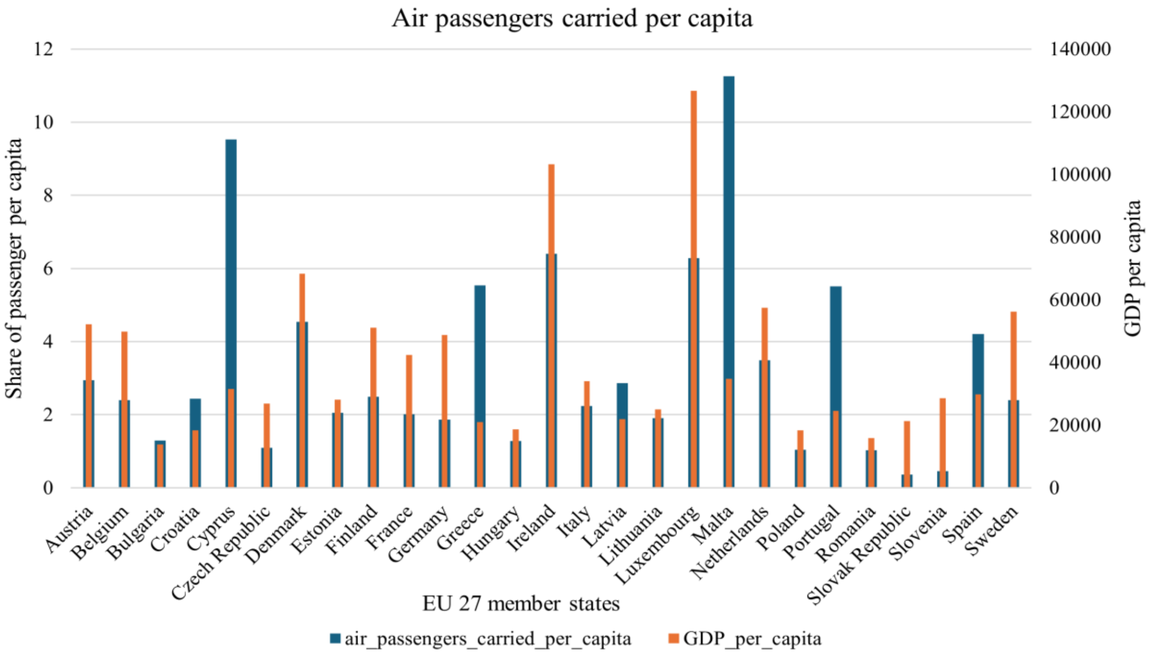
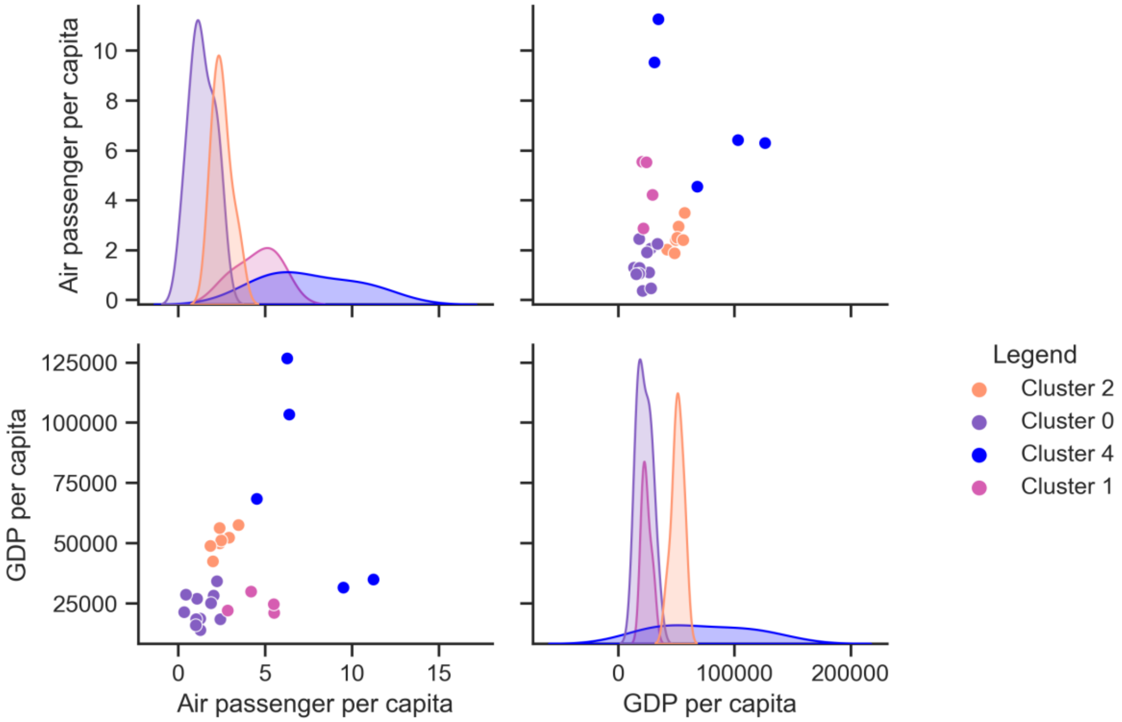


Figure 23. Air passengers carried per capita in EU27 countries, in relation with GDP per capita (Datasource: Eurostat, 2022).



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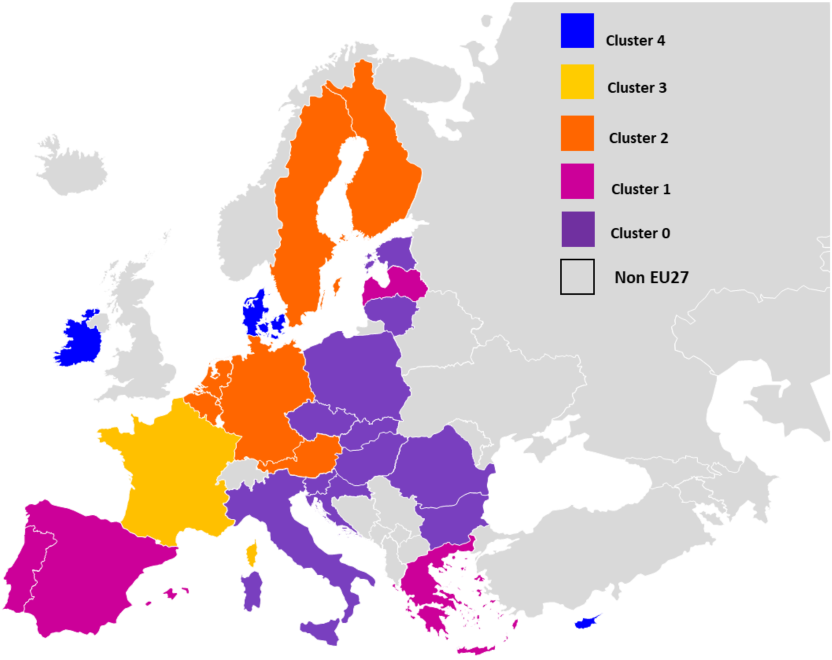

Figure 24 on Top, correlation matrix of air passenger per capita and GDP per capita. On the bottom, the resulting clustering classification for EU27 member states.

Figure 24 illustrates the EU countries with similar air passenger travel trends are placed into the same cluster. The countries fall in the cluster 0 such as Italy, Poland, Hungary etc., are highlighted with the purple colour. This trend also indicates that the GDP/capita could be an important factor which can significantly influence the public choice for the mode of transport. As the countries grouped into the cluster 0, their GDP/capita is lower than the countries fall into the cluster 4, especially Ireland and Denmark are the highest GDP/capita.

2.6.2. Sharing products

The implementation of the sufficiency scenario assumption related to the use of shared products among multiple residents in the same housing complex, as detailed in Deliverable 6.1 (Jacob & Taillard, 2024), analyses the shared use of a washing machine. This measure is estimated to save around ten washes annually per household. Consequently, this results in fewer washing machines being sold each year and a reduction in energy consumption due to the more efficient use of the appliance.

Modelling implementation and assumptions

This measure is modelled by reducing the households' final consumption of the Exiobase commodity "Machinery and equipment nec (29)", which analyses washing machines, together with an associated electricity consumption.

This measure exclusively involved the sharing of a commonly used household appliance, the washing machine. The sufficiency scenario assumption proposes the progressive adoption of a practice where multiple households share a washing machine. This approach allows for the purchase of fewer washing machines, which are used more frequently and loaded to near capacity as often as possible. Consequently, this leads to electricity savings while maintaining the same level of washing services provided to households. From an individual household perspective, this practice can save approximately the energy consumption of 10 fewer wash cycles per year.

Extending input data through countries clustering analysis

Figure 25 presents the historical data of municipal waste generation per capita for the five selected countries (Italy, Denmark, France, Latvia, and Germany) and the future trends obtained using the ARIMA and logarithmic curve fitting methods, as described in the methodology section (1.4). In this case, municipal waste generation per capita is used as a proxy for the level of product sharing, as lower waste generation could indicate higher levels of sharing and sufficiency, with people consuming fewer new products and instead sharing or reusing existing ones.

The historical data reveals stable trends in municipal waste generation per capita for all five countries over the observed period. This stability suggests that the level of product sharing and sufficiency practices have remained relatively constant in these countries.

The future trends obtained from the ARIMA and logarithmic models reflect the stability observed in the historical data. For all five countries, the projected municipal waste generation per capita remains relatively stable, aligning with the historical patterns.

As outlined in the methodology section, the final reference scenario for each country is obtained by taking the average of the ARIMA and logarithmic projections. This averaged result is then implemented in the MARIO model to assess the impact of sharing products on various sustainability indicators.

it is important to acknowledge that using municipal waste generation as a proxy for product sharing has its limitations. Waste generation is influenced by various factors beyond product sharing, such as overall consumption levels, waste management practices, and recycling rates. Therefore, while lower waste generation per capita may indicate higher levels of sharing and sufficiency, it is not a direct measure of product sharing practices. Further research using more specific indicators of product sharing would enhance the accuracy and robustness of the assessment.

Nevertheless, the stable trends observed in the historical data and the projected future trends provide a useful baseline for evaluating the potential impacts of promoting product sharing as a sufficiency scenario assumption.

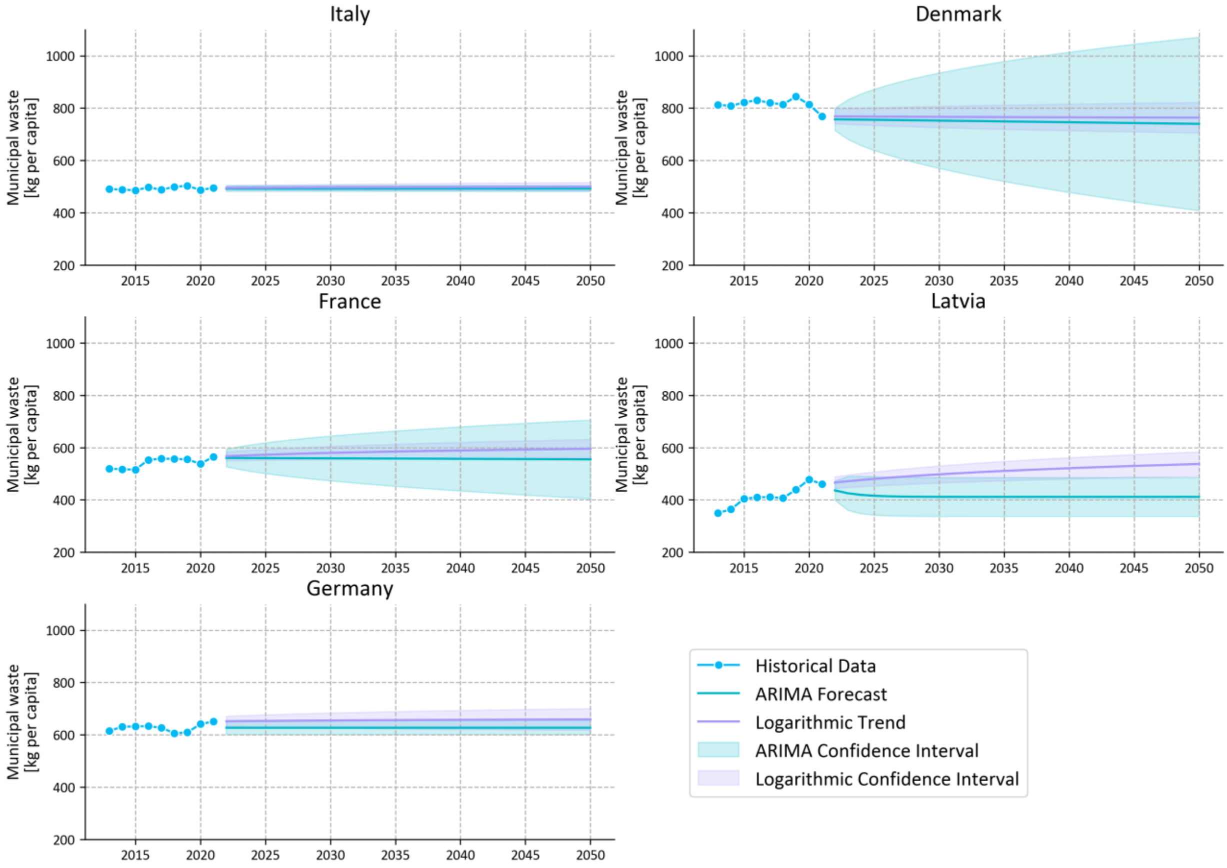

Figure 25 Reference scenario for sharing products (Data source: Eurostat, 2024b).

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Regarding the *Sharing product* sufficiency scenario assumption, the clustering approach is a proxy indicator, specifically the amount of municipal waste produced per capita annually in the EU member states. All the data are obtained from the Eurostat website[3] (Figure 26).

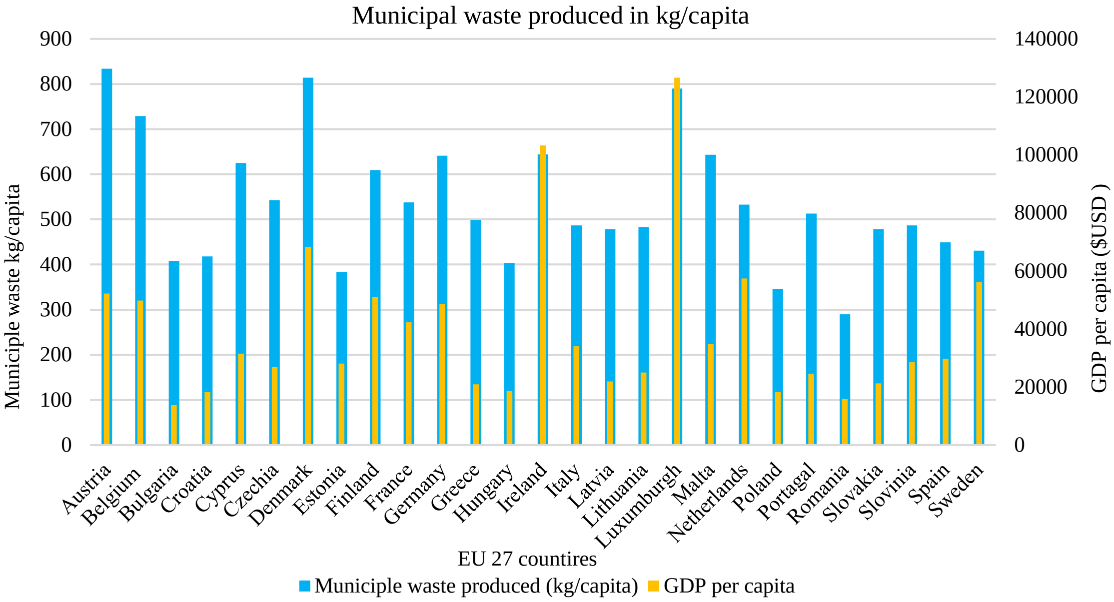

Figure 26. Municipal solid waste per capita produced in EU27 countries (Eurostat, 2024b)

The concept of sharing household products within the co-habitant as a sufficiency scenario assumption involves communal ownership and utilization of various items within a residential setting. Instead of each household or individual owning their own set of products, resources are shared among the residents to optimize resource usage, reduce waste, and promote sustainability. In this measure the clustering approach is implemented on 27 EU member states by using a proxy indicator the annual municipal solid waste produced (kg/capita) correlated with the GDP per capita ($USD/capita). The results presented in figure 26, proxy indicator shows, lower waste generation per capita could indicate higher levels of sharing and sufficiency, as people may be consuming fewer new products and instead sharing or reusing existing ones. The results show that the countries with highest municipal waste production correlation with the highest GDP/capita are sharing less products are placed in the fourth cluster while the countries with less waste production show more product sharing.

Figure 27 represents the map of the countries which have similar level of product sharing within household. The cluster 0-1 shows the highest number of countries which share more products based on the annual waste produced per capita, while the rest of countries placed in clusters 2-4 shows the highest annual waste production which led to less sharing of the products. It is important to note that the use of municipal solid waste data as a proxy for product sharing has its limitations. While this data was selected due to its availability for all countries and its historical trends, which allowed for both reference scenario creation and clustering, it may not accurately reflect the actual levels of product sharing in each country. For instance, as found in WP5, Denmark has a high number of households sharing washing machines compared to other countries, despite being in the cluster with the highest municipal waste production and, therefore, the lowest implied level of product sharing according to this proxy. This discrepancy highlights the need for caution when interpreting the results based on this proxy. Future research could benefit from more targeted data collection efforts to better represent product sharing practices across different countries.

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[3] Eurostat. https://ec.europa.eu/eurostat/databrowser/view/env_wasmun/default/table?lang=en

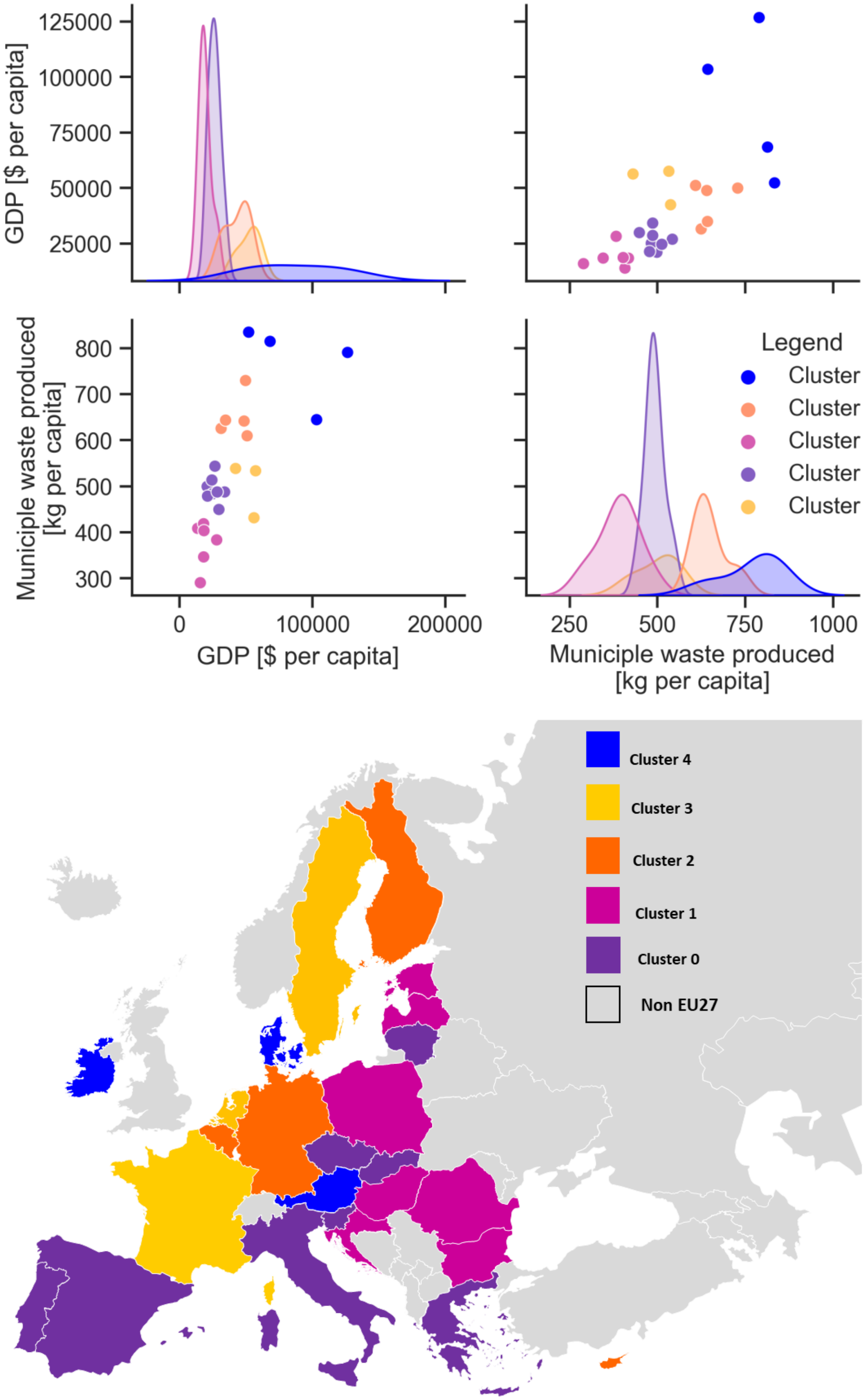

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Figure 27 on Top, correlation matrix of municipal waste per capita and GDP per capita. On the bottom, the resulting clustering classification for EU27 member states.

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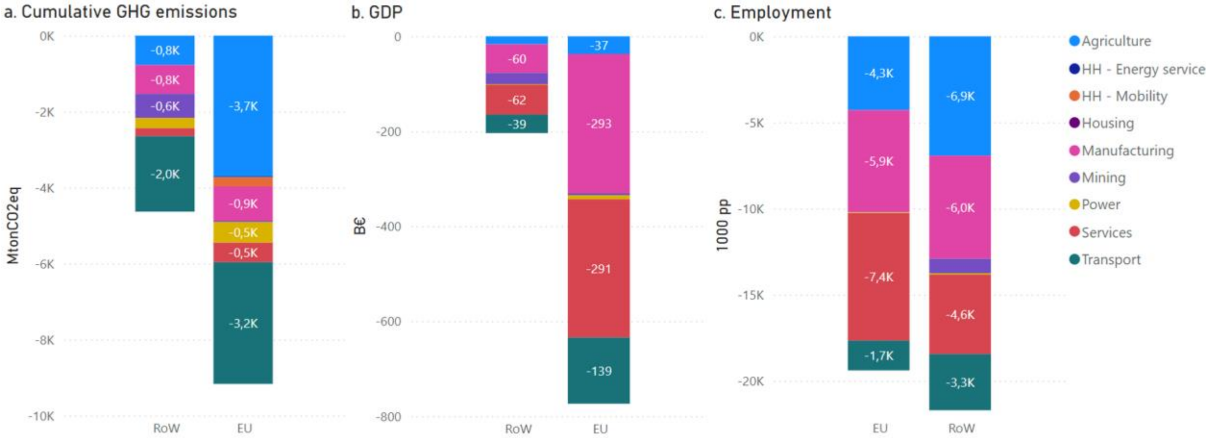
3. Results and discussion

This chapter analyses the overall results derived from the shocks implemented in the input-output model, based on the extended database described in the previous chapter. It is important to note that the similarity assumptions implied by the clustering analysis also affect these results.

The most significant subset of results is analysed and discussed, with various dimensions highlighted. Each European region, as well as non-European regions, can have different values for GDP, employment and greenhouse gases depending on the scenario. These values can be broken down into several categories and allocated to the sectors that constitute the economy.

3.1. Comprehensive impact assessment at EU level



from Reference	Absolute change	Relative change	Absolute change	Relative change	Absolute change	Relative change
EU	-9'166	-5.67%	-774	-4.03%	-19'396	-4.99%
RoW	-4'633	-0.28%	-204	-0.23%	-21'710	-0.17%
World	**-13'799**	**-0.75%**	**-978**	**-0.90%**	**-41'106**	**-0.32%**

Figure 28. Overall impact of all sufficiency scenario assumptions in 2050 in the EU and rest of the world (RoW) on main indicators: a) cumulative GHG emissions; b) GDP; c) employment. Impact is broken down by activity and reported in a table aggregating on regional basis, by means of absolute and relative variations with respect to reference

It is possible to identify an indicator for each of the three main dimensions of sustainability: cumulative greenhouse gas (GHG) emissions for the environmental dimension, GDP for the economic dimension, and employment for the social dimension.

These three indicators are presented in Figure 28, illustrating the effect of all measures combined, with a disaggregation into Europe versus the rest of the world, as well as by sector.

Regarding cumulative GHG emissions, it is evident that a significant portion of these reductions occur primarily within the EU, driven by a reduction in the agricultural sector, which includes cattle farming. The reduced consumption of bovine meat leads to a substantial decrease in emissions. Additionally, there is a supply chain effect linked to this measure and the cumulative impact of all other measures. Notably, there is a significant reduction in the rest of the world (RoW) in the mining sector, as less extraction is needed due to energy savings across various energy vectors. Overall, the cumulative emissions reduction due to sufficiency scenario assumptions from now until 2050 is approximately ~13.8 Gt CO_2 equivalent, corresponding to about 5% of the global carbon budget necessary to remain within the 1.5°C threshold with a 50% likelihood (Friedlingstein et al., 2023).

The sufficiency scenario assumptions also lead to substantial economic and social impacts. The measures are projected to result in a reduction of approximately ~4% in GDP within the EU by 2050. This reduction is significant and reflects the broad changes in consumption patterns and production processes that the sufficiency scenario assumptions entail. The economic impact is particularly pronounced in the services and manufacturing sectors, which experience substantial contractions, partly due to the large size of these sectors within the EU economy. The shift towards more sustainable

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practices and reduced consumption in certain sectors has wide-ranging effects on economic output, especially in industries closely tied to high emissions and resource use.

The social dimension, as indicated by employment, also sees notable impacts. The implementation of sufficiency scenario assumptions is expected to lead to a decrease of about ~20 million jobs within the EU by 2050. Interestingly, despite the measures being implemented within Europe, there are more job losses in the rest of the world compared to the EU. This is partly due to the higher productivity levels in Europe but also reflects the more labour-intensive nature of economies outside Europe. The contraction in employment in the RoW underscores the global interconnectedness of economic activities and the far-reaching impacts of consumption and production changes initiated within the EU.

In conclusion, the sufficiency scenario assumptions demonstrate substantial potential to contribute to global climate targets, achieving around 5% of the required reduction in the global carbon budget. However, these environmental benefits come at a notable economic and social cost, including a reduction in GDP and significant job losses both within the EU and globally. This underscores the importance of carefully considering the trade-offs and implementing supportive policies to manage the transition towards a more sustainable economy, ensuring that economic and social disruptions are minimized.

It is crucial to understand how these various sufficiency initiatives contribute to the aggregated results. By examining the impact of individual sufficiency scenario assumptions, the focus is particularly on their effects on GHG emissions. While there may be numerous other benefits, the primary motivation for evaluating sufficiency scenario assumptions is the reduction of greenhouse gas emissions.

As illustrated in Figure 29, the vast majority of the emissions reduction, which becomes increasingly evident over time, is primarily driven by two key measures: *Diets* and *Flying less*. These initiatives significantly outperform the others in terms of their impact on reducing GHG emissions.

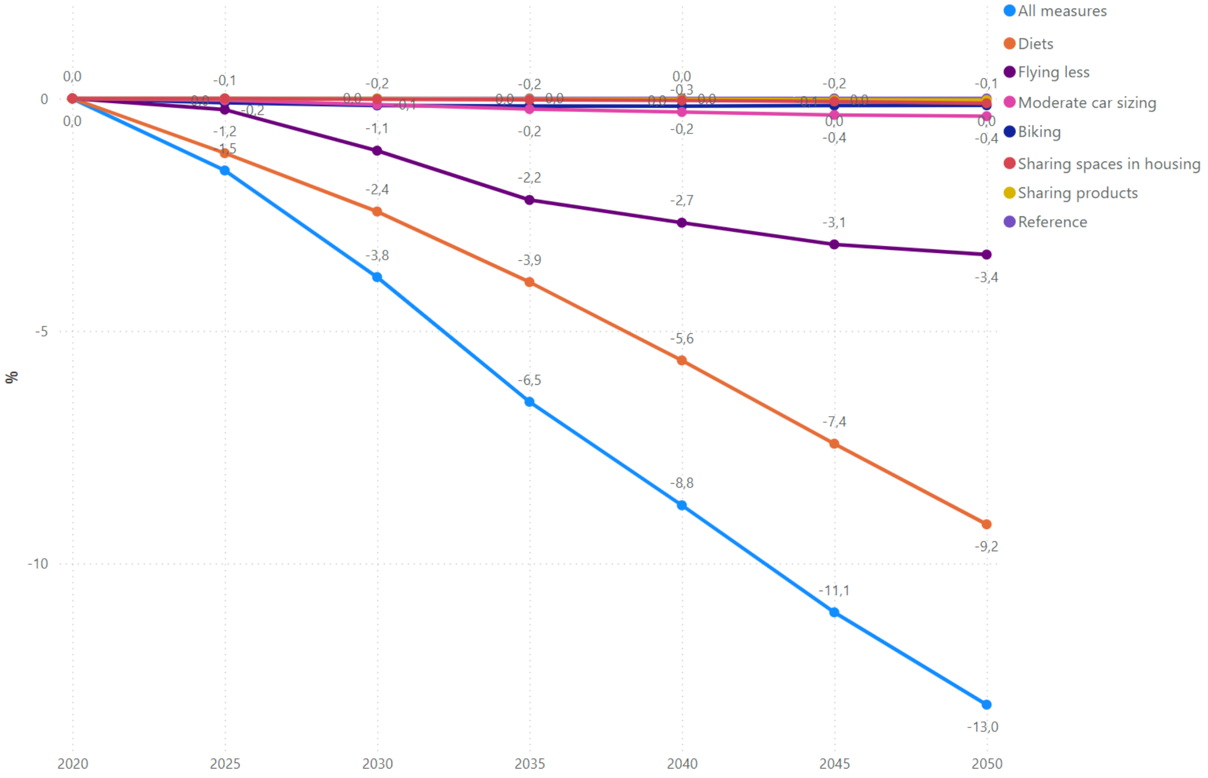

Figure 29. Relative reduction of GHG emissions brought by each sufficiency scenario assumption in the EU with respect to Reference scenario

The role of sufficiency scenario assumptions becomes increasingly significant as 2050 approaches, ultimately accounting for a 13% reduction in greenhouse gas emissions within the European Union compared to a scenario without these measures (*Reference*). This growing impact is due to the progressive implementation of each measure, which enhances their effectiveness over time.

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The *Flying less* measure quickly assumes a prominent role, with its trend stabilizing around 2035. In contrast, measures related to *Moderate car sizing*, *Cycling more*, *Sharing products*, and *Sharing spaces* are an order of magnitude less effective in reducing European emissions compared to *Diets* and *Flying less*. The following chapters delve into the contributions of each measure to better understand their individual impacts.

3.2. Impact of each sufficiency scenario assumption

3.2.1. Diets

The sufficiency scenario assumption regarding the change in diets results to be by far the most impactful among the modelled measures. As shown in Figure 29, the gradual transition to more vegetable-based diets allows to reduce GHG emissions by 9.5% with respect to the reference business-as-usual scenario in which the measure is not in place. The carbon footprint of each omnivore diets, is indeed significantly higher than vegetarian and vegan ones, as reported in Table 2: while the daily diet of an individual which consumes, among other foods, 170 g of meat in a day has a carbon footprint of roughly 14.8 $kgCO_2eq$/day, a vegan diet yields a 10-15 times lower impact: in fact, meat production is highly carbon intensive (producing 1 kg of beef meat may cause almost 100 kg of GHG emissions), while fruit's and vegetables' impact can be estimated around 1-2 $kgCO_2eq$/kg.

Table 2. Carbon footprint of each diet, expressed in $kgCO_2eq$ per capita per daily meals, in cluster countries

Diet	**Carbon footprint (kgCO2eq/day/capita)**				
	Denmark	**France**	**Germany**	**Italy**	**Latvia**
Omnivore 170g meal	9.01	9.71	10.66	14.88	16.58
Omnivore 75g meal	6.13	6.49	7.43	10.99	12.09
Flexitarian 30g meal	4.65	4.90	5.81	9.00	9.85
Vegetarian meal	3.89	4.27	5.33	8.89	9.93
Omnivore 100g opt meal	5.03	5.37	5.86	8.06	8.68
Omnivore 45g opt meal	3.47	3.68	4.17	6.06	6.48
Vegetarian opt meal	2.52	2.80	3.36	5.31	5.69
Flexitarian 20g opt meal	2.88	3.05	3.52	5.24	5.52
Pescetarian meal	2.75	2.48	2.61	3.21	2.68
Pescetarian opt meal	1.85	1.73	1.80	2.15	1.73
Vegan meal	0.90	0.93	0.92	1.06	0.79
Vegan opt meal	0.80	0.82	0.82	0.95	0.70

Most of the avoided impact coming from the change of diets would be attributed to the "Agriculture" sector: in 2050, this sector alone is responsible for 390 Mt CO_2eq avoided GHG emissions in the EU (comparable to the current emissions of Italy and of the five FULFILL countries, Denmark, Germany, France, Lativa and Italy considering cumulative changes – about 1.2 Gt CO_2), as shown in Figure 30. Only roughly 7% of this reduction is CO_2, while the majority is attributable to CH_4 and N_2O emitted by livestock.

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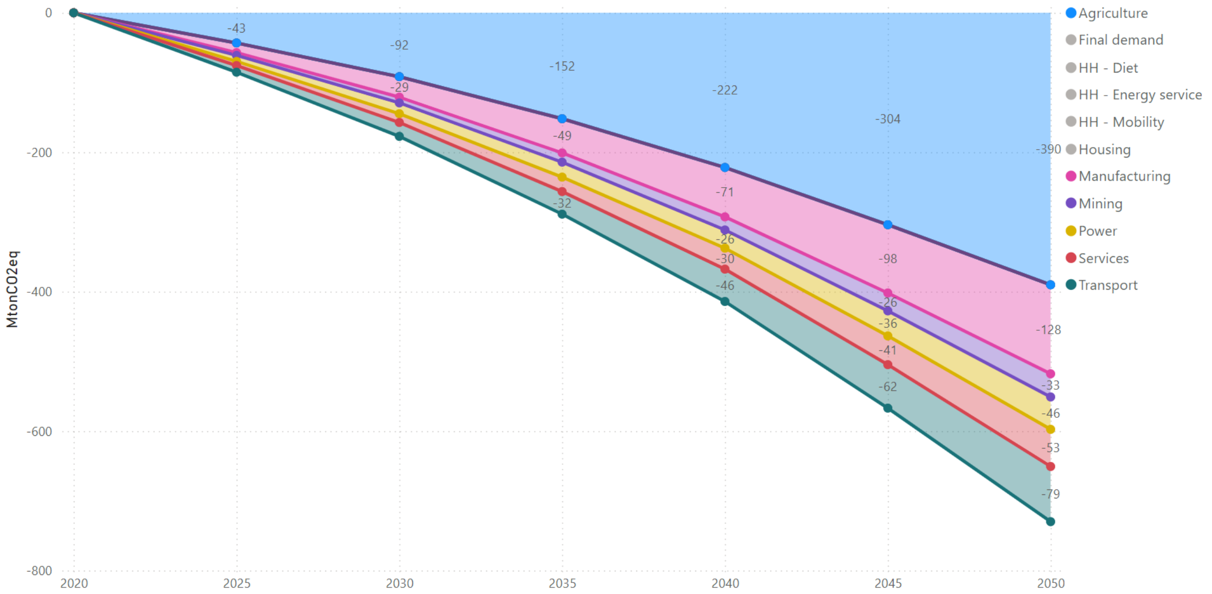

Figure 30. Yearly global GHG emissions reduction due to change in Diets by activity with respect to the Reference scenario

The transition to more environmentally-friendly diets has been modelled in each country, based on the results of the clustering analyses performed. The impact on each country depends therefore on the intensity of the transition assumed in that country and on the diets mix in the Reference scenario (i.e. how much each diet is diffused in a given country). In Figure 31, the same results shown at EU level in

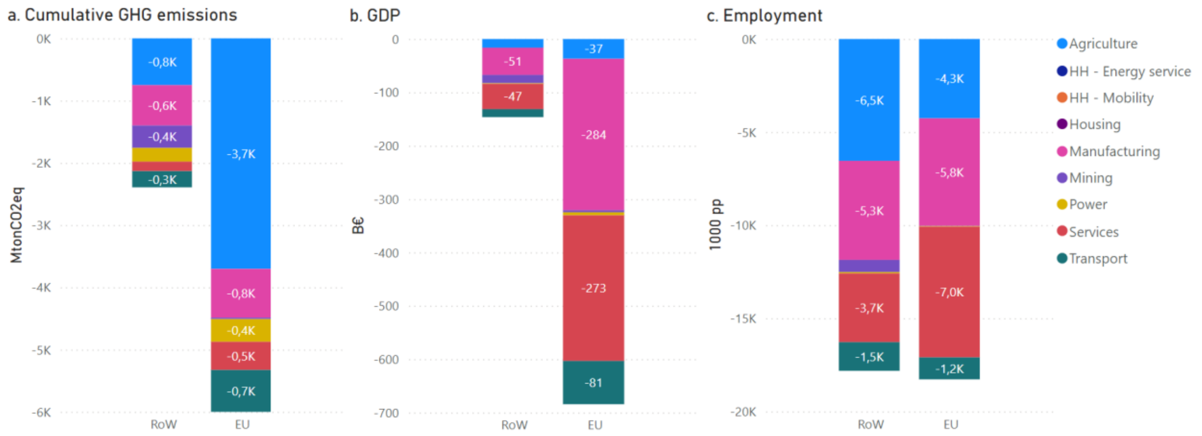

Figure 31. Overall impact of Diets measures in 2050 in the EU and rest of the world (RoW) on main indicators: a) cumul ative GHG emissions; b) GDP; c) employment. Impact is broken down by activity

The impact of dietary changes, being the most significant across all dimensions compared to all other measures, closely mirrors the overall impact of sufficiency scenario assumptions. Approximately one-third of the cumulative emission reductions originate from outside Europe, which nonetheless experiences a substantial reduction in agricultural emissions (3.7 Gt CO_2). The economic and employment impact predominantly affects the services sector, which also has the highest concentration of the workforce. In the rest of the world, which sees a reduction in the workforce comparable to that of Europe by 2050, the agricultural sector is most significantly affected.

3.2.2. Moderate car sizing

The *Moderate car sizing* sufficiency scenario assumption implies the increase of individuals attention towards smaller and more efficient (therefore less carbon-intensive) passenger cars. As reported in Figure 29, the impact of this measure is almost negligible, leading to a reduction in GHG emissions at EU level of 0.4% in 2050.

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This is explained by the findings reported in Table 3, where the carbon footprints of the two most adopted powertrain in the key cluster countries are compared for the *Reference* and the *Moderate car sizing* scenarios in 2020 and 2050. The results show how the environmental benefit brought by moving to smaller cars is much lower than the one brought by the decarbonization actions occurring independently on the sufficiency scenario assumption (e.g. electrification of power trains and decarbonization of the electricity mix). This is evident by comparing the last two columns of the table: the second-last column shows the variation of the carbon footprint from 2020 to 2050 in the *Moderate car sizing* scenario, while the last column reports the relative difference between the results of two scenarios in 2050. These latter values, apart from rare exceptions, are generally much lower than the former ones, indicating that the majority of the environmental impact reduction is attributable to the background policies and not to the sufficiency scenario assumption.

Moreover, the decarbonization of the electricity production mixes significantly influences the carbon footprint of Battery Electric Vehicles (BEV) which are also forecast to strongly penetrate in the private passenger transport mix of all the EU member states, reducing the relative impact of the sufficiency scenario assumption further.

Table 3. Carbon footprint (gCO_2eq/vkm) by passenger car powertrains in cluster countries in Reference and Moderate car sizing scenarios. Intra-scenario difference between 2020 and 2050 and across-scenario difference at 2050. Internal Combustion Engine Vehicle (ICEV), diesel & gasoline and Battery Electric Vehicle (BEV)

Country	**Powertrain**	**Carbon footprint (gCO2eq/vkm)**			**Δ 2020-2050 (%)**		**Δ scenarios 2050 (%)**
		2020	**2050**		**Reference**	**Moderate car sizing**	
			Reference	**Moderate car sizing**			
Denmark	ICEV, diesel & gasoline	219.7	247.9	206.8	13%	-6%	-17%
	BEV	54.3	29.5	24.9	-46%	-54%	-16%
France	ICEV, diesel & gasoline	198.7	104.8	100.4	-47%	-49%	-4%
	BEV	36.6	8.9	7.7	-76%	-78%	-13%
Germany	ICEV, diesel & gasoline	225.7	185.2	139.8	-18%	-38%	-25%
	BEV	111.9	69.9	56.4	-38%	-50%	-19%
Italy	ICEV, diesel & gasoline	187.4	147.12	134.4	-21%	-28%	-9%
	BEV	112.0	41.7	36.3	-63%	-68%	-13%
Latvia	ICEV, diesel & gasoline	249.5	151.5	131.7	-39%	-47%	-13%
	BEV	101.3	73.8	59.4	-27%	-41%	-20%

The analysis of the yearly GHG emissions reduction due to the *Moderate car sizing* measure in Europe by activity (Figure 32) reveals that the power sector accounts for most of the benefits. This is caused by BEV cars getting smaller in size (therefore having a better fuel economy), but also gain advantages from an increasingly cleaner electricity mix.

On the other hand, the environmental benefit of "HH – Mobility" (i.e. direct households' emissions of road private passenger transport) increase up to 2035, when diesel and gasoline cars begin to be strongly replaced by cleaner powertrains. The combined effect of the transition to lower-carbon vehicles and of the improved fuel economies of smaller cars, lead HH mobility in 2050 to represent less than 13% of the overall environmental benefit of the measure with respect to the *Reference* scenario.

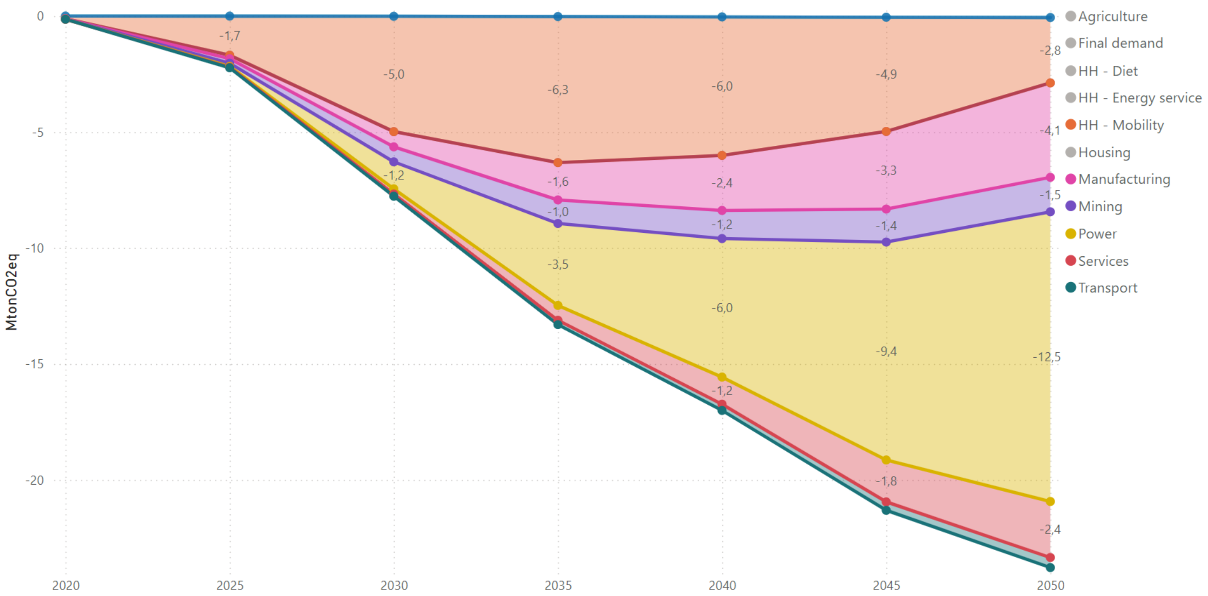

Figure 32. Yearly global GHG emissions reduction due to the transition towards smaller cars by activity with respect to the Reference scenario

In both the representation of emissions avoided by this sufficiency measure and the next one, there is a combined effect of *what* is being avoided and *how* that avoided action is fuelled. Specifically, in this case, the effects of an equal distance travelled in both the *Reference* and *Sufficiency* scenario are observed. Therefore, the transition to smaller cars as they become increasingly electric highlights a growing contribution from emissions in the power sector, which is not yet 100% carbon-free.

3.2.3. Cycling more

The impact of cycling more on total GHG emissions is minor: -0.15% by 2050Indeed, the assumptions made on the potential distance travelled by car replaceable with cycling are conservative: in 2050, only 1-to-3% (depending on the country) of the overall travelled distance by car is expected to be cycled.

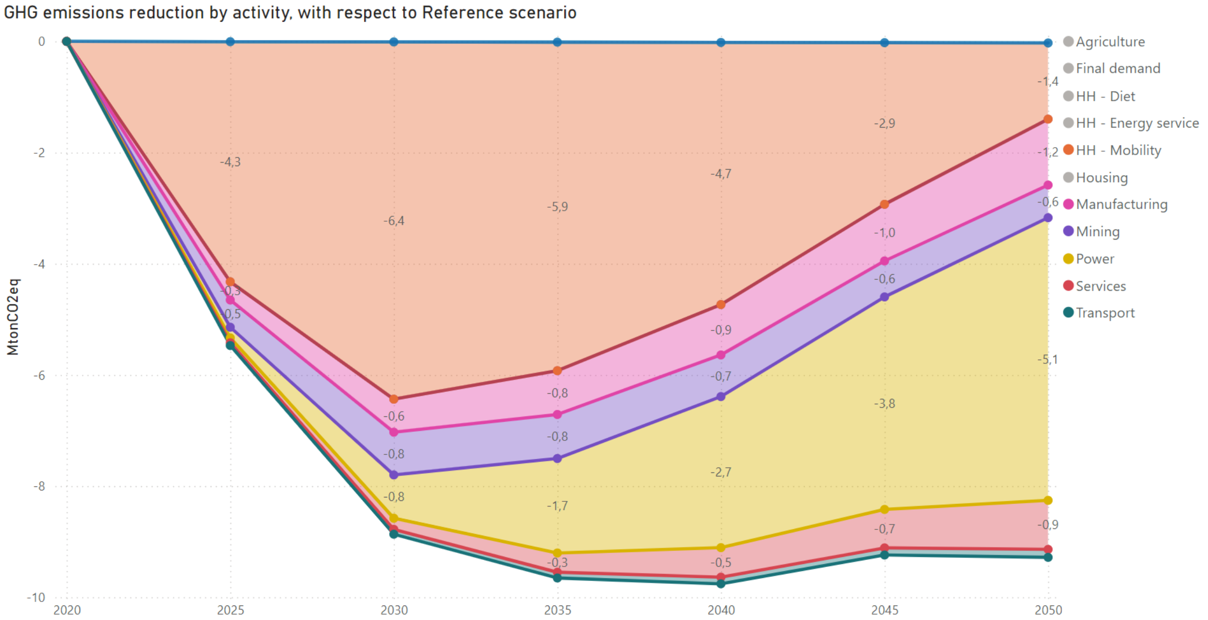

Figure 33. Yearly global GHG emissions reduction due to the transition towards cycling more by activity with respect to the Reference scenario

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As illustrated in Figure 33, the dynamics behind this measure are similar to the previous one: a significant portion of the emissions avoided are related to reduced driving activities. With less driving, there is a decrease in combustion emissions. These emissions diminish as the year 2050 approaches and the vehicle fleet becomes increasingly electrified. Consequently, there is a growing share of emissions from the electricity sector and fewer from the direct combustion of traditional cars (i.e., HH mobility), with minor contributions from other sectors. Interestingly, by 2035, the maximum reduction potential (around 10 Mt of CO_2 eq. compared to the absence of the measure) is already reached globally. This is because the modest reduction assumed in favour of bicycle-based mobility becomes comparable to the overall decarbonization of the system, reaching a plateau.

3.2.4. Flying less

Reducing aviation transport is the second most impactful sufficiency scenario assumption from the environmental standpoint, lowering EU GHG emissions in 2050 by 3.4%.

Figure 34 shows how most of the direct emissions would be reduced in the transport sector, especially attributable to the air transportation for obvious reasons.

The vast majority of emission reductions stem from the decreased use of air travel, leading to fewer direct emissions. These reductions, affecting both private individuals and industries, also account for the effects related to water vapor, which have been recently discussed in the literature and play an additional role beyond the traditional effects of combustion and the associated release of greenhouse gases. As in other cases, there is an indirect impact on the supply chain, with reductions also observed in the power and mining sectors due to the implicit use of fossil fuels assumed in the adopted database. Smaller contributions are associated with emissions avoided from goods and services that are not consumed due to the reduced number of air travels.

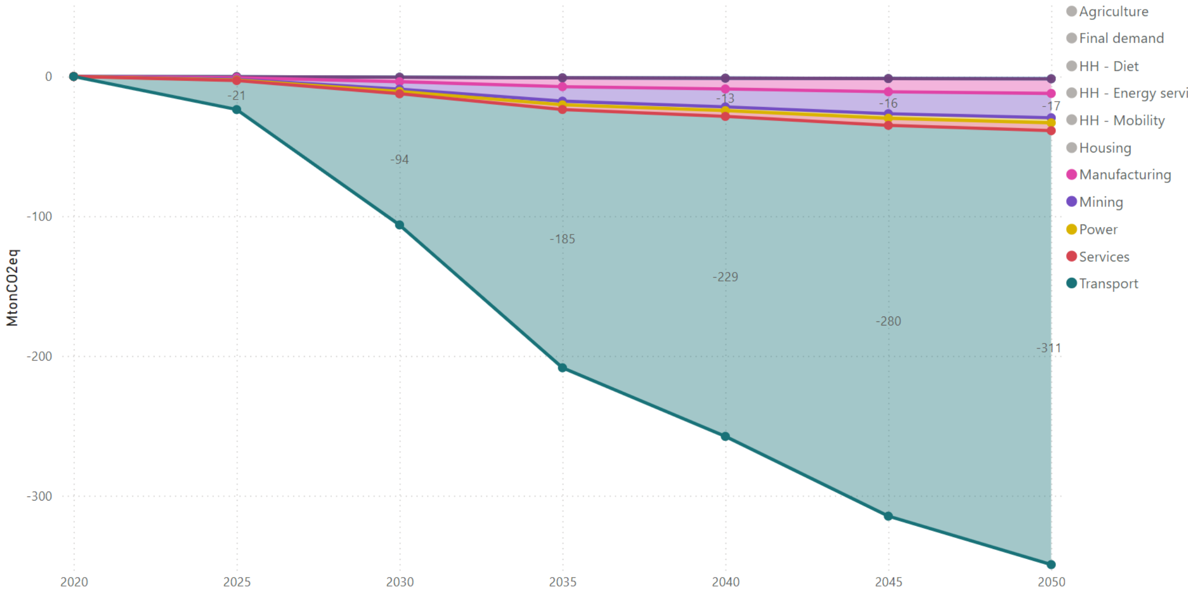

Figure 34. Yearly GHG emissions reduction due to Flying less sufficiency scenario assumption by activity with respect to the Reference scenario

3.2.5. Sharing spaces in housing

The impact of sharing spaces, therefore reducing the floor surface per capita in housing, is the second least environmentally impactful among the modelled sufficiency scenario assumptions, reducing only 0.11% of the European GHG emissions in 2050 with respect to the *Reference* scenario.

The rationale behind the reason why this measure is not particularly effective is similar to the one described for the *Moderate car sizing* measure: the background decarbonization processes (in this case the enhancement of efficiencies of heating systems and the transition towards cleaner technologies for heating such as heat pumps) brings a much more significant environmental benefit than the measure itself.

Also, as for the *Cycling more* measure, the assumptions on the reduced space per capita are not disruptive: individuals in fact, do not tend to move often and the ageing of the building stock is a process occurring over decades. In 2050, the floor surface per capita, depending on the country, reduces only from 3.4% and 5.1% GHG emissions per square meter.

As shown in Figure 35, the overall impact at European level in 2050 is around 6 Mt CO_2eq, which is comparable to the impact of around 2.8-to-4.5 million people (roughly 0.6%-to-0.9% of the current EU population) switching from an omnivore to a vegetarian diet. The reduction in emissions is primarily driven by a decreased direct impact from the energy services sector. Although this measure is not among the most significant in terms of its potential to decarbonise the economy, it shows a growing contribution even by 2050. Despite the electrification of a substantial portion of final consumption, the electricity system is not yet fully decarbonised, making the measure increasingly effective year after year. Additionally, the role of the services sector, associated with activities per square meter of housing services, leads to steadily increasing benefits, although these are less pronounced.

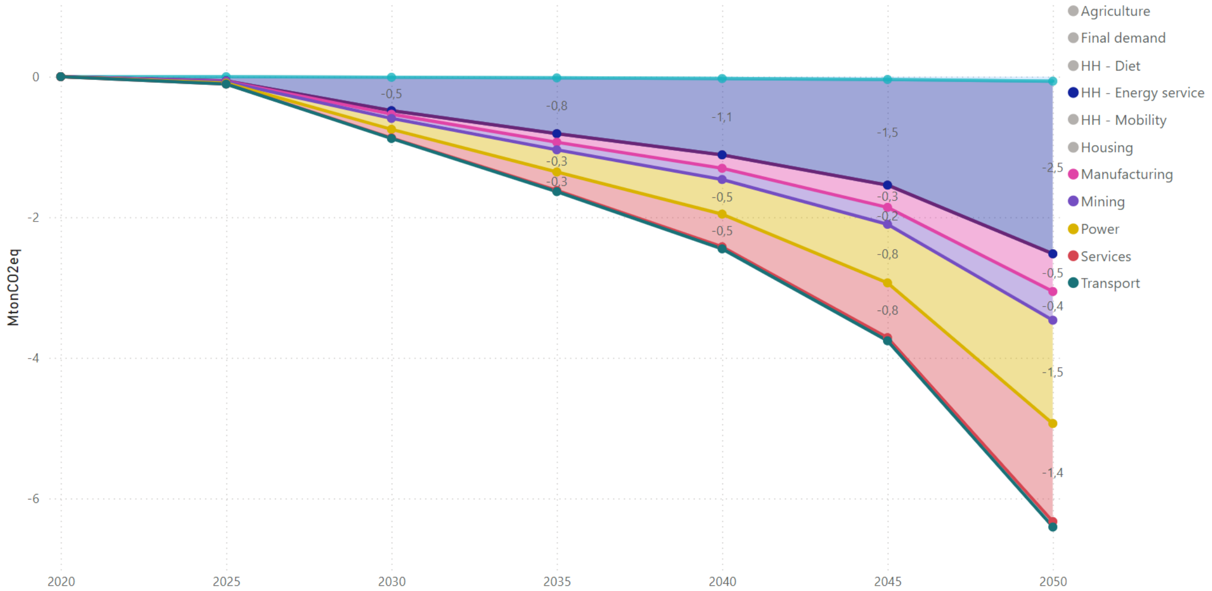

Figure 35. Yearly global GHG emissions reduction due to Sharing spaces in housing sufficiency scenario assumption by activity with respect to the Reference scenario

3.2.6. Sharing products

The least impactful sufficiency scenario assumption is the *Sharing products* measure. This measure is modelled by reducing the electricity consumption at residential level due to the sharing of washing machines. Moreover, thanks to the nature of the input-output model adopted, it is possible to model also a reduction in the demand for new washing machines sold.

Once again, the reduced effectiveness of the measure is attributable to the intensity of the measure itself: in 2050, the sales of new washing machines are expected to reduce by around 100 thousand to 1 million units, depending on the country.

In this case, as illustrated in Figure 36, a significant portion of the impact is seen in the manufacturing sector. Supply chain effects are evident as a result of producing fewer washing machines compared to the Reference scenario. Although these machines are also used less frequently, the impact on the Power sector is approximately one-third of that on the manufacturing sector alone. Naturally, the progressive adoption of this measure leads to a steadily increasing trend in emission reductions, though the variations differ every five years depending on the input assumptions.

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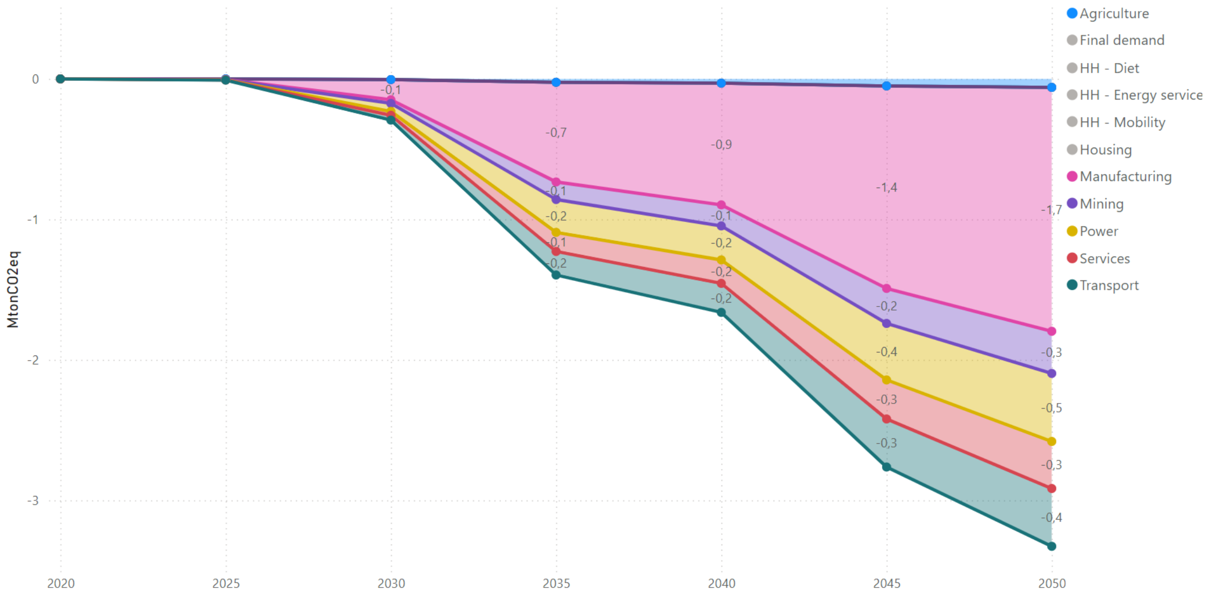

Figure 36. Yearly global GHG emissions reduction due to Sharing products sufficiency scenario assumption by activity with respect to the Reference scenario

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4. Conclusions

Sufficiency scenario assumptions have gained attention as a critical approach to achieving substantial decarbonization, supplementing technological advancements. While technological solutions are essential, they alone may not be enough to meet the ambitious climate targets. Sufficiency, which involves reducing overall consumption and optimizing resource use, presents a complementary pathway towards a more sustainable future. This report explores various sufficiency scenario assumptions and their impacts on greenhouse gas emissions, economic output, and employment.

In total, for all the sufficiency scenario assumptions analysed in the EU, the cumulative greenhouse gas emissions reduction potential until 2050 is about 13.8 Gt CO_2 equivalent (9.2 for EU and 4.6 for rest of the world), corresponding to a 6.6 % reduction for EU alone and about 5% of the global carbon budget.

Among the sufficiency scenario assumptions analysed, dietary changes and reduced air travel exhibit the most significant potential for GHG emission reductions. Dietary changes, particularly the shift towards plant-based diets, show a profound impact by reducing emissions in the agricultural sector, including livestock-related emissions. This measure alone contributes significantly to the overall emission reduction, representing a substantial share of the total potential savings. The *Flying less* measure also demonstrates a notable reduction in emissions, primarily by decreasing direct emissions from air travel. This measure's effectiveness is evident early on, with substantial impacts plateauing by 2035 as a consequence of domestic flight being assumed phased out by then. In contrast, other measures such as moderate car sizing, increased biking, and shared products and spaces, while beneficial, show comparatively smaller contributions to overall GHG reductions.

While the direct GHG reduction potential of measures like car sizing, biking, and sharing products and spaces may be limited, their broader impacts on other dimensions of sustainability should not be overlooked. These measures can lead to significant improvements in resource efficiency, reduced environmental degradation, and enhanced quality of life. For instance, shared housing and product usage can decrease material consumption and waste generation, contributing to a more circular economy.

The implementation of sufficiency scenario assumptions in the EU has substantial repercussions on the Rest of the World (RoW), particularly in terms of employment and GDP. While these measures primarily target consumption patterns within the EU, their effects ripple across global supply chains. The analysis reveals that the RoW experiences notable employment and economic impacts, often more pronounced than within the EU itself. This disparity can be attributed to the labour-intensive nature of certain sectors in the RoW and the interconnectedness of global markets.

The results presented in this report do not account for potential rebound effects, where the savings from sufficiency scenario assumptions might lead to increased consumption elsewhere. For instance, money saved from reduced air travel could be spent on other goods and services, potentially offsetting some of the GHG reductions. Interestingly, such rebound effects might also have positive impacts on employment, which are not captured by the input-output model. Reduced consumption in certain categories could lead to increased spending in others, potentially resulting in overestimating benefits of the measures.

Furthermore, these results should be interpreted in light of a key limitation of the model: while the most critical sectors such as electricity, private cars, and residential heating have been explicitly modelled and updated annually and regionally based on various assumptions and scenarios, the rest of the economy relies on the initial input-output table description. Consequently, the model does not account for potential increases in productivity and efficiency across sectors. This lack of consideration means the model may overestimate impacts—such as emissions, employment, and production factors per unit of output—due to its inability to reflect the likely productivity gains, i.e., the system's ability to achieve more with less.

The decarbonization of the electricity system and the parallel electrification of certain final consumptions (notably heating and private cars) could render some sufficiency scenario assumptions less relevant. However, the impacts of dietary changes and air travel reductions remain significant, underscoring the importance of focusing on these areas. Moreover, reducing the demand for electricity and heat can lower the costs associated with decarbonizing both the electricity production and the heating system, which is also a relevant aspect.

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While this report provides a comprehensive overview of the impacts of sufficiency scenario assumptions, it is constrained by several limitations. The scope of the analysis does not allow for an in-depth examination of every dimension and region. Detailed regional assessments and sector-specific studies are needed to fully understand the localized effects and to tailor sufficiency scenario assumptions more effectively. Additionally, the assumptions and data used, while robust, may not capture the full complexity of real-world scenarios, highlighting the need for continuous refinement and validation of the model. Moreover, the application of sufficiency scenario assumptions to all European countries required assuming that evolutions and/or total consumptions are based on similarities suggested by the clustering algorithm, which introduces an additional layer of approximation in the results.

In conclusion, sufficiency scenario assumptions offer a promising pathway to augment technological solutions in the quest for decarbonization. The significant GHG reductions from dietary changes and reduced air travel underscore their potential, while the broader benefits of other measures highlight the multifaceted nature of sustainability. However, the global implications and potential rebound effects must be carefully managed to ensure a holistic and effective approach to sustainability.

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