# The role of sufficiency measures in a decarbonizing Europe

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## Keywords

Energy scenarios, Energy systems modelling, Input-Output analysis, Impact assessment, Sufficiency, Lifestyle changes, GHGs emissions reduction

## Abstract

Europe's ambitious climate goals highlight the importance of combining energy policies with technological decarbonization; however, these efforts alone may not achieve the necessary emissions reductions. Existing models for low-carbon transitions often focus on technological interventions, without fully integrating the decarbonization potential of behavioural shifts towards sufficient consumption. A comprehensive model that incorporates both sufficiency and technological measures, with realistic adoption rates for sufficiency actions, is essential to effectively evaluate climate targets' feasibility. This study introduces a multi-regional, multi-sectoral model, based on an input-output framework, to quantify the decarbonization impacts of sufficiency measures on greenhouse gas (GHG) emissions, Gross Domestic Product (GDP), and employment under European Union (EU) specific scenarios through 2050. The model evaluates six sufficiency measures: reductions in air travel, personal living space, and vehicle size; increased product and space sharing; greater cycling adoption; and a shift toward plant-based diets. Combined, these measures may reduce EU annual GHG emissions by up to 13%, yielding global cumulative savings of 13.8 Gt $CO_2$eq by 2050, while having moderate first-order effects on GDP and employment. However, most of the emissions reductions stem from dietary changes and reduced air travel, while other measures – such as car downsizing and cycling – show limited effects due to their dependence on concurrent projected electrification and decarbonization of the energy system. The findings indicate that dietary changes and reductions in air travel provide the most substantial and resilient emissions reductions, making them critical priorities for policy support.

## 1. Introduction

The ambitious climate commitments adopted by Europe to deal with climate change invokes for the definition and application of appropriate policies. Understanding how to achieve a balance between mitigation and adaptation measures, particularly in terms of minimizing both the costs of climate-related damages and those of the mitigation policies themselves, is essential. In fact, European policy makers are having difficulties fulfilling their climate goals by decarbonizing the energy supply chain [1]: changes in lifestyle may provide a complementary contribution towards decarbonization of the economic system [2,3].

In this context, sufficiency is defined as a set of social, infrastructural, and regulatory conditions to enable individual and collective lifestyles transformation of households' behaviour, with the final aim of reducing energy demand and related Greenhouse Gases (GHG) emissions, while simultaneously contributing to societal well-being.

The objective of this study is to quantitatively assess the contribution that a set of sufficiency measures applied at the households' level may potentially bring in reducing overall GHG emissions directly and indirectly caused by each individual country of the European Union at 27 members (EU) region in future decarbonization scenarios. Specifically, potential changes in GHGs emissions, Gross Domestic Product (GDP) and employment induced by sufficiency policies are quantified as proxies of the environmental, economic and social dimensions of sustainability, respectively.

The rest of this article is structured as follows: section 1 concludes with a literature review on sufficiency modelling and its quantitative assessment. Section 2 outlines the materials and methods used in the study, which form the basis of the model. Section 3 explains the data and how they define the scenarios. Section 4 presents the results of the analysis. Finally, section 5 discusses the findings and provides conclusions.

## 1.1. Literature review

Sufficiency, aimed at reducing demand via shifts in consumption behaviours, complements efficiency measures but requires policy support for broad adoption [4]. Research categorizes sufficiency into four main areas – absolute reduction, modal shifts, product longevity, and sharing – across housing, nutrition, mobility, and miscellaneous [5].

Dietary shifts, especially reduced meat consumption, are significant in lowering GHG emissions. Studies indicate that aligning meat intake with nutritional guidelines could cut emissions from meat production by half, while modelling of zero food waste, lower calorie intake, and vegan diets suggests a possible 21% reduction in carbon footprints [6,7]. A recent analysis finds that reducing meat intake to healthy levels and avoiding ruminant meats could nearly halve food-system GHG emissions by 2050, with communication linking dietary changes to flight-equivalent emissions resonating with consumers [8]. Furthermore, models incorporating sustainable lifestyles, like plant-based diets and local economies, highlight the contribution of sufficiency-oriented lifestyles toward UN SDGs on responsible consumption, also adopting Environmentally Extended Multi-Regional Input-Output (EE-MRIO) model based on the EXIOBASE database [9] [10].

Sufficiency-driven changes in lifestyle, particularly in mobility and housing, are essential to achieving policy targets for emission reductions and energy security [11]. Studies using EE-MRIO models show that shifts like increased cycling and co-housing can significantly reduce emissions, with impacts varying widely across urban contexts [12]. Tailored policies and supportive infrastructure are thus crucial to enable adoption on a broad scale [13–15].

Integrating sufficiency into energy models is essential for capturing its impacts across sectors and regions, with studies highlighting the importance of embedding it within broader sustainability frameworks – also adopting EE-MRIO – to assess its role alongside efficiency and consistency [16–18]. Research also suggests an energy consumption threshold, beyond which additional use offers minimal well-being gains, positioning sufficiency as key for sustainable energy strategies [19]. However, achieving the needed temporal and regional granularity for long-term sufficiency impacts remains a challenge [20,21].

Although current research confirms the importance of sufficiency in reducing emissions, few studies offer a comprehensive, long-term quantitative framework that assesses environmental, economic, and social impacts in unison. Additionally, while some research explores individual sufficiency measures, such as dietary shifts or changes in mobility, limited evaluation exists on the combined effects of these measures within future decarbonization scenarios.

Recent research using ecological macroeconomic models has highlighted the complex relationship between decarbonization, economic systems and social outcomes. D'Alessandro et al. use their EUROGREEN model to show that while green growth policies can reduce emissions, they can exacerbate inequality and unemployment, while degrowth scenarios achieve greater environmental and social benefits despite higher public deficits [22]. Similarly, Nieto et al. use their MEDEAS-Europe model to challenge conventional assumptions about the energy transition, finding that achieving the EU's Energy Roadmap 2050 targets within a growth-oriented framework could limit economic development due to energy constraints [23]. Both studies converge on a critical insight: only scenarios that fundamentally rethink growth paradigms through reduced working hours, structural economic shifts and pro-worker policies can successfully reconcile climate goals with social welfare, suggesting that comprehensive sufficiency measures must be an integral part of effective climate policy.

Cap et al. examine the limits of industrial decarbonization in reducing household carbon footprints to levels compatible with the 1.5°C target. Using a scenario model for 49 countries (with a focus on the EU27), they find that while technological changes can lower emissions, they are insufficient alone to reach 1.5°C targets without lifestyle shifts [20]. Costa et al. investigate the impact of lifestyle changes on Europe's decarbonization efforts, revealing that behavioural modifications can contribute over 20% of the GHG emission reductions needed for net-zero targets by 2050. The most important conclusion is that without incorporating lifestyle changes, Europe will heavily rely on carbon removal technologies to meet its climate goals [21]. Zimmermann evaluates the environmental savings potential of sufficiency, consistency (i.e. using sustainable resources like circular materials and renewable energy), and efficiency measures in the European building sector using the EUCalc tool. Key results show that sufficiency measures can reduce greenhouse gas emissions by 16%, while efficiency and consistency measures can achieve reductions of 31% and 22%, respectively. The most effective sufficiency measure identified is the reduction of living space per capita. [16]. Bauer and Sterner examine the impacts of lifestyle changes on energy demand and greenhouse gas emissions in Germany. Using an energy system model, the study shows that it is possible to reduce final energy demand by 61% in 2050 relative to 2019 levels through a combination of technological measures and lifestyle changes, while saving 71 billion euro in 2050 [17].

The prevailing literature suggests the necessity for comprehensive models that integrate sufficiency measures within climate impact assessments, particularly with multi-sectoral and multi-regional perspectives. Only a limited number of studies attempt to conduct quantitative, long-term assessments of the environmental, economic, and social impacts of the proposed policies. Some of these studies, which are summarized in Table 1, adopt approaches that are somewhat comparable to this study. These studies highlight sufficiency's potential for emissions reduction, often focusing on actions like dietary shifts or mobility changes but rarely within broader decarbonization scenarios. This research advances the field by using an EE-MRIO model in a European energy transition context through 2050. With global scope and detailed EU27 country-level disaggregation, it captures sufficiency's regional and temporal impacts. Unlike prior work, this multidimensional framework assesses individual sufficiency measures across environmental, economic, and social indicators, offering more precise insights for policymakers.

*Table 1 – Literature review of articles including sufficiency measures in energy system modelling.*

| | | **Model characteristics** | | | | | **Model application and input data** | | | **Model results** | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Authors** | **Year** | **Model name** | **Modelling approach** | **Modelling Technique** | **Target year vs transition (time period)** | **Spatial resolution** | **Sufficiency measures** | **Sufficiency Measures estimation method** | **Input data** | **Dimensions** | **Indicators** |
| [10] | 2019 | EE-MRIO | Top-Down | Input-Output | Deviation with respect to baseline (2007) | Europe with global supply chains (43 countries and 5 rest-of-world regions) | 19 | Participatory backcasting workshops | EXIOBASE2 database | Environment | Carbon footprint, Human toxicity potential, Land footprint and Water footprint |
| [21] | 2021 | EUCalculator | Integrated assessment model | Simulation | Transition (2020 - 2050) (1 year, results provided every 5 years) | EU27 + UK and Switzerland (EU27+2), with capability for country-level analysis (but only aggregated results are provided) | 4 | Literature review and expert consultations | EU's Long Term Strategy (LTS) Baseline scenario | Environment, Energy | GHG emissions, Energy demand |
| [16] | 2022 | EUCalculator | Integrated assessment model | Simulation | Transition (2020 - 2050) | EU27 + UK and Switzerland (but only aggregated results are provided) | 27 | EUCalc (Highest ambition) | EUCalculator | Environment, Energy | GHG emissions, renewable & non-renewable energy |
| [24] | 2022 | AnyMOD | Bottom-Up | Linear programming | Target year 2035 | Germany | 44 grouped into sections of conventional electricity, mobility and heat. | Literature | Time series from openENTRANCE project, technology cost assumptions, renewable energy potential | Economy, Energy | Total costs, energy demand, production and storage capacities |
| [25,26] | 2022 | EnergyPlan | Bottom-up | Simulation (heuristic) | Target year 2030 (vision to 2050) | Denmark | 6 | Literature review<br>Survey data<br>Bottom-up calculations from CACTUS project | National energy statistics<br>Household survey data<br>Technical parameters from literature<br>CACTUS project assumptions | Environment, Energy, Economy | Primary energy use (PJ/TWh), Fossil fuel use (PJ), $CO_2e$ emissions, Energy system costs, Final energy demand, Installed capacity, Energy production mix |
| [27] | 2023 | PyPSA-Eur | Bottom-up | Linear programming | Transition (2020-2050) | 5 interconnected European countries (Belgium, France, Germany, Netherlands, and Great Britain) | 7 | Based on CLEVER scenario assumptions | Different databases: JRC-IDEES, Eurostat, CLEVER project, | Environment, Economy | Total annual system costs (€/year)<br>Grid expansion requirements (GW)<br>Installed capacities (GW)<br>Energy demand by |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | CORINE land-use database, Danish Energy Agency, ENTSO-E | | sector (TWh) $CO_2$ emissions (Mton/y) Investment costs by technology (€/year) Storage requirements (TWh) |
| [28] | 2024 | Simplified Energy Prospective and Interterritorial Analysis (SEPIA) tool | Bottom-up | Not specified | Transition (2019 - 2050) | European level (EU30: EU27 plus UK, Norway and Switzerland) with country-level detail | 15 | Based on CLEVER scenario assumptions | Collaborative Low Energy Vision for the European Region (CLEVER) scenario | Energy, Environment | Final energy consumption (MWh/cap), GHG ($CO_2$eq) |
| [17] | 2025 | Energy system model by Research Centre for Power Networks and Energy Storage (specific name not provided) | Bottom-up | Linear programming | Transition 2019 - 2050 (1 year, resolution 1 h) | Germany | 11 | Literature | GHG emission factors for fuels, industrial processes, industrial products, waste quantities and agricultural parameters | Environment, Energy and Economy | GHG emissions, Final energy demand, Total system costs |
| [22] | 2020 | EUROGREEN | Integrated assessment model | System dynamics, ecological macroeconomics model using IO tables | Transition (2014-2025) | France | Varies (e.g., reduced consumption) | Authors analysis | Eurostat, EU KLEMS, WIOD | Environment, Economy, Social | GHG emissions, GDP, Employment, Gini index |
| [23] | 2020 | MEDEAS-Europe | Integrated assessment model | System dynamics, ecological macroeconomics model using IO tables | Transition (2015-2050) | EU and Rest of the World | Varies (e.g., reduced consumption and worked hours) | Authors analysis | EU KLEMS, WIOD | Environment, Economy | GHG emissions, Total primary energy supply, GDP, Employment |
| This work | - | EE-MRSUT model built using MARIO [29] | Top-Down | Input-Output | Transition (2020 - 2050) | Global with focus on EU27 (with capability for country-level analysis) | 6 (*Diets*, *Flying less*, *Moderate car sizing*, *Cycling more*, *Sharing spaces*, *Sharing products*) | Focus groups and survey and other input from CLEVER scenario (négaWatt Association, 2023) | Exiobase v3.3.18 hybrid-units | Environment, Economy and Social | GHG emissions, GDP, employment |

# 2. Materials and methods

This chapter outlines the methodological approach used to assess the impact of sufficiency measures implemented in the European Union (EU) up to 2050. The model was developed based on the Leontief's Input-Output analysis framework [30,31]. Manipulation of the datasets, construction and solution of the mathematical model were performed through *Multi-functional Analysis of Regions through Input-Output* (MARIO), an open-source Python package [29].

## 2.1. Input-Output modelling framework

This study employs a model based on Environmentally-Extended Multi-Regional Supply and Use Table (EE-MRSUT in the following). It is grounded on Leontief's Input-Output analysis, a widely adopted (see section 1.1) analytical framework to capture the interdependencies within all sectors of the economy, allowing for the evaluation of both direct and indirect effects due to changes in final demand or technologies' structure.

Indeed, several studies have highlighted MRIO models to derive appropriate carbon footprint estimates based on consumption-based accounting frameworks [32,33]. The EE-MRSUT model employed in this paper is grounded on national economic and environmental accounts, and it consists of a set of linear algebraic equations that enables to quantify products and services supplied, traded and consumed within a cluster of national economies, and the related environmental consequences [30].

With reference to Figure 1, the supply ($\mathbf{S}$) matrix allocates data about the production of commodities by industrial activities, while the use ($\mathbf{U}$) 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 $\mathbf{Y}$ matrix. The total demand of commodities vector ($\mathbf{Q}$) is derived by summing intermediate transactions traced in $\mathbf{U}$ and $\mathbf{Y}$. The total supply of industrial activities can be calculated by summing all the outputs of each activity. From these matrices, coefficients matrices are derived ($\mathbf{s}$, market share matrix and $\mathbf{u}$, $\mathbf{v}$ and $\mathbf{e}$ matrices of specific use of commodities, factor of production or satellite accounts respectively) adopting an industry-based technology assumption, which means that all products produced by an industry are made using the same technology, regardless of the specific product mix (Figure 1).

The implementation of sufficiency measures in the I-O framework primarily – but not exclusively – involves modifications to final consumption vectors ($\mathbf{Y}$) across regions and sectors. These modifications depend on the specific sufficiency measure being modelled. For diets, private car transportation and heating measures, the model introduces specialized sectors, allowing for granular analysis of dietary, mobility and heating patterns, explicitly modelling specific requirements and technology penetration. When a specific scenario is active, the technical coefficients are adjusted accordingly – for example, modifying fuel consumption rates per kilometre when shifting to smaller or vehicles. This represents how specific scenarios influence not only final consumption patterns (through the $\mathbf{Y}$ matrix) but also the underlying production technologies' input requirements (through the $\mathbf{u}$ matrix) and market shares (through the $\mathbf{s}$ matrix), capturing the dual impact of behavioural and technological changes within the economic system. To effectively model the sufficiency measures, several new commodities were added to the framework (i.e. *Heating services*, measured in kWh; *Housing services* measured in m²; *Car mobility* measured in km, and *Meals* in unit quantities). Additionally, new activity sectors were introduced to the model: one for each type of diet, one for each type of vehicle powertrain and one for each residential heating technology. The quantities and specific sectors affected vary by measure and are detailed in subsequent sections where each sufficiency action is discussed. Readers are directed to the supplementary material for a detailed technical description of the model's equations (also reported in Figure 1) and their underlying assumptions, while all modifications are fully documented in the open-source GitHub repository for complete transparency and reproducibility.

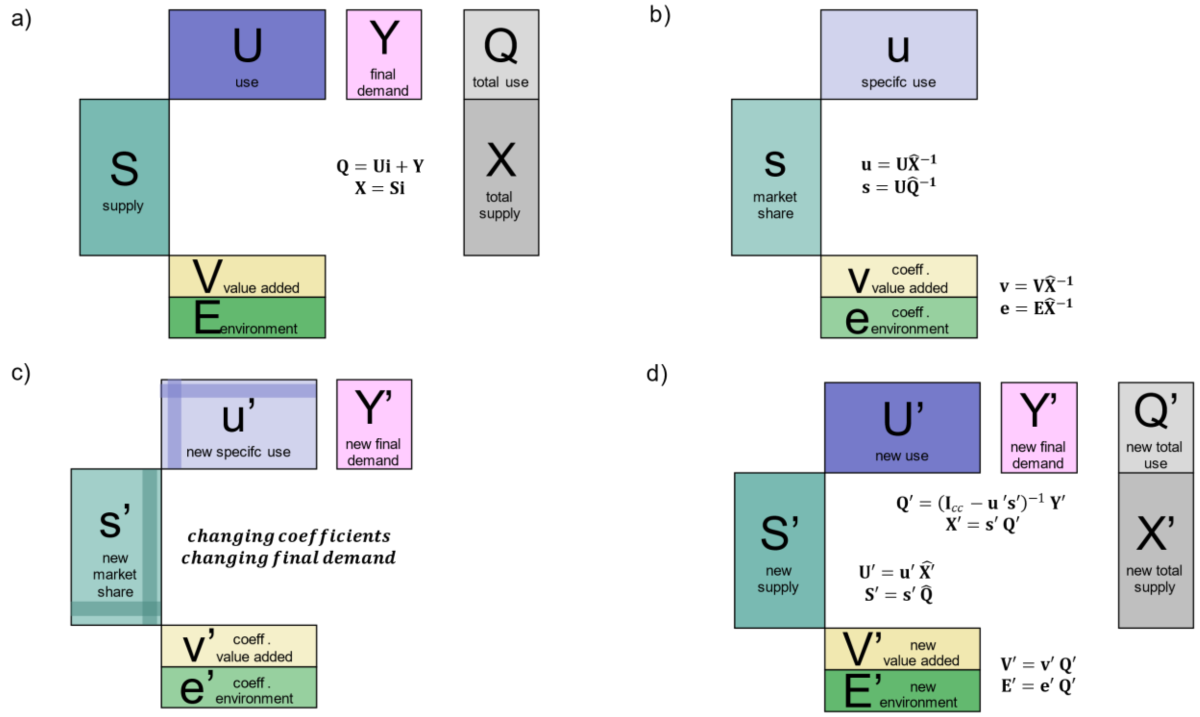



*Figure 1 – Mathematical structure of the input-output framework adopted in this research: a) the original EE-MRSUT is adopted and total production by activities and commodities are computed b) matrices of coefficients are computed adopting an industry-based technology assumption c) shock on coefficient matrices and final demand is performed c) flow matrices are computed and represent the results of each run – defined by each scenario and year – of the model.*

The EE-MRSUT model is built on the Leontief production function, which assumes fixed input coefficients to produce goods and services. This allows for the calculation of total (direct and indirect) requirements to meet a given final demand. To simulate dynamic changes over time, the model was run at 5-year intervals from 2020 to 2050, inclusive. For each period, the input-output coefficients and final demand vectors were updated. However, these updates were limited to specific sectors and parameters directly affected by the sufficiency measures and energy transition scenarios, while the rest of the economic structure remained constant.

## 2.2. Scenario analysis: method and core assumptions

Scenario analysis is performed based on the so-called *ceteris paribus* principle. In essence, a *Reference scenario* is defined by setting yearly products’ demand and by imposing structural technology changes (such as change in renewables penetration in the power sector), leaving the rest of the production system unchanged (baseline condition). The measures under investigation are then collected into a set of *Sufficiency* scenarios, where each measure is introduced as a deviation with respect to the *Reference* scenario, hence assessing their impact compared to the scenario assumed as the baseline. A more detailed list of scenario assumptions is included in sections 3.2, 3.3 and 3.3.1.

In essence, the *Reference* scenario includes sector-specific changes that are more relevant in the assessment of energy transition: (1) Growing final demand by product, region by region;

(2) electrification of final energy uses, in residential transport and heating sectors; (3) decarbonization of the power sector. The impact of each measure is determined by the net variation in the input-output model's results for a certain year, comparing indicators between the *Reference* scenario and the corresponding *Sufficiency* scenario.

Due to the intrinsic nature of the adopted modelling framework, some remarks are needed. In general, the impact of the analysed scenarios is not considering eventual spillover effects, highlighted for instance by Sorrel et al. [34], induced by the assumed structural changes, as well as any other macroeconomic and social response mechanism. For example, sufficiency scenarios generally lead to a reduction in economic activity, hence generating households' savings which could be reinvested in other sectors, generating further impacts (e.g. savings on utility bills might be used by a household for additional travel). Accounting for such effects would have implied relying on more sophisticated approaches, such as Computable General Equilibrium (CGE) or Stock-Flows-Consistent (SFC) models [35], grounded on further underlying theoretical assumptions and data requirements lying beyond the scope of this study.

# 3. Data input

The model described in the previous chapter can be powered by various input data and initial input-output tables. This section outlines the data used to feed the model for the case study under consideration. Details can be explored in the code repository of this study at https://github.com/SESAM-Polimi/FULFILL_MARIO.

## 3.1. Empirical economic and environmental accounts

The study is grounded on the Exiobase v3.3.18 hybrid-units input-output database, adopted in its supply-use version [36]. The database has a rich regional and sectoral coverage, encompassing 43 countries (including all the EU member states and their main trade partners) plus 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. The database includes environmental extensions, covering a multitude of 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.

The following indicators have been assumed as proxies for the environmental, social and economic dimensions:

- Greenhouse Gas Emissions (GHGs, in tonnes of $CO_2$ equivalent, using Global Warming Potential over a 100-year period: GWP100)
- total employment (in thousands of workers)
- Gross Domestic Product (GDP, in constant 2011 euros)

Beside the high sectoral disaggregation and the coverage of all EU regions, the database has the significant benefit of defining transactions of energy-related products in physical units: considering the yearly dynamics of the model, this feature allows to get rid of the numerical distortions due to changes in prices of commodities.

Despite these advantages, the database lacks an explicit representation of residential consumption categories, which are crucial for accurately modelling consumer diets, energy use in homes (particularly for heating), and private car usage. Therefore, such categories have been explicitly introduced in the original database, and the related technical coefficients (e.g., vehicles' efficiencies and stock shares) were characterized. A detailed description of the approach adopted to prepare the database for scenario analysis, including assumptions and a complete list of sectors and regions is provided in Supplementary Material and in the code repository.

## 3.2. Extending input data through countries clustering

Both the input data used to define the background changes, and the changes introduced by sufficiency measures have been collected for five *key countries*: Italy, Latvia, Germany, France, and Denmark. The data for the remaining 22 countries were derived by adapting the input data for the five key countries to population specifics through a clustering methodology. Exceptions were made for certain input data that are not easily treated in this manner. For instance, the demand for private car transport services in Gvkm for each country from 2025 to 2050 was sourced from EUROSTAT [37].

To analyse sufficiency scenario and evaluate their impacts on lifestyle, energy consumption, and climate in EU 27 member states, this study introduces a clustering approach. While not all local nuances can be captured by grouping different regions, this clustering method specifically incorporates socio-economic, infrastructural, and cultural factors that enable or constrain sufficiency implementation across different national contexts. The detailed assessment of these five diverse countries – spanning Northern, Southern, Eastern, and Central Europe – provides crucial insights into how sufficiency measures interact with varying cultural norms, traditional living patterns, and infrastructure readiness. The methodology employs K-means clustering at the European level, supplemented by elbow and silhouette score techniques to determine the optimal number of clusters. A constraint was imposed on the K-means algorithm, known as "seeding," where the five *key countries* were pre-assigned to different clusters, setting the initial centroids. 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 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 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.

In the description of the data used in each data instance on section 3.3, the application of clustering is referenced according to the previously outlined methodology, to extend data input to all EU. This approach is applied on a case-by-case basis to the most suitable dataset, ensuring that each country is assigned to its corresponding cluster.

## 3.3. Scenarios description

In this section, the changes in the inputs that informed the model presented in the methodology are described. Specifically, these changes focus on two fundamental aspects of the modelling exercise:

1. Background changes: this part outlines the projected changes in the energy system and economy over the study period.
2. Sufficiency measures: this subsection details the selected measures and their implementation in the model.

The combination of these two elements defines all scenarios modelled over the 2020-2050 timeframe, as specified by the project scope. The section provides a comprehensive overview of the data and assumptions underlying the analysis, enabling readers to understand the basis for the subsequent results and conclusions.

### 3.3.1. Background changes

**Reference scenario**

This section defines the background conditions underpinning the sufficiency measures analysed in this study, focusing on the role of decarbonisation in the power sector and the electrification of private vehicles and domestic heating systems. The aim is to assess the extent to which these technological advancements influence the effectiveness of sufficiency measures.

A main background evolution scenario is considered: a *Reference* scenario, reflecting current trends in electrification and decarbonisation. To ensure that these evolutions are representative of the entire European context, input data from the five main countries is extended to other EU nations using a clustering approach, thereby capturing diverse national trends in transport and heating systems. Unlike approaches that maintain static technology shares, our *Reference* scenario deliberately incorporates technological evolution in line with observed market trends and existing policies, enabling a more realistic assessment of how sufficiency measures complement ongoing sectoral transitions. This methodological choice enriches the traditional business-as-usual paradigm with contextually relevant sectoral dynamics, while maintaining the assumption of no significant changes in lifestyle or consumption patterns. In fact, it does include ongoing technological advances, such as the electrification of the transport sector and the decarbonisation of the power grid. The *Reference* scenario serves as a baseline for evaluating the impact of sufficiency measures. All results presented in section 4 are expressed as deltas from this *Reference* scenario for each corresponding year, isolating the specific contributions of sufficiency measures within the evolving technological landscape.

To reflect the main actions towards energy transition, the following changes have been implemented in the database for each year: (1) projecting prospective future demand of goods and services by region; (2) projecting the expected structural technology changes – that may vary in different background scenarios – in the residential heating, transport and power sector (see next subsections).

Regarding the first item, the economic growth projections with GDP forecasts is crucial. It recognizes expanding economic activity and consumption volumes. This approach ensures sufficiency measures are evaluated against a growing economic base, avoiding underestimation of their potential impact and benefits in a dynamic economy. The modelling of changes in final demand adopts data from the OECD's long-term projections for GDP and population growth across EU member states [38]. The projected growth in final consumption reflects expected growth in GDP of all EXIOBASE region, with adjustments for future changes in economic activity and consumption patterns when a sufficiency measure is active in the scenario.

**Business-as-usual scenario**

A *Business-as-usual* scenario that includes only the evolution of final demand – without considering the expected changes discussed in the following sections of this chapter – has been modelled. This scenario is intended only to highlight the importance of evaluating sufficiency measures without the assumption of a static energy system.

**Residential heating and transport evolution**

The model's data on energy efficiency improvements and technology penetration rates are primarily derived from the FULFILL project, which in turn draws extensively from the comprehensive dataset developed in the CLEVER project [39,40]. Several key data sources were utilized. Eurostat was chosen as the preferred database when relevant data were available, ensuring statistical consistency across countries and official validation. When Eurostat data were insufficient, the Odyssée-MURE database [41] was employed, offering comprehensive information on demand by energy vector and sector for European countries. Additionally, national sources provided by project partners and data from the FULFILL project's Task 3.1 survey were used to supplement and cross-check the primary sources [42].

For residential heating and transport specifically, the model integrates data on energy use per square metre, vehicle kilometres (vkm) travelled, and technology market shares, including the penetration of electric vehicles (EVs) and heat pumps (see Figure 2). These data were collected for five *key countries*, with consistency checks performed across various sources to ensure robustness and alignment with official statistics.

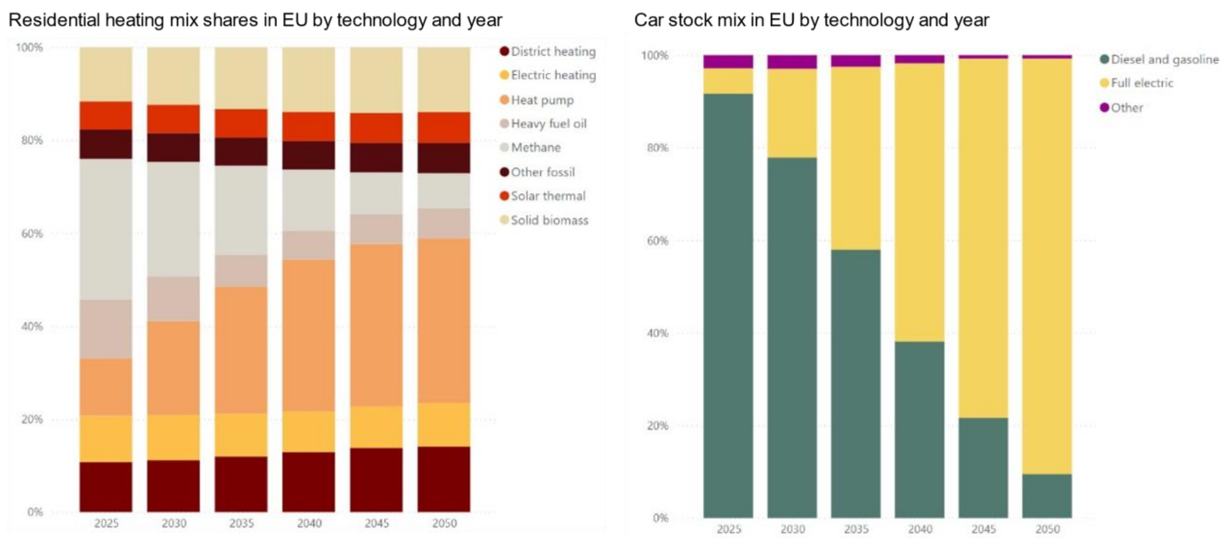



*Figure 2 – Residential heating stock and passenger car stock market shares by technology in the EU*

A *Quicker Transition* scenario, which assumes faster uptake of EVs and heat pumps and accelerated decarbonisation of the power sector, is used to assess the resilience of sufficiency measures to a faster transition. In this scenario, the penetration of EVs and heat pumps is accelerated by five years, and the decarbonisation of the power sector is faster, in line with the International Energy Agency's (IEA) Net Zero by 2050 scenario [43]. For the private car sector, powertrain efficiencies and penetration data from five key countries were extended to all European nations through clustering based on current sales trends. Regarding domestic heating, the model used heated surface data from HOTMAPS [44] and expanded it according to the penetration of heating systems, ensuring a coherent representation across the EU. The *Quicker transition* assumes that residential transport and heating trends accelerate between 2025 and 2030, aligning with expert-judgment pathways for faster decarbonisation of these sectors. The rationale behind running both *Reference* and *Quicker transition* scenarios is to assess whether sufficiency measures retain their relevance when technological decarbonisation progresses at an accelerated pace.

**Decarbonisation of the power sector**

The decarbonisation trajectory of the power sector in the model is based on a comprehensive analysis of national commitments and policy targets across EU member states, built on

International Energy Agency's (IEA) Energy Policy Reviews or equivalent documentation. This approach ensures that the baseline scenario reflects current policy landscapes and stated ambitions for each country. However, to account for potentially more ambitious decarbonisation pathways within the *Quicker transition* set of scenarios, an expert-based upscaling method was also employed. This method draws upon the IEA's Net Zero scenario, which outlines a rapid decarbonisation pathway for the power sector globally [43]. The IEA's projections were carefully adapted to the EU context, with country-specific mixes developed through expert judgment to reflect the overall European mix described by the IEA Net Zero scenario. As electricity becomes increasingly central to residential heating and transport through technologies like heat pumps and EVs, the carbon intensity of electricity production plays a pivotal role in determining the overall impact of sufficiency measures.

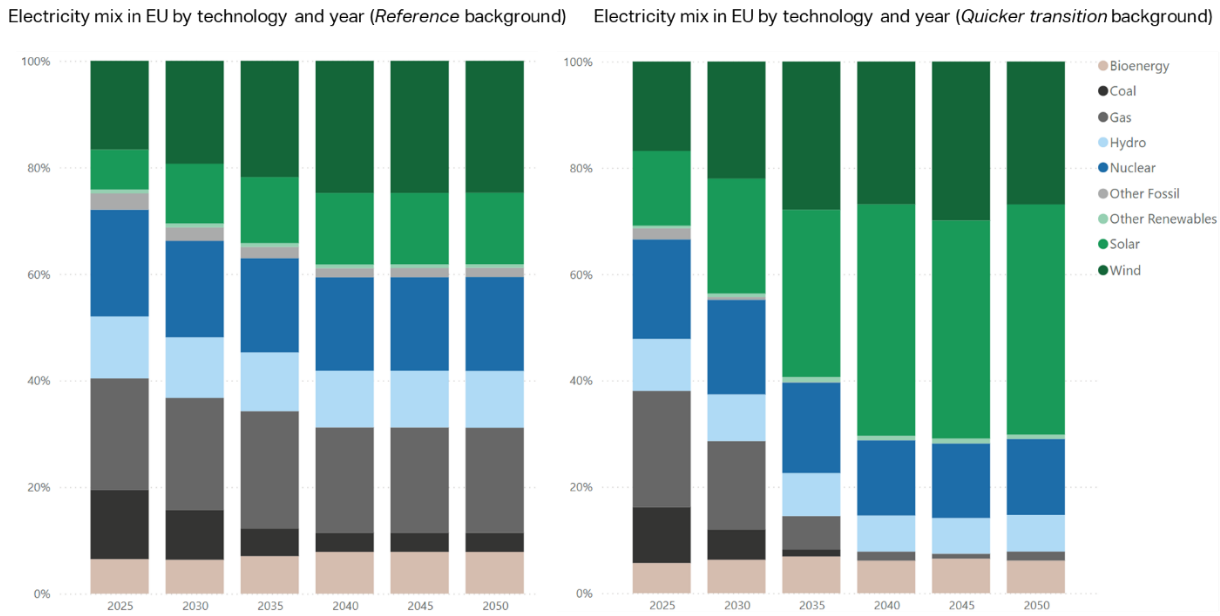



*Figure 3 – Electricity mixes in EU in a Reference and a Quicker transition background scenario*

### 3.3.2. Sufficiency measures overview

Here below an overview about the modelled sufficiency measures is synthetically provided. These measures have been introduced considering not only the specific contribution of each initiative (e.g., the marginal impact reduction from driving 1 km in a small car versus a medium-sized vehicle) but also their plausible adoption rates across different regions. The estimation of the parameters defining these sufficiency measures (e.g., the extent of reduction in air travel or the shift towards plant-based diets over time) is informed by a combination of existing literature, findings from social science research within the FULFILL project [45,46], and alignment with the "Collaborative Low Energy Vision for the European Region" (CLEVER) scenario [39]. Where specific information directly supported the projected evolutions, it has been referenced within the descriptions of each measure below. In cases where literature was less direct, the chosen figures reflect plausible pathways of behavioural change informed by expert judgment within the project consortium, aiming for consistency with ambitious decarbonization scenarios while considering societal and infrastructural constraints. Figure 4 illustrates simplified representations of more complex dynamics underlying the assumptions used to model penetration trajectories for each sufficiency measure across *key countries*. The analysis incorporates a range of factors, such as policy frameworks, infrastructure readiness, and behavioural trends, to assess how quickly and widely these measures could be adopted. While the figure illustrates general trends, the actual effectiveness of each measure will vary depending on local conditions and the interaction between technological penetration, efficiencies and overall economic growth in each EU country.


*Figure 4 – Proxies of penetration assumptions for sufficiency measures across key countries modelled from 2025 to 2050.*

The *Diets* measure focuses on promoting more sustainable dietary patterns by reducing meat consumption and encouraging the adoption of plant-based diets. This measure aims to reduce greenhouse gas emissions, particularly methane ($CH_4$) and nitrous oxide ($N_2O$), which are primarily associated with intensive livestock farming. The projected increase in the adoption of less resource-intensive diets is based on trends and scenarios explored in [46], which integrated social science insights on dietary shifts. The specific penetration rates, with non-omnivorous diets projected to represent between 43% and 53% of total meal consumption in Europe by 2050, are aligned with scenarios for sustainable food systems aimed at significant GHG reductions [6,8]. The penetration of less resource-intensive diets is expected to increase progressively. Initially, non-omnivorous diets account for about one-quarter of the total, with roughly 70% of these classified as flexitarian. The extension of this sufficiency measure across European countries, through clustering, used historical per capita meat consumption data from each European country as the reference metric for modelling.

*Sharing spaces* in housing involves a reduction in the average living area per capita, particularly targeting people over 65 living in 1-2 person households with excess space. By decreasing housing surface area, energy consumption for heating, cooling, and lighting is substantially reduced. Adoption projections are based on analysis of demographic trends in [46] and the potential for space sharing identified through survey data [42]. The projected progressive growth reflects a social shift toward co-housing and space-sharing practices, quantified in [45] through clustering of EU countries based on average floor area and number of rooms per person, in line with the convergence toward more sustainable lifestyles discussed in the context of the CLEVER project [39]. The adoption of this measure is projected to grow steadily over time, with an increasing proportion of the elderly population embracing shared living arrangements. By 2050, the target population is expected to account for 26-31% of the total across five key countries. This gradual uptake reflects a societal shift towards co-housing and space-sharing practices, reducing the environmental impact of larger, underutilised homes. For the *Sharing spaces* in housing measure, clustering was performed using average floor area and number of rooms per person, grouping countries into five clusters based on these indicators.

*Moderate car sizing* focuses on reducing the average vehicle weight per capita by shifting consumer preferences towards smaller, more energy-efficient cars. Lighter vehicles consume less energy per kilometre travelled, thereby lowering overall transport-related energy consumption. The evolution toward smaller cars was modeled in [46] through the projection of market shares by automotive segment, taking into account current trends and the decarbonization goals of the transportation sector also outlined in the CLEVER project [39]. Vehicle weight assumptions by segment (described in [45], based on ICCT data) and the gradual replacement of the existing car fleet with more compact models were used to estimate the impact on energy demand. Penetration of this measure will occur progressively as market shares for smaller vehicles expand, with older, larger cars gradually being replaced by more compact models. By 2050, smaller cars are anticipated to dominate the vehicle stock, driven by consumer demand for greater fuel efficiency and lower operating costs. In the case of the *Moderate car sizing* measure, clustering was carried out using data on car sales by segment, grouping countries into four clusters according to similarities in sales patterns between small cars and SUVs.

*Sharing products*, specifically washing machines, aims to reduce individual ownership by promoting shared use of laundry facilities. This leads to more efficient use of washing machines, decreasing electricity consumption per capita for clothes washing. Projections of declining individual ownership of washing machines are based on behavioural change scenarios explored in [46], which consider factors such as urbanization and availability of shared services. Detailed modelling of the evolution of the washing machine fleet and its energy consumption is described in [45], which includes a stock model and assumptions about the intensity of use of shared washing machines. As shared laundry facilities become more prevalent, households will increasingly turn to communal solutions, driven by both cost and sustainability considerations. For *Sharing products* like washing machines, municipal solid waste per capita served as a proxy indicator for clustering, correlated with GDP per capita.

*Cycling more* seeks to increase the distance travelled by bicycle per capita, reducing reliance on cars for short-distance travel. This shift leads to significant energy savings as bicycles require no fuel, offering a zero-emission alternative to motor vehicles. The projected increase in the use of bicycles as a daily mode of transportation (quantified in [45] with a substitution rate of 80%) is based on the active mobility trends analysed in Deliverable 5.3 [46] and the sustainable mobility promotion goals also outlined in the context of the CLEVER project [39]. The change per capita is closely tied to the expansion of cycling infrastructure and the growing appeal of cycling as a sustainable mode of transport. Penetration of cycling as a primary mode of transport is expected to rise steadily, with daily bicycle trips projected to account for 6-30% of all trips by 2050, depending on the country. However, for each assumed additional kilometre travelled by bicycle, only 800 metres have been subtracted from private car transport demand. The *Cycling more* measure relied on the share of trips made by bicycle versus car, with clustering assigning countries to the five groups based on similar modal shares.

*Flying less* focuses on reducing the frequency and distance of air travel per capita, particularly for short-haul flights, by promoting alternatives such as rail transport and remote work meetings. This shift significantly reduces the carbon intensity of personal travel, given the high energy consumption associated with aviation. This includes water vapor effects beyond traditional combustion emissions. Projections on the reduction of air travel are based on the scenarios of behavioural change in the transportation sector analysed in [46], which consider increasing environmental awareness and the availability of more sustainable travel alternatives. Penetration of this measure is applied broadly, with reductions in both domestic and intra-EU flights. By 2035, domestic flights are expected to be largely phased out, while short-haul international flights will see substantial declines by 2050. For the *Flying less* measure, clustering used data on air passengers per capita, linked to GDP per capita, forming four clusters of countries with comparable air travel patterns.

# 4. Results

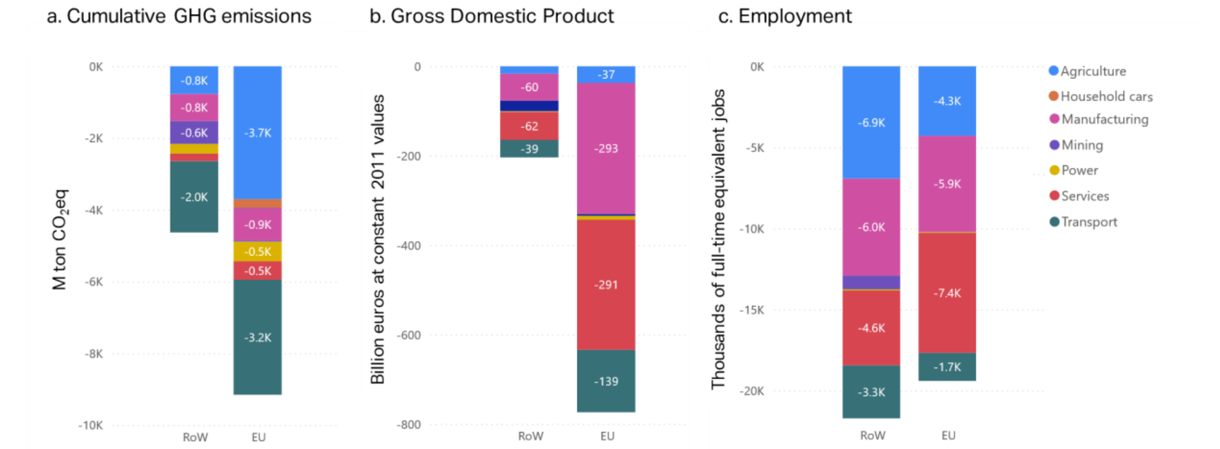
## 4.1. Joint implementation of all Sufficiency measures

This section presents the results of the macroeconomic and environmental impacts of sufficiency measures across the EU with supply-chain effects on the Rest of the World (RoW) based on one main scenario (i.e., the *Reference* scenario). The results are presented within a *ceteris paribus* framework, meaning that the analysis isolates the effects of sufficiency measures by holding other factors constant (such as productivity, labour efficiency, and technological advances) beyond those explicitly included in the model. The primary indicators evaluated are GHG emissions reductions, GDP, and employment changes, along with their respective sectoral contributions.

The overall results of the 6 sufficiency measures within the modelling framework highlight substantial impacts across the three main indicators. By 2050, these measures combined are projected to reduce annual GHG emissions within the EU by approximately 13%, equivalent to a global cumulative of 13.8 Gt $CO_2$. However, this comes with a ~5% reduction in GDP and a loss of ~19 million jobs in the EU with respect to the *Reference* scenario. The effects are even more pronounced in the RoW, where labour-intensive sectors are hit harder due to their global interconnectedness with the EU economy (see Figure 5).

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 are a supply chain effects linked to the introduction of sufficiency measures. Notably, a significant reduction in RoW's mining sector, as less extraction is needed due to energy savings across various energy vectors, is observed. Overall, the cumulative emissions reduction due to sufficiency measures 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 [47].

The sufficiency measures assumptions also lead to substantial economic and social impacts. The measures are projected to result in a reduction of approximately ~5% in GDP within the EU by 2050 with respect to the *Reference* scenario. 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 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.




| from ***Reference*** | Absolute change | Relative change | Absolute change | Relative change | Absolute change | Relative change |
|---|---|---|---|---|---|---|
| EU | -9'155 | -5.71% | -774 | -4.03% | -19'402 | -4.99% |
| RoW | -4'632 | -0.28% | -204 | -0.23% | -21'711 | -0.17% |
| **World** | **-13'787** | **-0.75%** | **-977** | **-0.90%** | **-41'112** | **-0.32%** |

*Figure 5 – Overall impact of all sufficiency measures 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*

The social dimension, as indicated by employment, also sees notable impacts. The implementation of sufficiency measures is expected to lead to a decrease of about ~19 million yearly full-time equivalent jobs within the EU by 2050 with respect to the *Reference*. 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.

## 4.2. Breakdown by single Sufficiency measure

As illustrated in Figure 6, most 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.

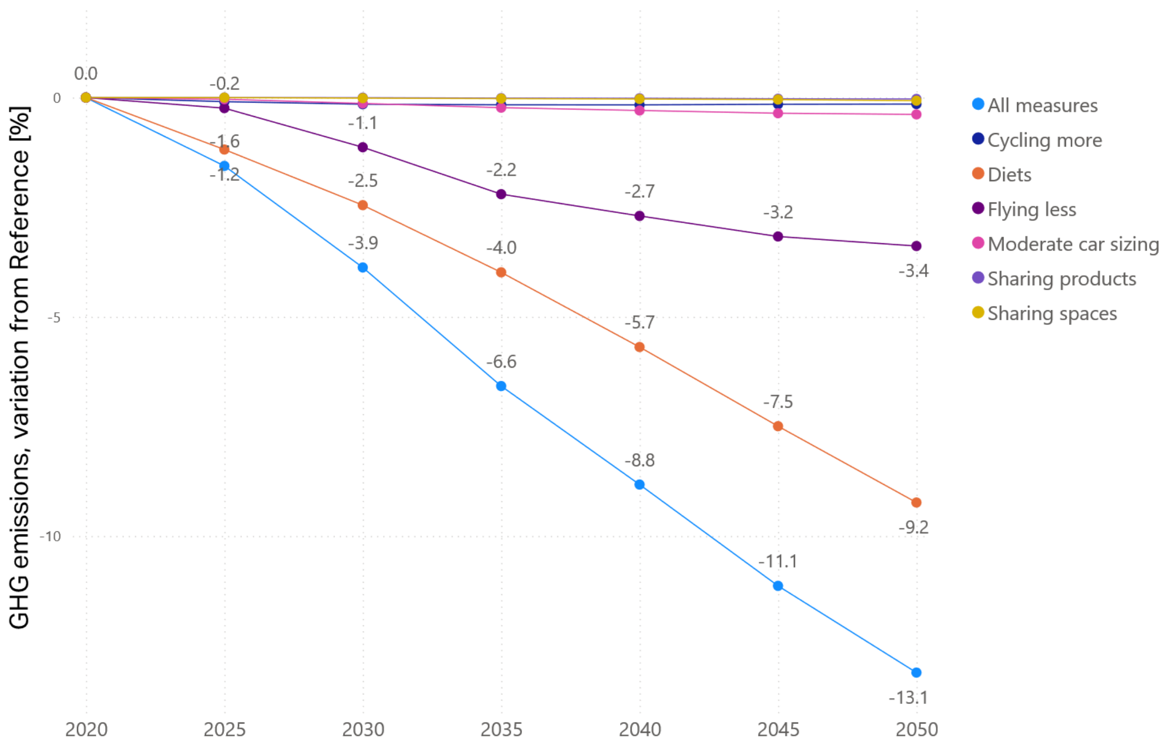



*Figure 6 – Relative reduction of GHG emissions brought by each sufficiency scenario assumption in the EU with respect to Reference scenario*

The role of sufficiency measures in EU becomes increasingly significant as 2050 approaches, already accounting in 2035 for a 6.6% reduction in GHG 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.

The transition to more plant-based *Diets* has the greatest impact among modelled measures, reducing GHG emissions by 9.2% compared to the *Reference* scenario. Omnivorous diets have significantly higher carbon footprints than vegetarian or vegan diets. A diet with 170 g of meat per day produces about 14.8 kg$CO_2$eq/day, while a vegan diet is a factor 10-15 lower. Meat production is highly GHG emission intensive, with beef generating up to 100 kg$CO_2$eq/kg, compared to 1-2 kg$CO_2$eq/kg for fruits and vegetables. By 2050, dietary changes in the EU could avoid 390 Mt $CO_2$eq emissions in the agriculture sector alone, mostly from reduced $CH_4$ and $N_2O$ from livestock. This is comparable to current annual emissions from Italy [47]. The impact of dietary changes mirrors the overall impact of sufficiency scenarios, with one-third of emission reductions occurring outside Europe. While Europe sees significant agricultural emission reductions (3.7 Gt $CO_2$), the economic and employment impacts are concentrated in the services sector. The rest of the world experiences comparable workforce reductions by 2050, primarily affecting the agricultural sector.

*Flying less* is the second most impactful measure, lowering EU GHG emissions by 3.4% in 2050. Most reductions come from decreased air travel, affecting both private and industry emissions. Indirect reductions occur in power and mining sectors, with minor savings from reduced consumption of travel-related goods and services. 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*.

*Moderate car sizing* reduces EU GHG emissions by 0.38% in 2050. This small impact is partially due to decarbonization actions like electrification and cleaner electricity having a larger effect than car size reduction: by 2050, average passenger battery electric vehicle transport service emissions per km is more than halved with respect to 2020. The power sector accounts for most emissions savings as smaller EVs become more prevalent, highlighting the importance of decarbonizing electricity generation.

*Cycling more* reduces GHG emissions by only 0.15% by 2050, as just 1-3% of European passenger car transport service demand is replaced. Emissions savings come mainly from reduced driving, with a shift from direct car emissions to electricity sector emissions as vehicles electrify. The measure's impact plateaus around 10 $MtCO_2eq$ by 2035 due to overall system decarbonization.

*Sharing spaces in housing* reduces EU GHG emissions by only 0.07% in 2050. This small impact is due to small overall penetration of the measure and background decarbonization processes, such as improved heating efficiencies. By 2050, floor surface per capita decreases 3.4-5.1%, saving 6 $MtCO_2eq$, equivalent to 2.8-4.5 million people becoming vegetarian. Benefits grow over time as the electricity system decarbonizes, with additional savings from reduced services per square meter.

The *Sharing products* measure, involving the reduced use of residential washing machines, results in lower electricity consumption and a reduced demand for new machines but with very marginal impacts (i.e., 0.03%) in GHG reduction. By 2050, sales of new washing machines are projected to decrease by 100’000 to 1 million units, varying by country. Most of the impact occurs in the manufacturing sector due to fewer machines being produced, with a smaller effect on the power sector. Emission reductions increase progressively, though changes vary every five years based on input assumptions.

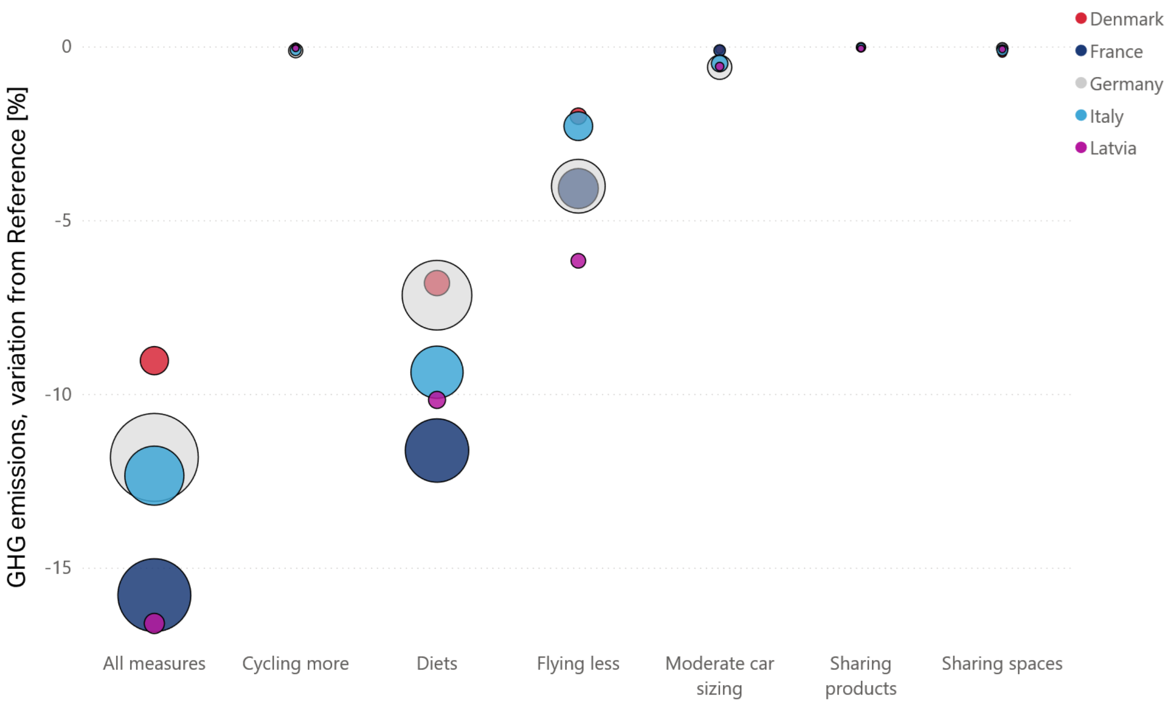



*Figure 7 – Relative GHG emissions reduction in the reference scenario for one or all six sufficiency measures, with bubble size representing the absolute reduction for each country with respect to reference scenario without Sufficiency measures implemented, in each key country, as identified by legend colours.*

Figure 7 illustrates both absolute and relative GHG emission reductions achieved through sufficiency measures in the five primary countries of the analysis. The most notable reductions are associated with *Diets* and *Flying less*, which show the highest impacts (from -2.0% – *Flying less* in Denmark – to 11.6%, *Diets* in France). Interestingly, in larger countries such as Italy, measures like *Moderate car sizing* contribute reductions comparable to *Diets* in smaller countries such as Denmark, about 2.5 $MtCO_2eq$. This highlights that while some measures may offer higher unitary reduction potential, significant results can still be achieved in larger countries.

The most pronounced reduction is observed in the *All measures* scenario, with Latvia displaying the greatest percentage decrease (i.e., 16.6%), followed by France and Italy (i.e., 15.8% and 12.4% respectively). *Diets* show consistent GHG reductions across all countries, with Germany and France experiencing the largest impacts in the measure of 91 and 74 $MtCO_2eq$ respectively. The *Flying less* also yields substantial emissions decreases, particularly in Germany and France generating respectively 56% and 35% of the reductions achievable with the *Diets* measure.

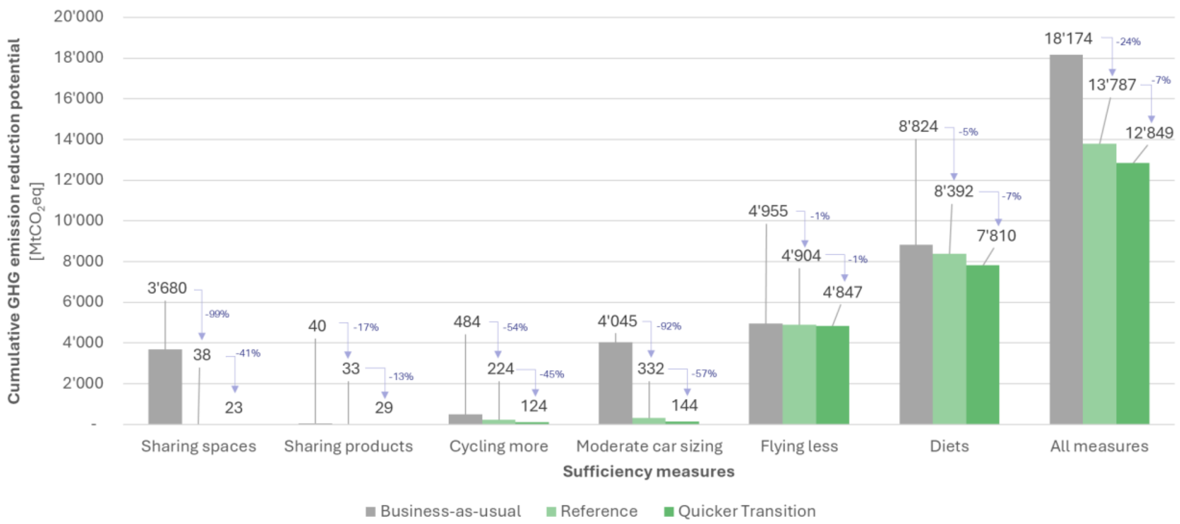



*Figure 8 – Cumulative GHG emission reduction potential by sufficiency measure and its possible lost potential in case of quicker transition*

The analysis resumed in Figure 8 reveals that *Diets* and *Flying less* not only offer the highest potential for emissions reductions but are also more resilient to a faster-than-expected transition. *Diets* could save up to 8.39 $GtCO_2eq$ in the *Reference* scenario, with only 6.9% of that potential being hampered by a quicker transition. Similarly, reducing air travel could yield 4.9 $GtCO_2eq$, with a minimal 1.1% risk of benefit loss if the transition accelerates. In contrast, measures like *Moderate car sizing* and *Cycling more* face much higher risks, with potential losses of 56.8% and 44.6%, respectively, under a *Quicker transition* scenario. Without incorporating the evolution of energy systems in accordance with current policies and market trajectories, these two measures would have appeared approximately 100 times more effective in emissions reduction (as illustrated in the *Business-as-usual* scenario in Figure 8), highlighting the importance of establishing realistic baseline conditions for accurately assessing sufficiency interventions. This misrepresentation would lead to an overall overestimation of the sufficiency measures analysed by 24%, even though *Flying less* and *Diets* remain relatively unaffected by this change in background scenario assumptions.

This highlights the importance of focusing on high-impact, resilient measures such as *Diets* and *Flying less* in climate strategies, as they maintain effectiveness even in scenarios of more rapid transition.

Additionally, it is possible to compare the contribution to cumulative emissions reduction by examining the *Reference* scenario with *All measures* implemented and the *Quicker transition* scenario, against the *Reference* scenario without any sufficiency measures. This comparison provides insight into the relative contribution of sufficiency when contrasted with a faster transition in global power and European residential heating, and private car usage. The comparison of cumulative emissions reductions reveals that the potential of a quicker transition is approximately 15 times greater than that of sufficiency measures (i.e., 200.6 Gt $CO_2$eq).

# 5. 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 study explores various sufficiency measures and their impacts on GHG emissions, economic output, and employment. In total, for all the sufficiency measures analysed in the EU, the cumulative GHG emissions reduction potential until 2050 is about 13.8 Gt $CO_2$ equivalent (9.2 Gt $CO_2$ for EU and 4.6 Gt $CO_2$ for the rest of the world), corresponding to a 6.6% reduction for EU alone and about 5% of the global carbon budget. These findings align with broader literature indicating that behavioural changes and sufficiency measures are essential complements to technological solutions. Studies by Costa et al. and Zimmerman et al. suggest that behavioural modifications could contribute to GHG emission reductions toward achieving European net-zero targets by 2050 at a magnitude comparable to that identified in this analysis [16,21].

Among the analysed sufficiency measures, 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 ~61% to the overall emission reduction potential to 2050 of the sufficiency measures here considered, representing a substantial share of the total potential savings. This prominent role of dietary changes is consistent with findings by Hallström et al., who estimate that aligning meat consumption with nutritional guidelines could reduce emissions from meat production by half, and with Steinitz et al., who conclude that reducing meat intake to healthy levels and avoiding ruminant meat could nearly halve food system emissions by 2050 [6,8]. Reducing flying essentially accounts for most of the remaining contribution (i.e. 35% out of 39%) of the impact of sufficiency measures, primarily by decreasing direct emissions from air travel. This measure's effectiveness is evident early on, with substantial impacts plateauing by 2035 because of domestic flight being assumed phased-out by then. In contrast, the other observed measures such as moderate car sizing, increased biking, and shared products and spaces, while beneficial, show comparatively smaller contributions to overall GHG reductions, accounting just for the remaining ~3%. This contrasts with findings from both Koide et al., who suggested significant emission reduction potential from increased cycling and Zimmerman et al., who identified reduction in per capita living space as the most effective sufficiency measure for emissions mitigation in the European building sector [12,16]. The analysis highlights that diet changes and reduced air travel offer the highest potential for GHG emissions reductions from changes in consumers' behaviours, with these measures proving more resilient to a faster technological transition compared to others. While diet shifts maintain a large portion of their effectiveness under accelerated decarbonisation, reduced air travel could also remain highly impactful, although the lack of assumed technological improvements in aviation leaves room for potential future reductions in the measure's efficacy. In contrast, measures such as moderate car sizing and increased cycling face much greater risks of diminished effectiveness in a scenario of rapid transition. This underscores the importance of focusing on resilient, high-impact measures in climate strategies, while remaining mindful of potential future advancements in aviation that could affect the efficacy of air travel reduction strategies.

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 determine a hierarchy of consumption behaviour in the circular economy [48] to support policymakers, as well as define strategies to be modelled by researchers [49]. Furthermore, higher cycling rates, alongside reduced car use, significantly lower pollution-related mortality and likely improve health for active participants [50]. Moreover, limitations in the high-level modelling of vehicle fuel consumption and emissions may have led to an underestimation of the projected benefits of transport-related measures considered in this research [51]. 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 [28].

The implementation of sufficiency measures in the EU has substantial side effects 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 study do not account for potential rebound and spillover effects, where savings from changes in household energy savings might lead to increased income and then energy consumption elsewhere [52]. For instance, money saved from reduced air travel could be spent on other goods and services, potentially offsetting some of the GHG reductions [7]. 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. Moreover, while this study quantifies the potential of sufficiency measures for decarbonization, it is crucial to acknowledge that the successful and equitable implementation of such measures necessitates careful consideration of social impacts and the design of just transition strategies, ensuring that the benefits of sustainability are shared across society and potential negative consequences, such as job displacement, are effectively addressed, as highlighted by the broader perspective on well-being and equity in sufficiency pathways [28,50].

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. While incorporating productivity changes through adjusted technical coefficients would have been theoretically possible, this would require extensive speculation across multiple dimensions and introduce complex price-consumption interactions, contradicting the ceteris paribus approach applied to isolate sufficiency impacts. Computable General Equilibrium (CGE) frameworks incorporate price flexibility and supply-side dynamics through endogenous adjustments, whereas our methodological approach deliberately isolates sufficiency effects without price-mediated responses. This choice enhances analytical clarity regarding direct impacts, though it potentially overestimates certain effects by not capturing productivity-enhancing feedback mechanisms.

While this study provides a comprehensive analysis of the impacts of a limited set of sufficiency measures, it is constrained by other limitations. The scope of the analysis does not allow for an in-depth examination of each country and all key dimensions of sustainability – environmental, social, economic, and governance. 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 measures 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, this study provides a quantitative assessment of the effectiveness of sufficiency measures within the sustainability framework, emphasizing their role in addressing climate change. While the model highlights that the impact of sufficiency on greenhouse gas reductions is limited compared to more rapid transition strategies, it underscores the significant potential of dietary changes and reduced air travel. These sufficiency measures can augment technological solutions in the quest for decarbonization. However, it is crucial for policymakers to balance the acceleration of transitions with the implementation of sufficiency measures, as both approaches can complement each other. The broader benefits and potential rebound effects associated with these strategies must be carefully managed to ensure a holistic and effective approach to sustainability.

## Acknowledgement

The authors gratefully acknowledge the contributions of all FULFILL project partners, whose collaboration has been invaluable to this research. Special thanks go to negàWatt for their dedicated support in the project, particularly for their assistance with input data processing and provision. This study has greatly benefited from the collective expertise and resources provided by each partner.

## Author contributions: CRediT

**Conceptualization**: All authors; **Data Curation**: NG, LR, MGP; **Formal Analysis**: All authors; **Funding Acquisition**: WS, MVR; **Methodology**: All authors; **Project Administration**: WS; **Software**: LR, NG, MVR, MGP; **Supervision**: WS, MVR; **Visualization**: NG, LR, MVR, MGP; **Writing – Original Draft**: All authors; **Writing – Review & Editing**: All authors.

## Funding sources

This research has been supported by the European Commission H2020 programme, under the funding agreement n°101003656 project FULFILL - Fundamental Decarbonisation Through Sufficiency by Lifestyle Changes.

## Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) NG used to improve language and readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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