Integration of energy sufficiency assumptions in bottom-up models and overall impact of sufficiency

Indicators and factors for the integration of energy sufficiency in models

Fundamental decarbonisation
through sufficiency by lifestyle changes

FULFILL

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2	**Wuppertal Institut für Klima, Umwelt, Energie GGMBH**	WI	DE	
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4	**Notre Europe - Institut Jacques Delors**	JDI	FR	
5	**Association négaWatt**	NW	FR	
6	**Politecnico di Milano**	POLIMI	IT	
7	**International Network for Sustainable Energy-Europe**	INFORSE	DK	
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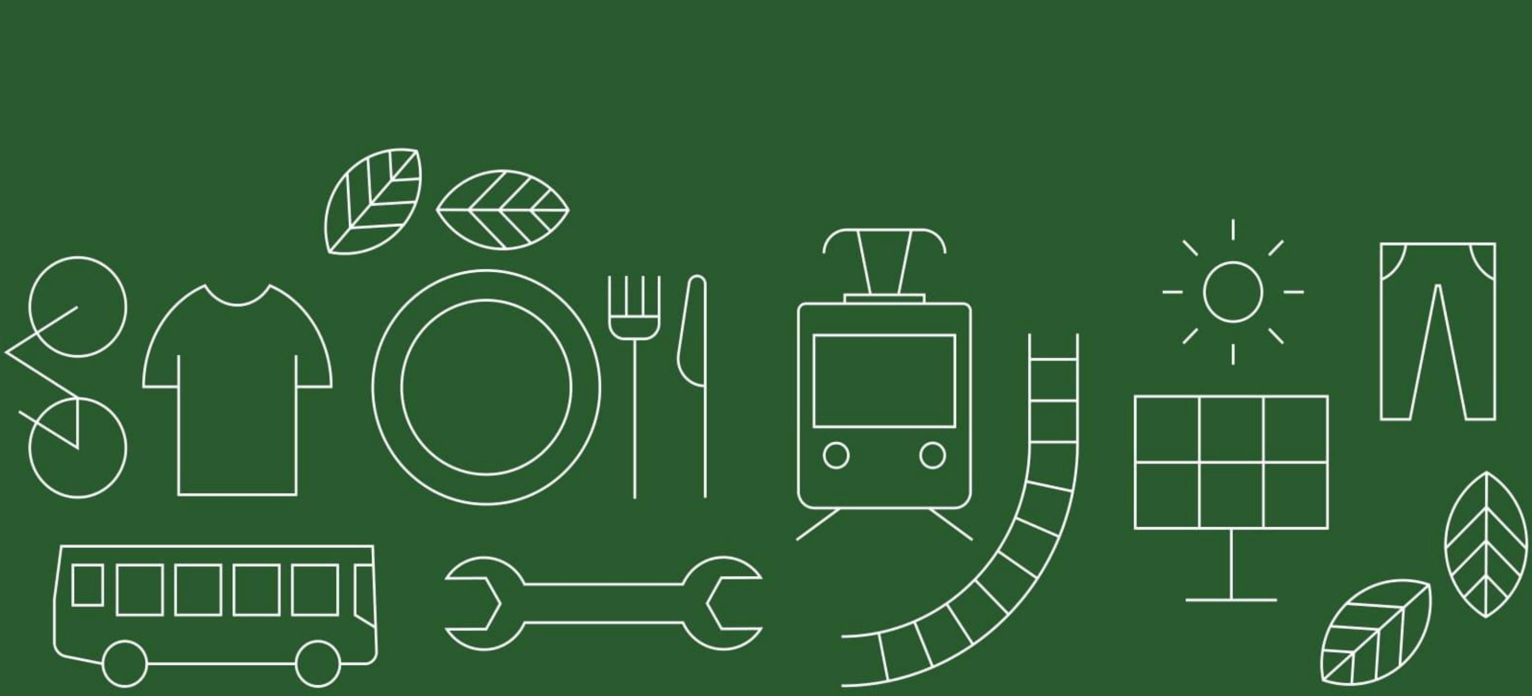

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List of Abbreviations

AR6	Sixth Assessment Report of the IPCC on climate change
BAU	Business as usual scenario
C1	Pathways limiting warming to 1.5°C with no or limited overshoot (probability higher than 50%), as described in IPCC AR6 report
ECF	European Climate Foundation
EPAC	Electric pedal-assisted cycles
ESTAT	Eurostat
EU27	European Union as defined in 2023
EU28	EU27 + UK
FEC	Final Energy Consumption
GHG	Greenhouse gases
ICE	Internal combustion engine
IMP	Illustrative mitigation pathways (see AR6, WGIII, chapter 3, p.15(309))
IMP-LD	An IMP called "Low demand" and described as "efficient resource use and shifts in consumption patterns, leading to low demand for resources, while ensuring a high level of services"
IMP-SP	An IMP called "Shifting pathways" and described as "how shifting global pathways towards sustainable development, including by reducing inequality, can lead to mitigation"
IPCC	Intergovernmental Panel on Climate Change
LCV	Light commercial (or duty) vehicle
LMDI	Logarithmic Mean Divisia Index
NDC	Nationally Determined Contribution
REF	« Reference » scenario (scenario modelling what happens **without** a given sufficiency scenario assumption)
SDG	Sustainable development goals
SUF	« Sufficiency » scenario (scenario modelling what happens **with** a given sufficiency scenario assumption)
WGIII	Working Group who elaborates the 3rd section of the IPPCC assessment reports on climate change which treats about mitigation of climate change. It can also designate the corresponding section of the reports.

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Abstract / Summary

This report presents the outcomes of task 6.1 within the FULFILL project. It focuses on quantification of impacts of sufficiency assumptions defined in task 5.3, mostly in terms of final energy consumption reductions, but also in some cases on other aspects as well.

Led by the négaWatt Association in collaboration with all project partners, this task aimed at bridging the gap between the data produced in task 5.3, and the requirements of impact assessment models used in tasks 6.2 and 6.3. This report outlines the methodologies and data sources used to perform this quantification work, and highlights a few methodological challenges and areas for further research.

It concludes with a broader analysis of the overall impact of sufficiency, beyond mere final energy consumption and the set of sufficiency assumptions quantified in work package 5, through a meta-analysis of several energy transition scenarios.

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Introduction and Overview

Purpose and objectives of the report

This report aims at describing the role of task 6.1 within the FULFILL project, linking it to both upstream (cf. deliverable 5.3 in FULFILL, 2024) and downstream (tasks 6.2 and 6.3) activities.

The first chapter will deal with general methodological issues, and more specific explanations will be provided for each quantified sufficiency scenario assumption[1] in the second chapter, along with their key results. The third chapter raises a few issues, which are open to discussion and possible further research. The fourth and last chapter expands the scope of analysis to the impact of sufficiency as a whole, beyond the mere quantified scenario assumptions in tasks 5.3 and 6.1, based on a meta-analysis of several energy transition scenarios.

Objectives of task 6.1

Most of the work carried out in this task is about the quantification of 5 sufficiency scenario assumptions:

- Translate disaggregated indicators produced in task 5.3 into more aggregate indicators, which can feed bottom-up models.
- Design and apply *ad hoc* bottom-up models to assess the impact of each sufficiency scenario assumption on final energy consumption, and when possible or required by further tasks (6.2 and 6.3), convert it into some other useful indicators (e.g. number of products sold).
- Exchange with project partners on the way bottom-up (task 6.1) and top-down (task 6.2) models work, in order to ensure consistency of data handed over from one task to another.
- Carry out this impact assessment in each of the 5 European countries covered in FULFILL. A further activity of the task aims at expanding results to the EU level, using a clustering approach. This activity, although mentioned in the Grant Agreement as part of task 6.1, will be described in deliverable 6.2.

Finally, the broader impact of sufficiency has been assessed, to go beyond the selected scenario assumptions, which account for only a share of the total potential.

How this work fits in with the rest of the project

This task has been designed as an intermediary step in a process quantifying the impact sufficiency scenario assumptions identified in work package 5. More specifically, task 5.3 produced baseline physical trajectories for several sufficiency scenario assumptions, in 5 selected countries (Denmark, France, Germany, Italy and Latvia):

- Sharing spaces in housing,
- Sharing products,
- Moderate car sizing,
- Biking,
- Flying less,
- Diets (eating less meat and dairy),

[1] By "sufficiency scenario assumption" we mean the projected changes for a given sufficiency lever on a set of sufficiency indicators, from a starting point to a target year, including a characterisation of the pace of change with a defined time step, as defined in deliverable 5.3 in (FULFILL, 2024).

- Working less.

The « diets » scenario assumption, modelled in task 5.3, has mostly impacts on GHG emissions (not final energy consumption (FEC)), therefore integration into bottom-up models is less relevant and has not been performed in task 6.1. Likewise, considering the complexity of modelling the "working less" assumption, it has not been included in the quantification work in task 6.1 either.

Task 6.1 strived to translate results from task 5.3 into proper inputs to feed the impact assessment models used in tasks 6.2 (impact on GHG emissions, energy consumption, economic factors) and 6.3 (social impact). Ultimately, the objective is to provide valuable input for the work planned in task 6.5 (recommendations for NDCs and NECPs).

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 lifestyles 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.
    - 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 lifestyle
- 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.

1. Methodology

This chapter will deal with the overall methodology followed throughout task 6.1. More details will be provided in the next chapter, on how each individual sufficiency scenario assumption has been dealt with.

1.1. Overview of the modelling process

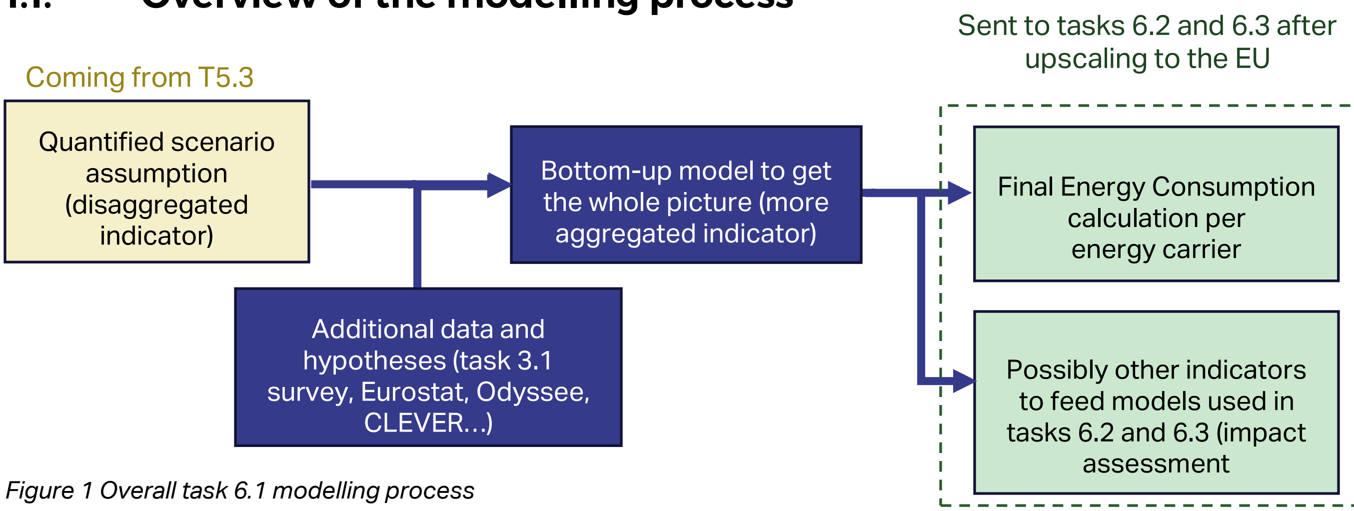


Figure 1 Overall task 6.1 modelling process

For all scenario assumptions, the following process has been applied (see Figure 1):

- Trajectories produced in task 5.3 are taken as inputs. They usually describe the evolution of one or several target indicators (closely related to the sufficiency measure and its impact) over the years (2019, 2030, 2040 and 2050), for each of the 5 countries and for two scenarios: "with" and "without" the scenario assumption.
- Some additional historical data and prospective assumptions are gathered.
- These data are then combined within bottom-up models to produce final energy consumptions (with the breakdown per energy carrier) for the whole trajectory until 2050.
- For some scenario assumptions, when possible and relevant for the tasks 6.2 and 6.3 models, additional indicators are calculated. This has been the case for "sharing products", "car sizing" and "biking".
- Results for the 5 countries will then upscaled to the EU, using a clustering method (cf. deliverable 6.2).

1.2. Impact assessment as a comparison between "sufficiency" and "reference" scenarios

There are many different methods to isolate the effect of a given lever (sufficiency, efficiency or others), in a context of many different changing parameters – which is usually what happens in energy transition scenarios.

In order to have a clear and simple to explain approach, it has been decided to assess the impact of each sufficiency scenario assumption by comparing the outcome of two scenarios:

- A "reference" (REF) scenario, modelling what happens **without** a given sufficiency scenario assumption.
- A "sufficiency" (SUF) scenario, modelling what happens **with** a given sufficiency scenario assumption.

NB: the REF scenario is not a *status quo*, which would be highly unrealistic considering the current pace of changes, and the overarching aim to reach carbon neutrality within 2050. Therefore, the REF scenario embeds technological efficiency improvements and changes in the energy system. Sufficiency levers may also be included, provided they are not too closely related to the studied scenario assumption.

This scenario is mostly based on the "CLEVER" project, offering enough detailed prospective hypotheses on each of the 5 countries, within a consistent 1.5°-compatible energy transition scenario (négaWatt Association, 2023).

This impact assessment approach (comparison of SUF and REF scenarios) has been deemed easier to implement and explain than other more sophisticated methods such as LMDI or Shapley (and its variants). Moreover, it is also more conservative, as the sufficiency scenario assumption is assessed **after** taking into account other efficiency and sufficiency levers, thus diminishing its apparent effect.

1.3. Main sources of historical data

Eurostat has been chosen as the preferred database, when relevant data was available, as it ensures statistical consistency across countries, is officially validated and mostly consistent with national statistics. It also offers rather long time series, which was a requirement of the models used in task 6.2.

When data was not available on a given indicator and/or a given country (data is sometimes "secreted"), we used mostly the Odyssée-MURE database, used as part of the CLEVER project. This is a comprehensive database on energy demand and its main factors for each of the European countries. In most cases, its data comes directly from national statistical bodies, but in some cases the data has been reprocessed.

In any case, consistency checks have been made on most indicators to compare Eurostat, Odyssée-MURE and national sources provided by project partners, either as part of the CLEVER project or the current FULFILL project. In several cases, data from task 5.3 has been readjusted to better match official (Eurostat) statistical data.

When relevant, data from the task 3.1 FULFILL survey (FULFILL, 2023c) has also been used, to cross-check aggregated statistical data.

1.4. Bottom-up and physical approach

The modelling approach belongs to the "bottom-up" family of models, combining several disaggregated physical indicators to move up towards more aggregated indicators (such as the final energy consumption).

Each scenario assumption has required an *ad hoc* model to properly catch its specificities, but the overall logic remains similar, and is partly based on tools and methods developed in the CLEVER project:

We start from a given indicator influencing energy consumption (e.g. surface per capita in m²/cap);

We add some technical scenario assumptions[2] on indicators related to efficiency (e.g. heating appliance efficiencies in %, heating needs in kWh/m²) and energy market shares (e.g. share of houses heated with gas boilers, wood stoves, heat pumps…);

- By multiplying and adding these different factors, we end up with a final energy consumption, broken down by energy carrier.

This approach is called "physical" by opposition to "econometric" models, as it does not include at this stage scenario assumptions on the overall economy (GDP), or purchasing power of a given actor. These aspects should nevertheless be considered in tasks 6.2 and 6.3.

[2] By "technical scenario assumption" we mean the projected changes for a given physical indicator, from a starting point to a target year, including a characterisation of the pace of change with a defined time step.

1.5. Integration into the models used in tasks 6.2 and 6.3

Continuous exchanges occurred with partners working on downstream tasks 6.2 and 6.3, to gain a better understanding of the logic and requirements of our respective models.

As such, it turned out that:

- Final energy consumption with a detailed breakdown per energy carrier could be fed into the input-output model used in task 6.2.
- Beyond final energy consumption, some other quantitative data on the evolution of non-energy demand (e.g. number and weight of cars sold), as well as more qualitative information, would be useful.
- If available, historical data on the main indicators from at least 10 years in the past would be useful to the task 6.2 model.
- Task 6.3 will mostly draw upon task 5.3 data, which delved deeper into sociological aspects.

2. Calculating the impact of sufficiency scenario assumptions

This chapter will provide details on the quantification process for each scenario assumption, and its results, as well as specific points of discussion for improvement / further research (beyond what will be said more generally in chapter 3). Some additional details and comments on data are available in annexes.

NB: as a reminder, results presented here are only an intermediary step in the quantification process, meant to feed further impact assessment activities in tasks 6.2 and 6.3.

2.1. Sharing spaces in housing

Results from task 5.3 (integration of SSH findings in quantified sufficiency assumptions)

Task 5.3 has quantified a reduction in housing surface per capita (m²/cap) for a targeted category of the population (people over 65 years old, living in a 1 to 2 people household, with significant spare space[3]).

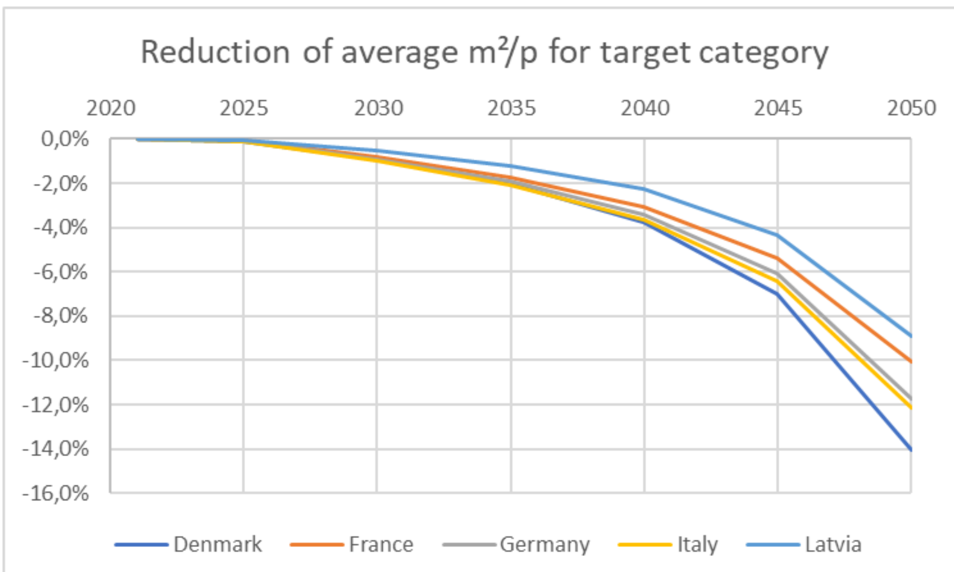


Figure 2 Trajectories taken from task 5.3 for the "sharing space" scenario assumption (FULFILL, 2024)

[3] The threshold defined in m²/cap is slightly different from one country to another.

Modelling approach

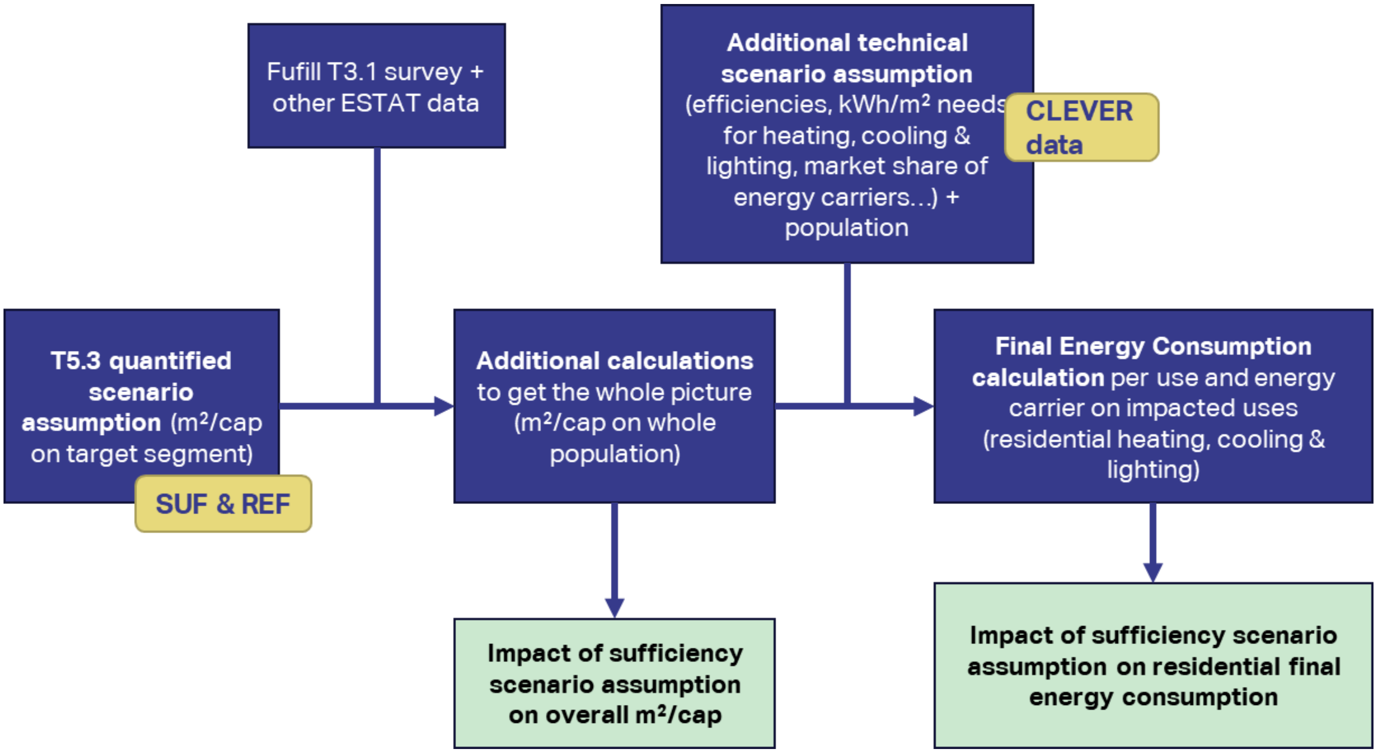


Figure 3 Overview of the modelling process for "sharing spaces in housing"

As a first step, we had to translate reductions in m²/cap for **the target population**, into reductions in m²/cap for **the whole population**, both for the sufficiency (SUF) and reference (REF) scenarios. In order to do this, we relied on Eurostat data and FULFILL task 3.1 survey data (FULFILL, 2023c).

Then this m²/cap has been translated into final energy consumption, using additional indicators coming mostly from CLEVER trajectories (cf. annex 1).

Table 1 Main characteristics of sufficiency (SUF) and reference (REF) scenarios for "sharing spaces in housing"

Sufficiency scenario (SUF)	Reference scenario (REF)
Reduced average m²/cap for the target population category[4]	Stable m²/cap for the target population category
Increasing share of target population category within the total population, according to Eurostat projections	Same as SUF
Progressive reduction of heating needs (kWh/m²) through better insulation and lower setpoint temperature	Same as SUF
Evolution of market shares of heating appliance energy sources and overall improvement of heating, cooling and lighting appliances	Same as SUF

[4] People over 65 years old, living in a 1 to 2 people household, with significant spare space.

Results

To quantify the scenario assumption impact on total residential m² (and its associated final energy consumption), we had to quantify the size of the target segment relatively to the total population. We thus relied on Eurostat data, for both historical data and projections[5] for the people above 65 years old (slightly larger than the target segment, but still a very good proxy).

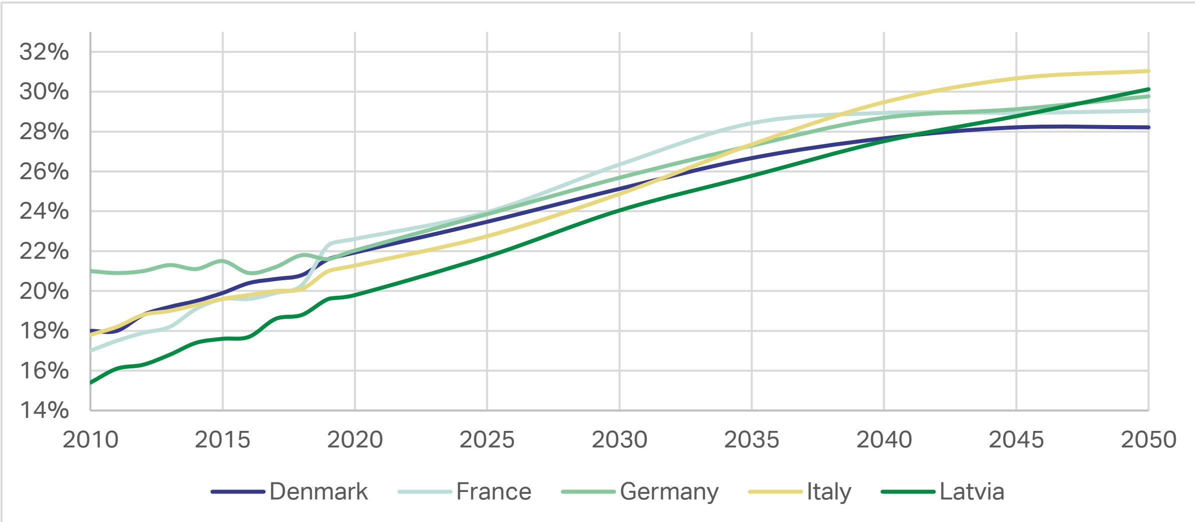


Figure 4 Share of targeted segment (vs. total pop), according to Eurostat historical data and projections

NB: this progressive increase in the size of the target segment naturally has a significant (positive) influence on the impact of the sufficiency scenario assumption.

The task 3.1 survey was rather consistent with Eurostat data in terms of segment size (indicating a good sampling), except for Denmark and Italy. We did keep Eurostat's estimates in any case.

In order to get the average m²/cap for the whole population, we had to determine the m²/cap for the population **outside** the targeted segment (younger and/or larger households) in 2019/2020, combining:

- Overall average m²/cap from CLEVER data
- m²/cap on target segment from task 5.3[6]

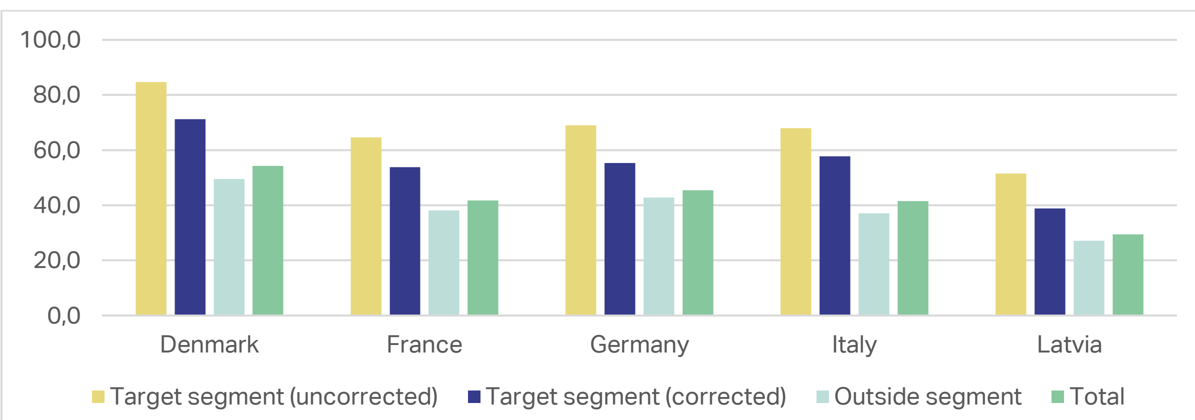


Figure 5 Surface area (m²/cap) in 2020 for different population segments[7]

It has been assumed that m²/cap for the population outside the target segment remains constant in the future.

[5] The projection scenario used is the "baseline" one.
[6] These values have been slightly corrected, as described in annex 1.
[7] "Corrected" means data has been adjusted to match Eurostat data, as explained in chapter "A1.1 Sharing spaces in housing" of annex 1.

The relative reduction (difference between SUF and REF scenarios) of overall m²/cap is as follows:

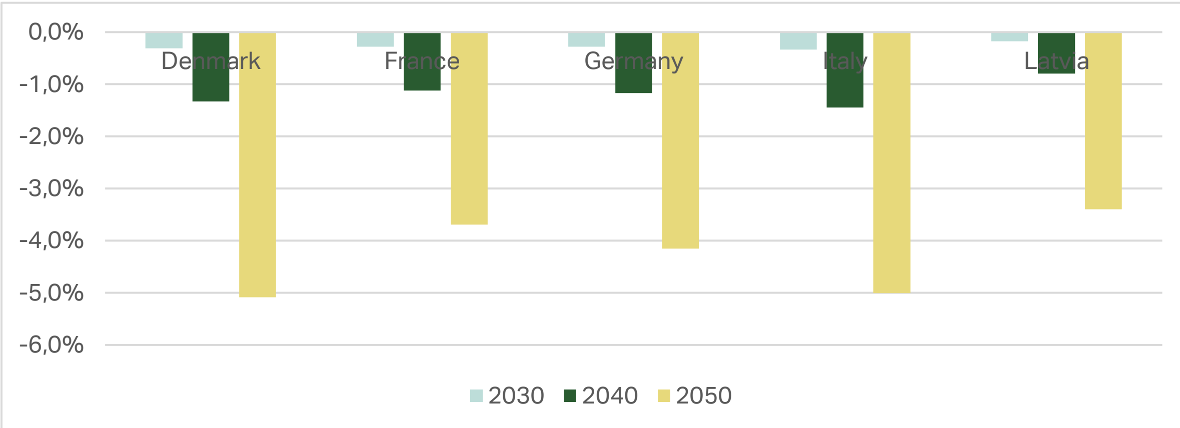


Figure 6 Relative housing surface area (m²/cap) reduction for each country, for the '"sharing spaces in housing" SUF scenario (vs. REF scenario)

The impact in 2050 is rather significant, and there is a sort of acceleration over time, which can be explained by two main factors:

- The pace of deployment of the sufficiency scenario assumption modelled in task 5.3 is not linear;
- And to a lesser extent, the share of the target segment (older people) is growing as shown above.

Then, the m²/cap indicator has been translated into final energy consumption, thanks to a bottom-up calculation tool, derived from CLEVER demand modelling tools.

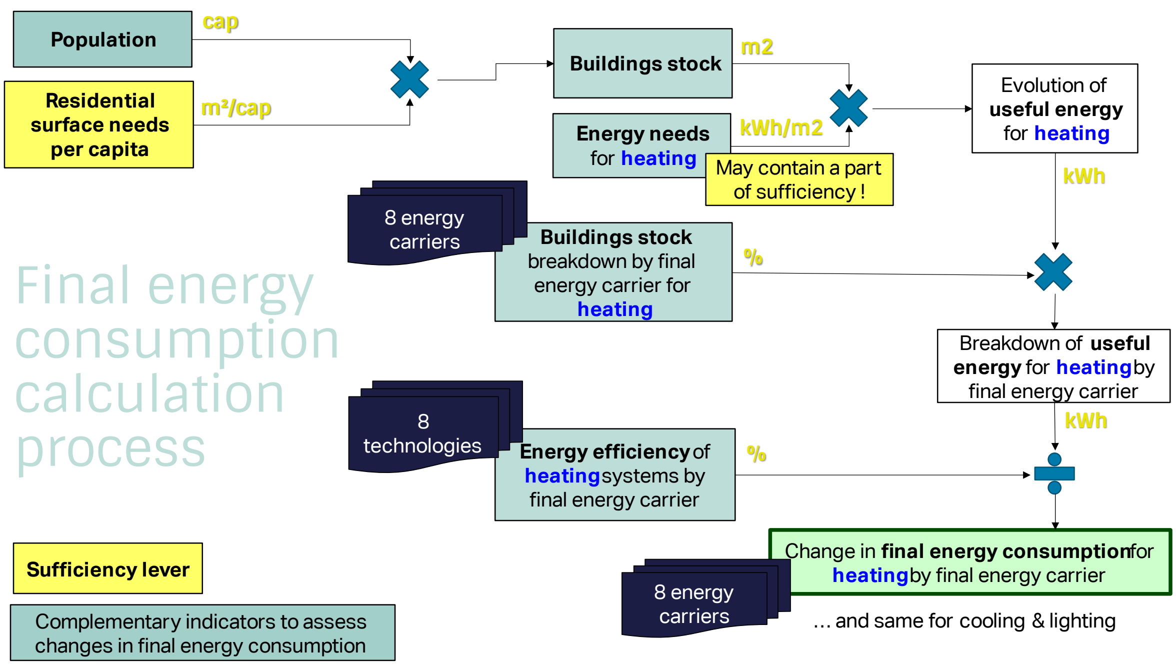


Figure 7 Final energy consumption modelling process for the "sharing spaces in housing" scenario assumption

Energy needs for heating, cooling and lighting (kWh/m²) have been considered similar across the population by default (as no dedicated data was available). Therefore, with fixed kWh/m² ratios[8], the relative impact on final energy consumption is exactly the same as for the surface area (see Figure 6).

The trajectory of FEC reduction is as follows:

[8] Cf. annex 1 for more details on this indicator.

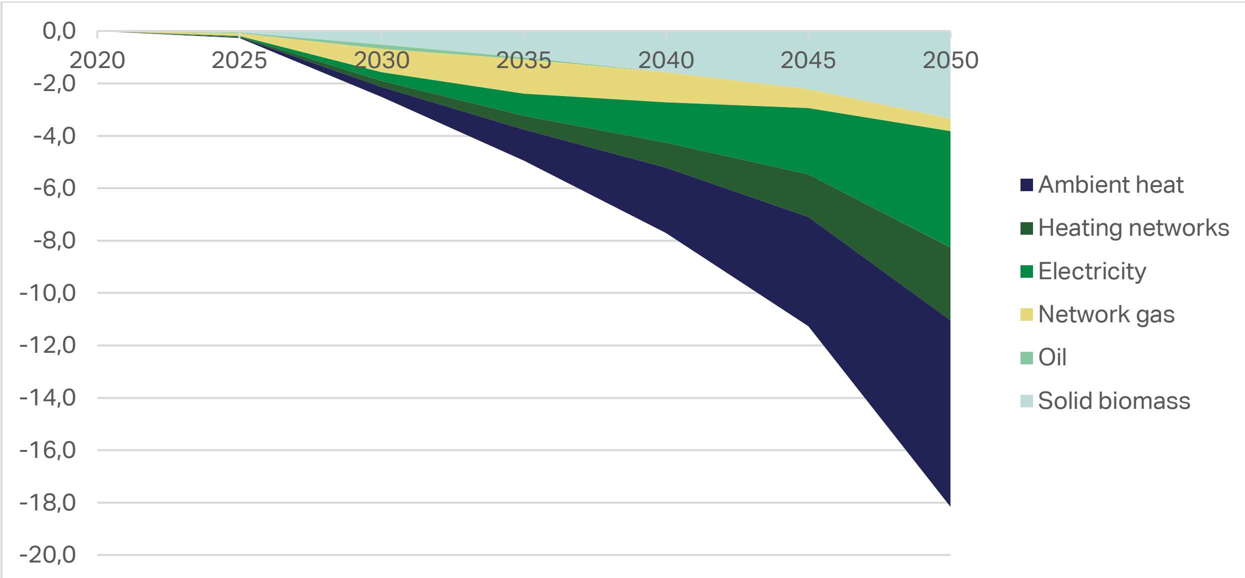


Figure 8 Absolute FEC reduction, per energy carrier, for the 5 countries, for "sharing spaces in housing" (TWh)[9]

The absolute reduction of FEC goes up to 18 TWh in 2050 across the 5 countries. A large share of it consists of ambient heat and electricity, because of the progressive deployment of heat pumps in CLEVER trajectories. GHG emission abatement (vs. REF scenario) would thus occur on the fossil parts of network gas & electricity.

Discussion

A few possible areas of improvement of the modelling have been identified.

First, the ongoing dynamic on m²/cap has not been modelled accurately, to take into account both historical trends (towards increasing m²/cap in all countries) AND convergence of living standards between countries (lower income countries have a legitimate right to reach "decent" living standards). These upwards trends should theoretically play a role both within and without the task 5.3 target segment, whilst they have been ignored. It is likely that factoring this in would yield and increased impact assessment of the "sharing spaces in housing" scenario assumption, as:

- Extending the historical increase in m²/cap means average building sizes keep increasing, and/or the average number of people per housing keeps decreasing;
- Therefore, there would be an increasing potential for sharing spaces in terms of target population (more 1 or 2 people households);
- And/or larger buildings would be shared, which would increase the effect of sharing spaces as well.

Nevertheless, more research would be needed to understand the possible impact of such historical trends on our evaluation, by:

- Carrying out a detailed analysis of the factors behind the historical increase in m²/cap;
- Designing of a building stock model (with details on its allocation by population categories).

[9] Coal and solar heating have been removed from the chart as they are rather small in comparison of the other energies.

As such, the CLEVER project assumed a kind of convergence[10] towards sustainable lifestyles, which in some cases resulted in an increase in living standards (still slightly lower than what would happen in a “business as usual” scenario) as shown in the following graphs:

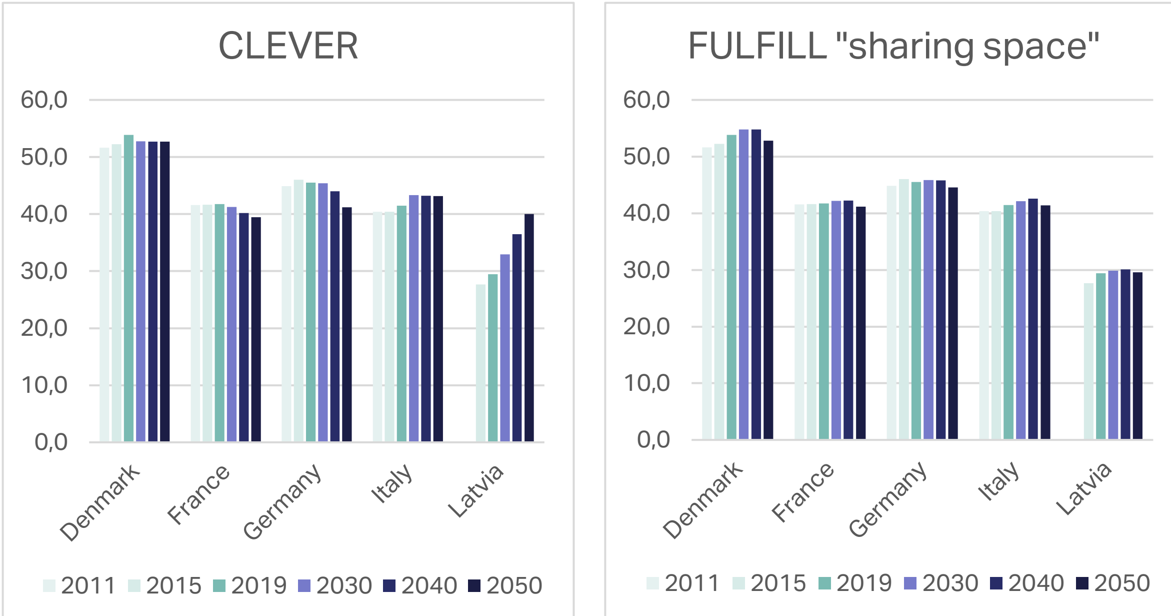


Figure 9 Comparison of average m²/cap for total population between CLEVER and FULFILL projects

The difference between the two approaches is particularly visible in Latvia. For reference, in this country 25% of people over 65 years old live in overcrowded places according to EU-SILC survey (against 2% in France, 1% in Denmark and 10% in Italy).

Another improvement would be to factor in the fact that energy needs (in kWh/m²) may be different for the different population groups:

The ratio of actual heated surface vs. the total housing surface may be different (a 1 or 2 people household living in a very large house probably does not need to heat the whole surface);

- Setpoint temperatures may be different;
- Insulation may be different too;
- Etc.

Some additional data from task 3.1 survey could have been mobilized for some of these aspects, which are otherwise rather difficult to quantify using statistical data. We did however lack time to investigate this survey data further.

Finally, one may think of a kind of synergy between this scenario assumption, and the “sharing products” scenario assumption, as sharing spaces in housing obviously leads to an increase in products sharing practices (including e.g. washing machines).

[10] The corridor was defined as 32-40 m²/cap, with an exception for countries with already very high values and strong historical dynamics such as Denmark, which are meant to stabilise to take account of the building stock inertia.

2.2. Moderate car sizing

Results from task 5.3 (integration of SSH findings in quantified sufficiency assumptions)

Task 5.3 has modelled the evolution of segment market shares for cars, in each of the 5 countries:

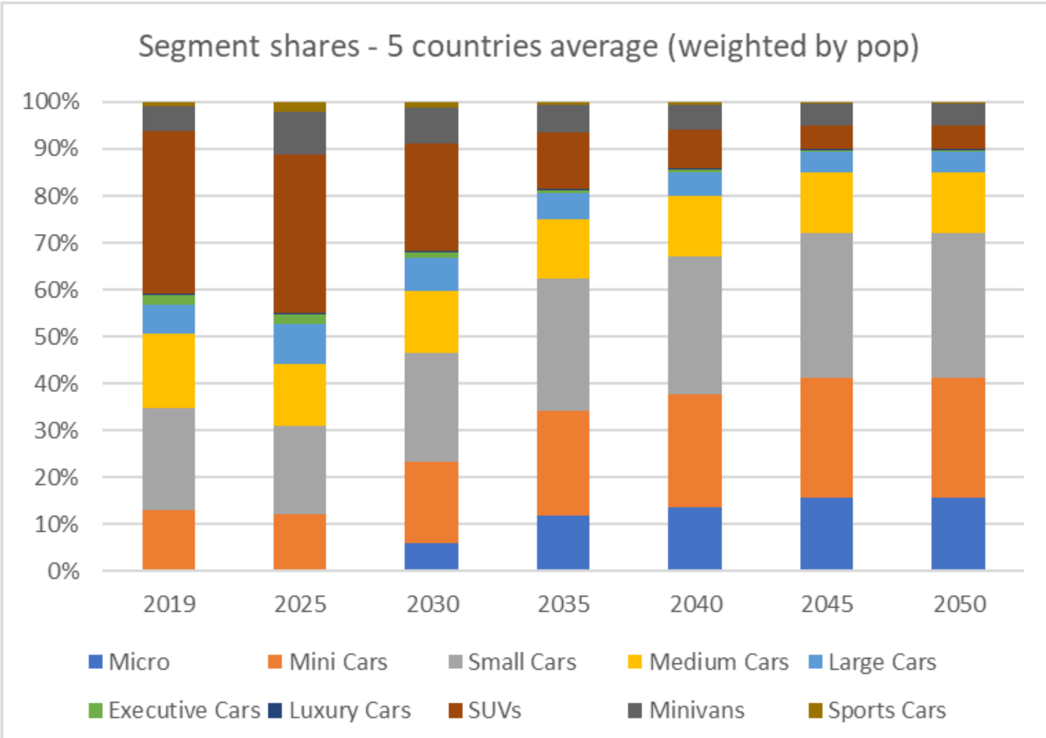


Figure 10 Trajectories taken from task 5.3 for the "moderate car sizing" scenario assumption (FULFILL, 2024)

Modelling approach

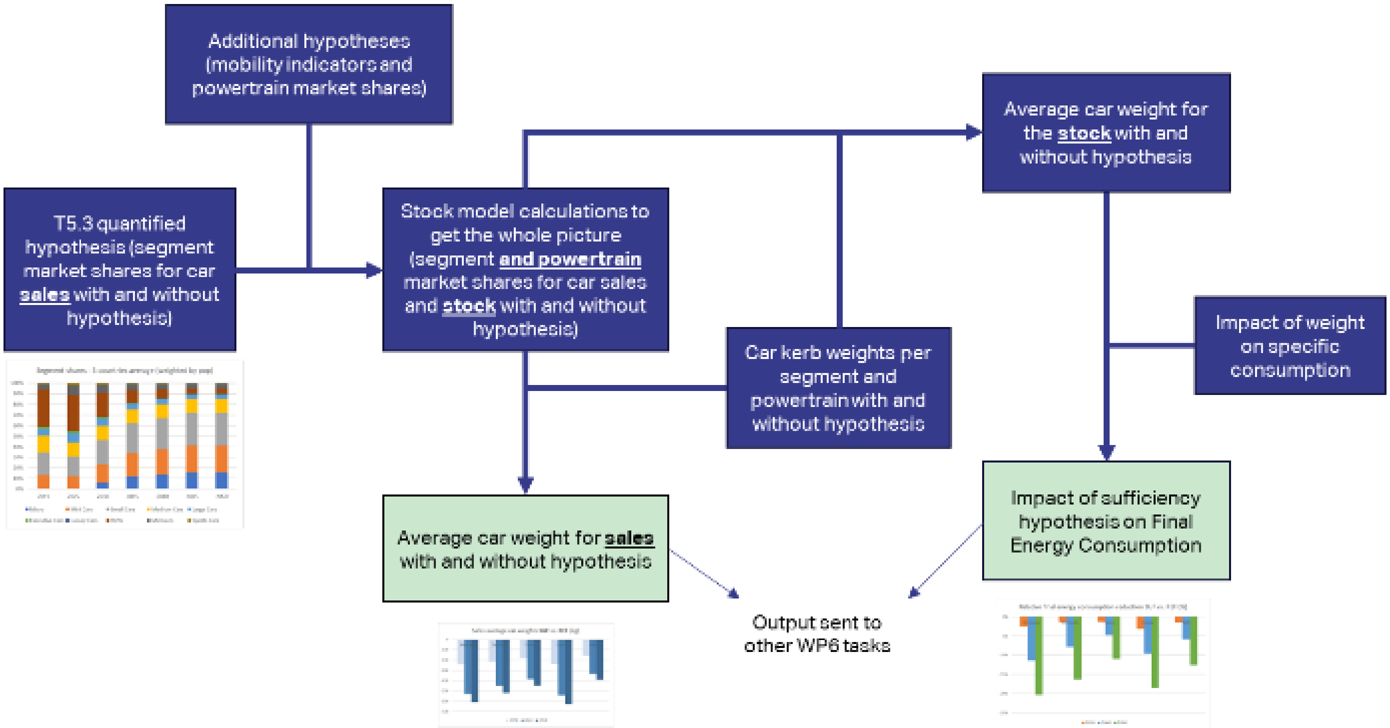


Figure 11 Overview of the modelling process for "moderate car sizing"

These market share evolutions have two main effects, which have been modelled:

- Cars sold (and thus manufactured) tend to be lighter, requiring less materials and thus less energy.
- On average, the stock of cars is lighter and thus slightly less energy intensive.

The impact of lighter cars manufacture will be dealt with in task 6.2, from the total weights of car sold calculated in this task. In order to calculate this total weight, two indicators had to be determined:

Kerb weights for each car segment and powertrain (cf. annex 1 for explanations on how they have been set).

- Number of cars sold, which are also meant to decrease, according to reduced car usage, as modelled in CLEVER trajectories (and most energy transition scenarios).

To evaluate how sales would evolve relatively to changing mobility needs, but also to calculate variations of the average weight of the car stock (cf. second effect mentioned above), we had to run a Python-based stock model developed by négaWatt (BAMASI). This model requires a certain number of mobility and technical indicators, as explained in more detail in annexes 1 and 2.

This also implied making assumptions on the development of new powertrains, not only because it has an impact on the type of energy carrier consumed (and thus saved), but also because the weight of battery-powered cars is higher.

Then, this evolution of the average weight of the car stock has been converted into energy savings, with assumptions made on additional consumption caused by car overweight (cf. annex 1 for details).

Finally, a bottom-up model has been used to determine the amount and type (energy carrier) of final energy consumption saved with the "moderate car sizing" scenario assumption.

Table 2 Main characteristics of sufficiency (SUF) and reference (REF) scenarios for "moderate car sizing"

Sufficiency scenario (SUF)	Reference scenario (REF)

Progressive shift towards smaller car segments, as defined in task 5.3	Status quo on the car segment market shares
Stable car kerb weights within each segment	Continuous increase in kerb weights, according to past dynamics (cf. annex 1)
Car traffic is progressively reduced through increased car occupancy, modal shift to other means of transport, and overall mobility needs reduction	Same as SUF
Following car traffic reduction, car sales are also progressively reduced	Same as SUF
Increased efficiency of cars for a given powertrain and segment	Same as SUF
Progressive shift towards battery electric powertrains	Same as SUF

Results

Cars sold in the sufficiency (SUF) scenario are significantly lighter than in the reference (REF) scenario:

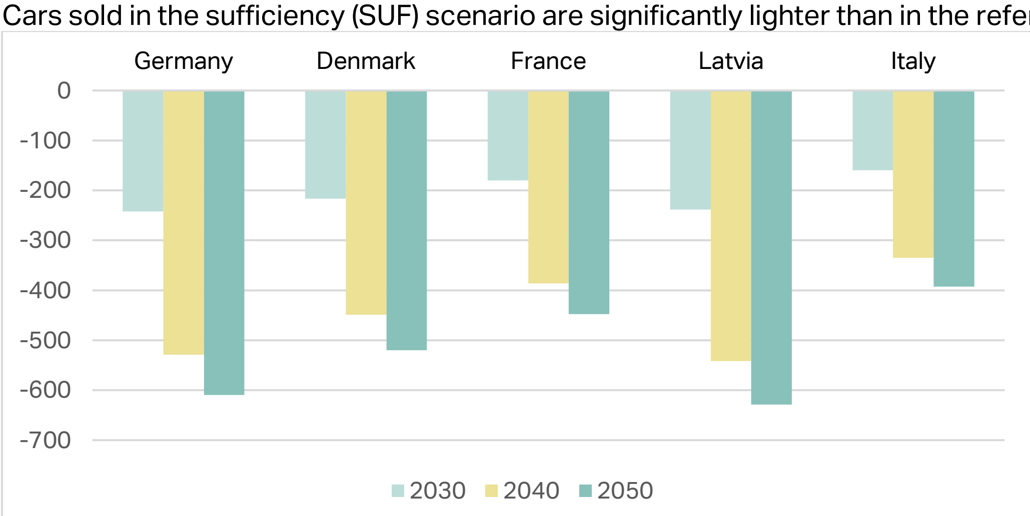


*Figure 12 Average car weight reduction in SUF scenario (vs. REF scenario) for car **sales** (kg per vehicle)*

This will result in less materials to produce and assemble, and thus less energy consumption and emissions associated with car manufacture (this will be quantified in task 6.2).

As explained above, these evolutions in sales also have an impact on the average weight of the stock, although slightly delayed because of the stock inertia:

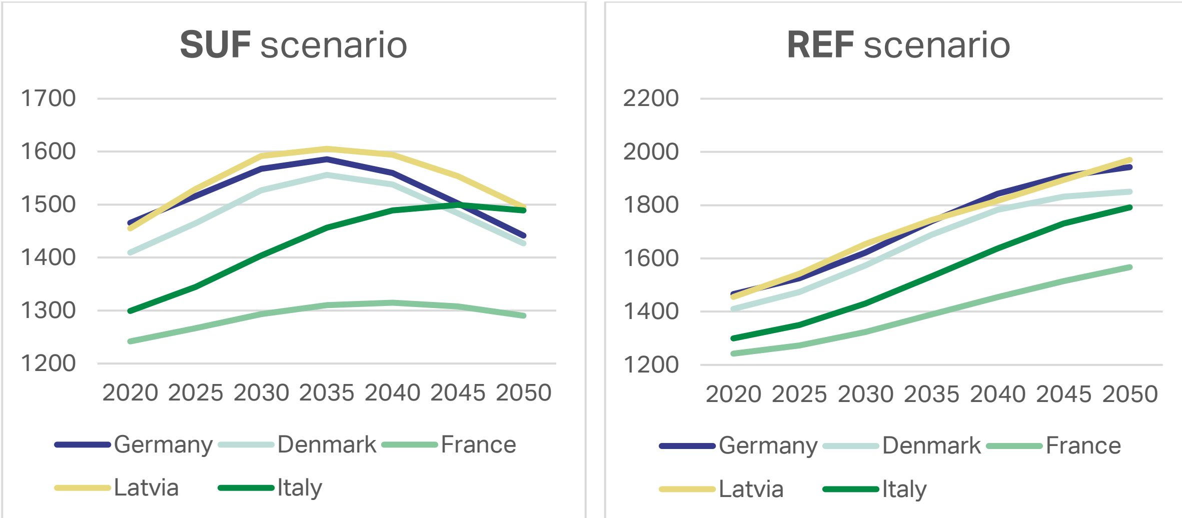


Figure 13 Average car weight trajectories for SUF and REF scenarios for the car ***stock*** *(kg per vehicle)*

NB: Average weights keep increasing in the SUF scenario at the beginning of the period, because of the deployment of battery electric vehicles, which tend to be heavier than ICE cars. Nevertheless, average car weights end up much higher in REF (1839kg in average for the 5 countries in 2050) than in SUF scenario (1434kg).

Lighter cars result in less energy consumed:

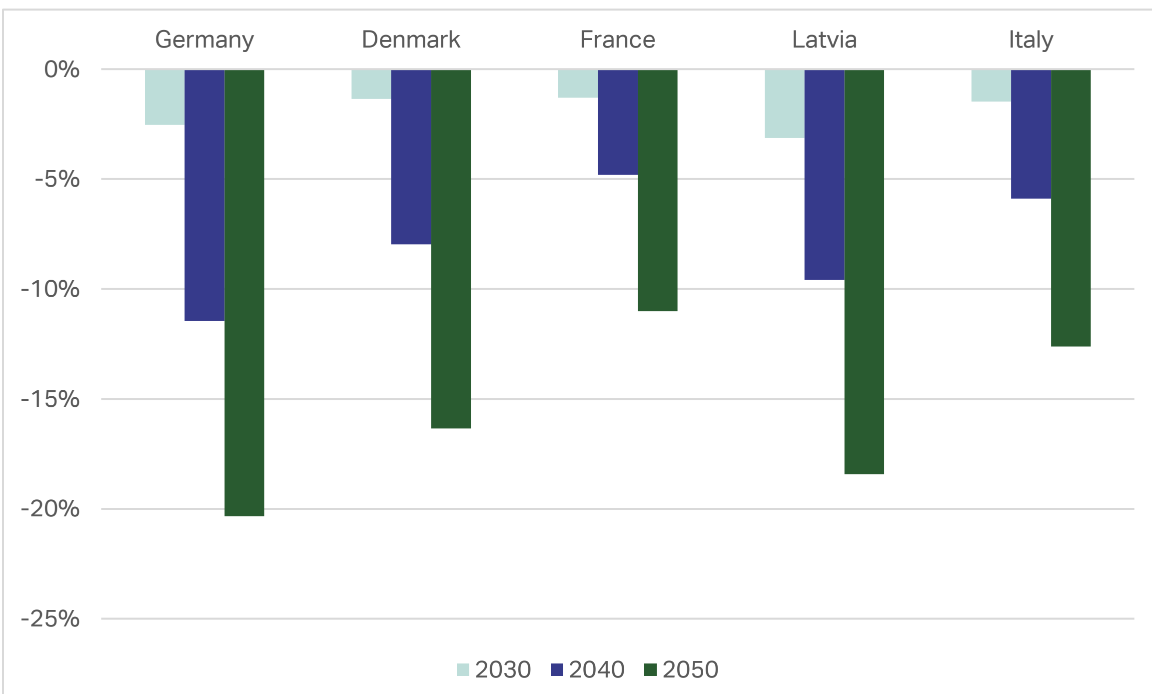


Figure 14 Relative FEC reduction for car use for each country, for the "moderate car sizing" SUF scenario (vs. REF scenario)

Reduction levels shown above are far from negligible, up to 20% compared to REF scenario. With the massive deployment of battery electric vehicles, this saved energy consists mostly in electricity in the long run, and in the medium term up to 6.7 TWh of fossil liquid fuels are also saved across the 5 studied countries:

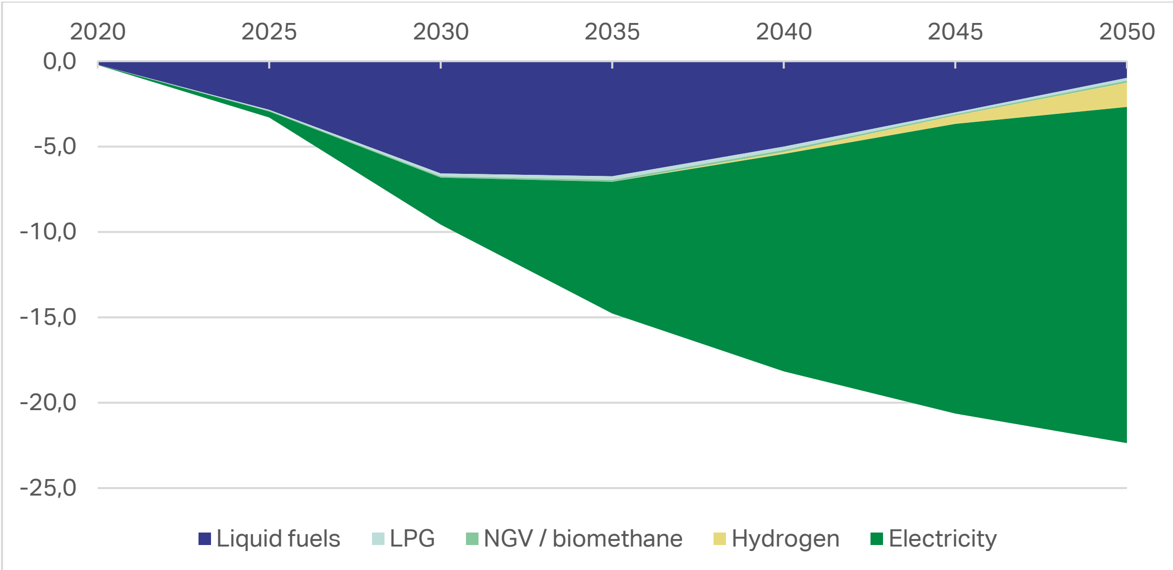


Figure 15 Absolute FEC reduction per energy carrier, for the 5 countries, for "moderate car sizing" (TWh)

Discussion

This hypothesis mobilised rather significant modelling resources in terms of tools (BAMASI), but also data, which highlighted the challenge of extending this approach to a large number of countries. Latvia in particular appeared to have less data available, or poorer quality of data, more tests would need to be carried out on other European countries, should one want to replicate this work across the EU (without performing a cluster analysis, as it will be done in the following task of this work package).

Still, some improvements could possibly be made to the modelling, by differentiating some indicators by segments and/or by powertrain, such as the average use (km per vehicle per year), the vehicle lifetimes and occupancies, etc. The main constraint would be again the availability of data, but also the complexity of the model.

Finally, a rather significant uncertainty remains on the weight vs. specific consumption relationship as explained in annex 1. On top of this uncertainty, which certainly deserves additional research and data, one may express strong doubts on an analysis based on manufacturer-declared values. For example, a recent study from French think tank I4CE applied correction factors of 1.39 to manufacturer emission levels, to come closer to real-life emission levels (I4CE, 2021).

2.3. Sharing products

Results from task 5.3 (integration of SSH findings in quantified sufficiency assumptions)

Task 5.3 has quantified a reduction in the ownership rate of washing machines, through different levers to share these appliances as illustrated in the graph below.

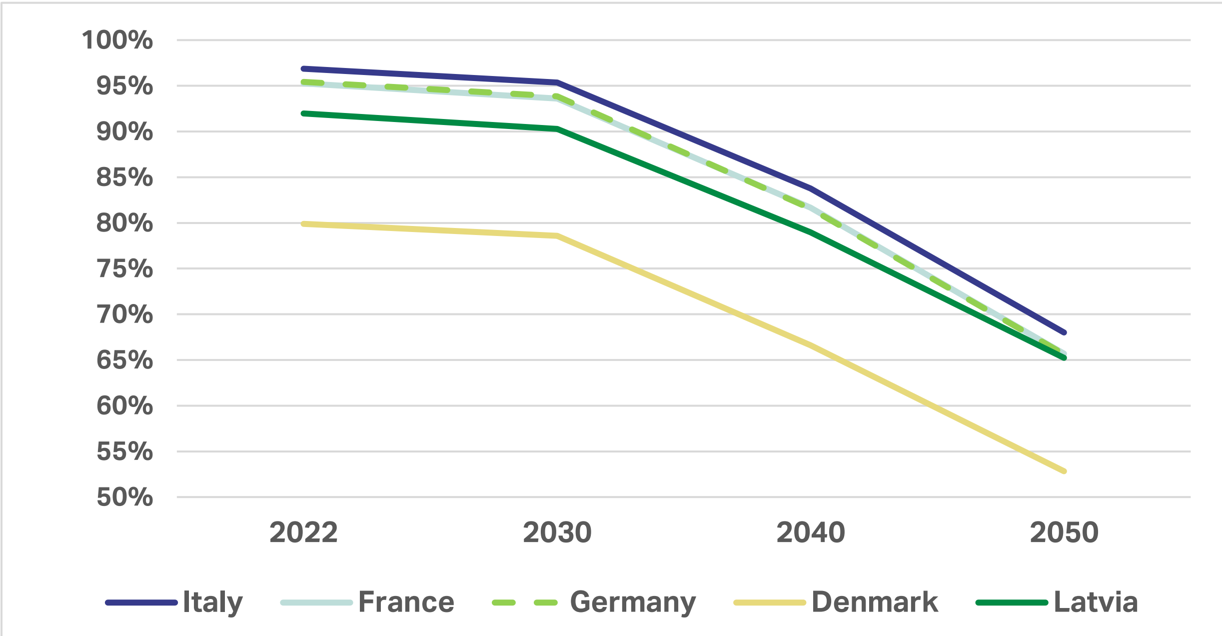


Figure 16 Residential ownership rates of washing machines taken from task 5.3 (FULFILL, 2024)

Out of the task 5.3 trajectories, it is possible to estimate the number of washing machines in stock at a given time (including washing machines in dwellings and in communal laundry rooms).

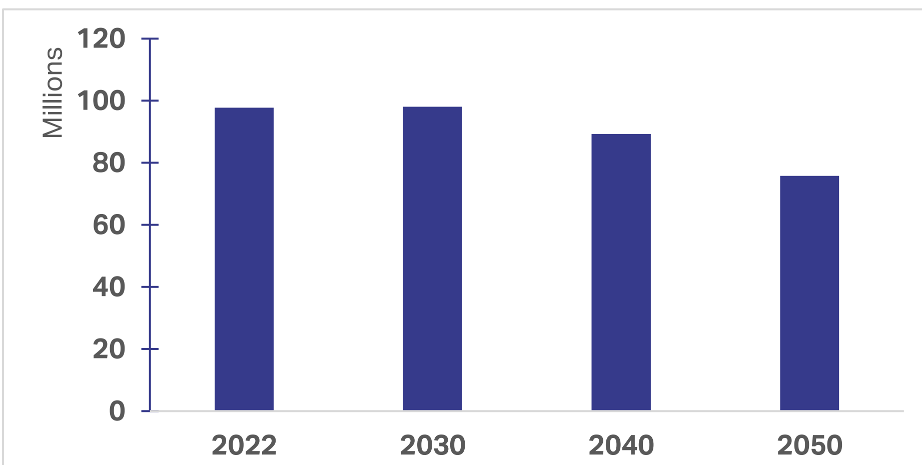


Figure 17 Stock of washing machines over the 5 countries taken from task 5.3 (FULFILL, 2024)

Modelling approach

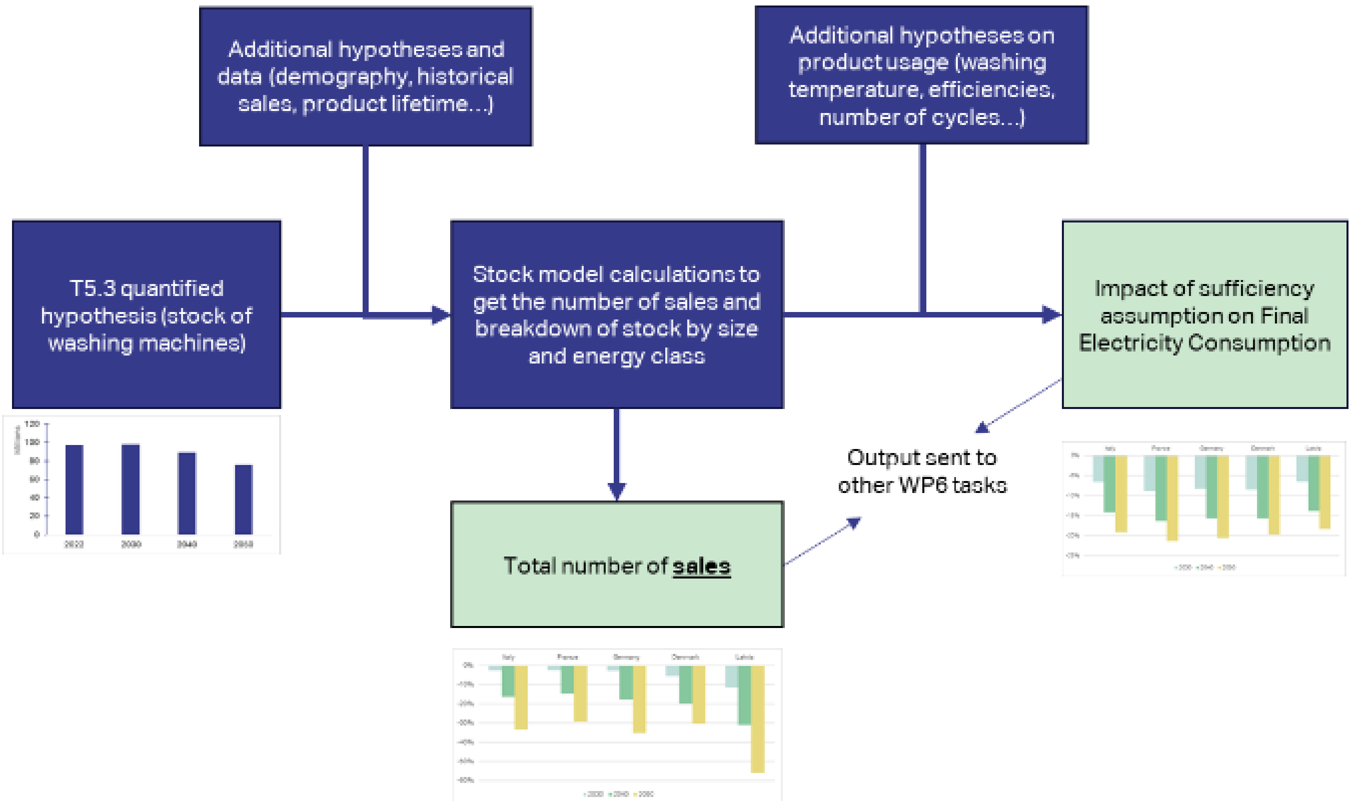


Figure 18 Overview of the modelling process for "sharing products"

These quantified results had to be translated into **sales trends**[11] and **electricity savings** over 2010-2050 for each of the 5 countries.

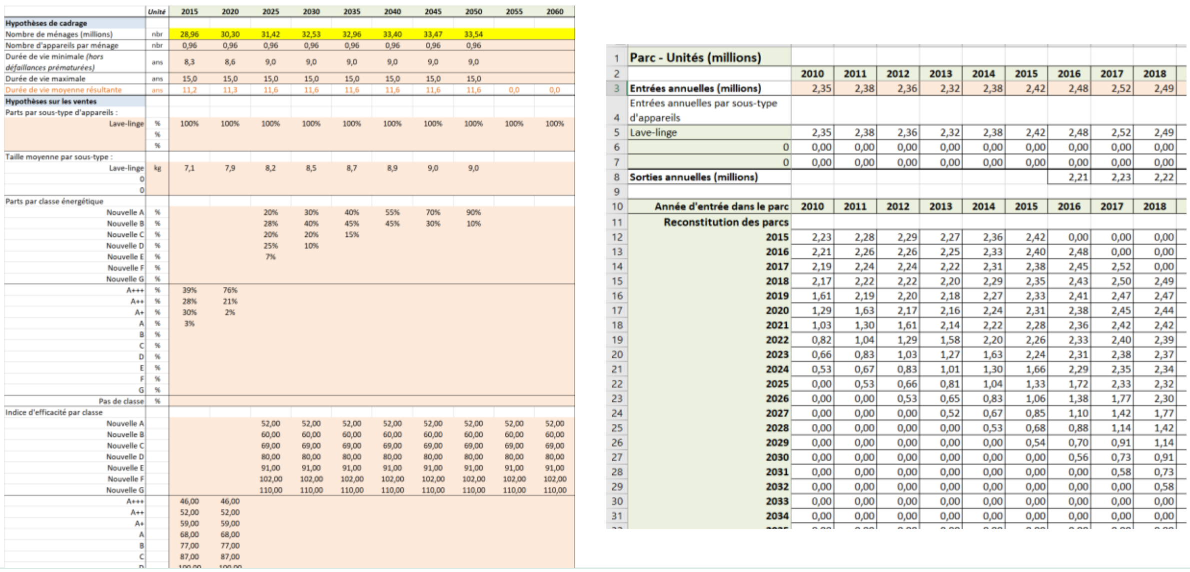
To switch from numbers of washing machines in use to data on annual sales, a "**stock model**" is required. This type of model simulates the relationship between sales trends and numbers and types of machines present in households.

For its 2022 French energy scenario, négaWatt has developed such detailed models for numerous appliances (including cars, cf. the "moderate car sizing" scenario assumption). They have been reused and adjusted to the purpose of this project. The stock model requires as input:

- Historical data and future projections on population and number of households
- Historical data on annual sales
- Historical data and assumptions on the ownership rates, the product lifetime and the distribution of sales by size and energy class
- Historical and future trends on product usage (number of cycles, washing temperatures…)

From this, the model reconstructs the flow of products entering and exiting homes and the composition of machines inside homes each year.

[11] Sales will be useful input data for input-output models used in task 6.2, to evaluate externalities of appliance manufacture.



	Unité	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Hypothèses de cadrage											
Nombre de ménages (millions)	nbr	28,96	30,30	31,42	32,53	32,96	33,40	33,47	33,54		
Nombre d'appareils par ménage	nbr	0,96	0,96	0,96	0,96	0,96	0,96	0,96	0,96		
Durée de vie minimale *(hors défaillances prématurées)*	ans	8,3	8,6	9,0	9,0	9,0	9,0	9,0	9,0		
Durée de vie maximale	ans	15,0	15,0	15,0	15,0	15,0	15,0	15,0	15,0		
Durée de vie moyenne résultante	ans	11,2	11,3	11,6	11,6	11,6	11,6	11,6	11,6	0,0	0,0
Hypothèses sur les ventes											
Parts par sous-type d'appareils :											
Lave-linge	%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	%										
	%										
Taille moyenne par sous-type :											
Lave-linge	kg	7,1	7,9	8,2	8,5	8,7	8,9	9,0	9,0		
0											
0											
Parts par classe énergétique											
Nouvelle A	%			20%	30%	40%	55%	70%	90%		
Nouvelle B	%			28%	40%	45%	45%	30%	10%		
Nouvelle C	%			20%	20%	15%					
Nouvelle D	%			25%	10%						
Nouvelle E	%			7%							
Nouvelle F	%										
Nouvelle G	%										
A+++	%	39%	76%								
A++	%	28%	21%								
A+	%	30%	2%								
A	%	3%									
B	%										
C	%										
D	%										
E	%										
F	%										
G	%										
Pas de classe	%										
Indice d'efficacité par classe											
Nouvelle A				52,00	52,00	52,00	52,00	52,00	52,00	52,00	52,00
Nouvelle B				60,00	60,00	60,00	60,00	60,00	60,00	60,00	60,00
Nouvelle C				69,00	69,00	69,00	69,00	69,00	69,00	69,00	69,00
Nouvelle D				80,00	80,00	80,00	80,00	80,00	80,00	80,00	80,00
Nouvelle E				91,00	91,00	91,00	91,00	91,00	91,00	91,00	91,00
Nouvelle F				102,00	102,00	102,00	102,00	102,00	102,00	102,00	102,00
Nouvelle G				110,00	110,00	110,00	110,00	110,00	110,00	110,00	110,00
A+++		46,00	46,00								
A++		52,00	52,00								
A+		59,00	59,00								
A		68,00	68,00								
B		77,00	77,00								
C		87,00	87,00								

1	Parc - Unités (millions)									
2		2010	2011	2012	2013	2014	2015	2016	2017	2018
3	Entrées annuelles (millions)	2,35	2,38	2,36	2,32	2,38	2,42	2,48	2,52	2,49
4	Entrées annuelles par sous-type d'appareils									
5	Lave-linge	2,35	2,38	2,36	2,32	2,38	2,42	2,48	2,52	2,49
6	0	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
7	0	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
8	Sorties annuelles (millions)							2,21	2,23	2,22
9										
10	Année d'entrée dans le parc	2010	2011	2012	2013	2014	2015	2016	2017	2018
11	Reconstitution des parcs									
12	2015	2,23	2,28	2,29	2,27	2,36	2,42	0,00	0,00	0,00
13	2016	2,21	2,26	2,26	2,25	2,33	2,40	2,48	0,00	0,00
14	2017	2,19	2,24	2,24	2,22	2,31	2,38	2,45	2,52	0,00
15	2018	2,17	2,22	2,22	2,20	2,29	2,35	2,43	2,50	2,49
16	2019	1,61	2,19	2,20	2,18	2,27	2,33	2,41	2,47	2,47
17	2020	1,29	1,63	2,17	2,16	2,24	2,31	2,38	2,45	2,44
18	2021	1,03	1,30	1,61	2,14	2,22	2,28	2,36	2,42	2,42
19	2022	0,82	1,04	1,29	1,58	2,20	2,26	2,33	2,40	2,39
20	2023	0,66	0,83	1,03	1,27	1,63	2,24	2,31	2,38	2,37
21	2024	0,53	0,67	0,83	1,01	1,30	1,66	2,29	2,35	2,34
22	2025	0,00	0,53	0,66	0,81	1,04	1,33	1,72	2,33	2,32
23	2026	0,00	0,00	0,53	0,65	0,83	1,06	1,38	1,77	2,30
24	2027	0,00	0,00	0,00	0,52	0,67	0,85	1,10	1,42	1,77
25	2028	0,00	0,00	0,00	0,00	0,53	0,68	0,88	1,14	1,42
26	2029	0,00	0,00	0,00	0,00	0,00	0,54	0,70	0,91	1,14
27	2030	0,00	0,00	0,00	0,00	0,00	0,00	0,56	0,73	0,91
28	2031	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,58	0,73
29	2032	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,58
30	2033	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
31	2034	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

Figure 19 Screenshots of the appliance stock model

For determining the electricity savings, fewer annual cycles and better loading practices were assumed among washing machines sharers (see deliverable 5.3 in FULFILL, 2024). Also, SUF scenario supposes that the trend to wash at lower temperatures continues more systematically and intensively than in the REF scenario. As for other scenario assumptions, the model has been adjusted to each of the 5 countries and run on two scenarios:

Table 3 Main characteristics of sufficiency (SUF) and reference (REF) scenarios for "sharing products"

Sufficiency scenario (SUF)	Reference scenario (REF)
Decrease in ownership rates due to sharing - in line with the assumptions made in task 5.3	Stabilised or linear increase in ownership rate
Slight increase of 4% of average product lifetime until 2030	Same as SUF
Increase in average product size to reach 9 kg in 2050	Same as SUF
Progress in energy efficiency inspired by past trends (steady increase to better energy classes)	Same as SUF
Sustained decrease in average washing temperatures	Stabilisation of average washing temperatures
Reduction of the number of cycles per household in sharing practices (better loading)	No reduction of the number of cycles per household

Results

Table 4 Results for "sharing products" (electricity used for washing clothes, TWh/year)

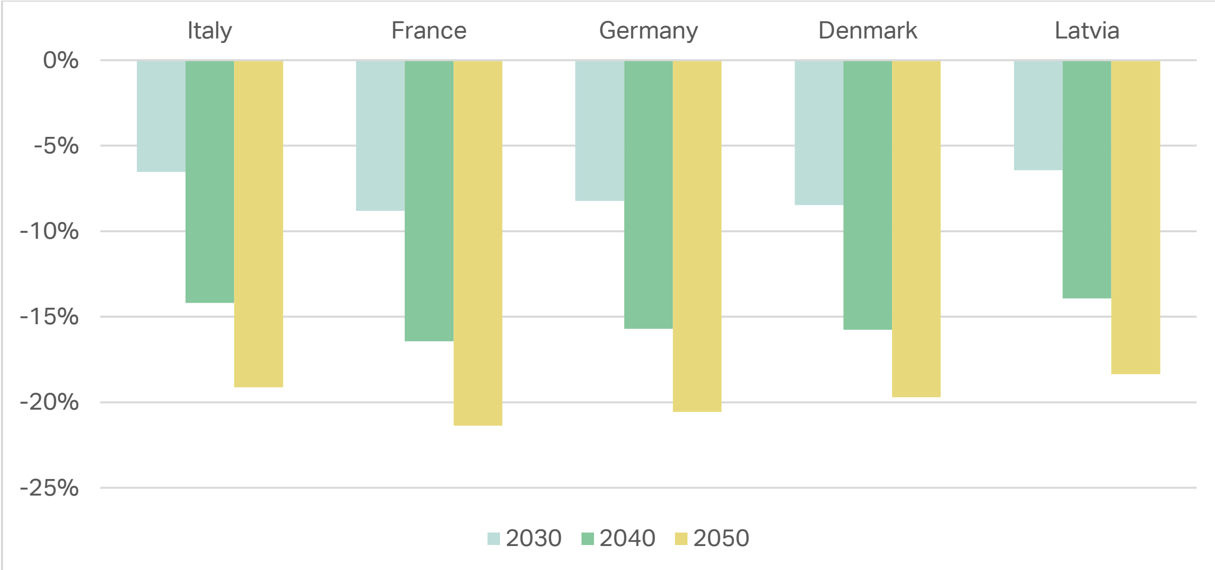


Figure 20 Relative FEC (electricity) reduction for washing clothes for each country for the "sharing products" SUF scenario (vs. REF scenario)

While not negligible, electricity consumption reductions stemming from increased sharing of washing machines are not of the same order of magnitude as for other scenario assumptions studied in this task:

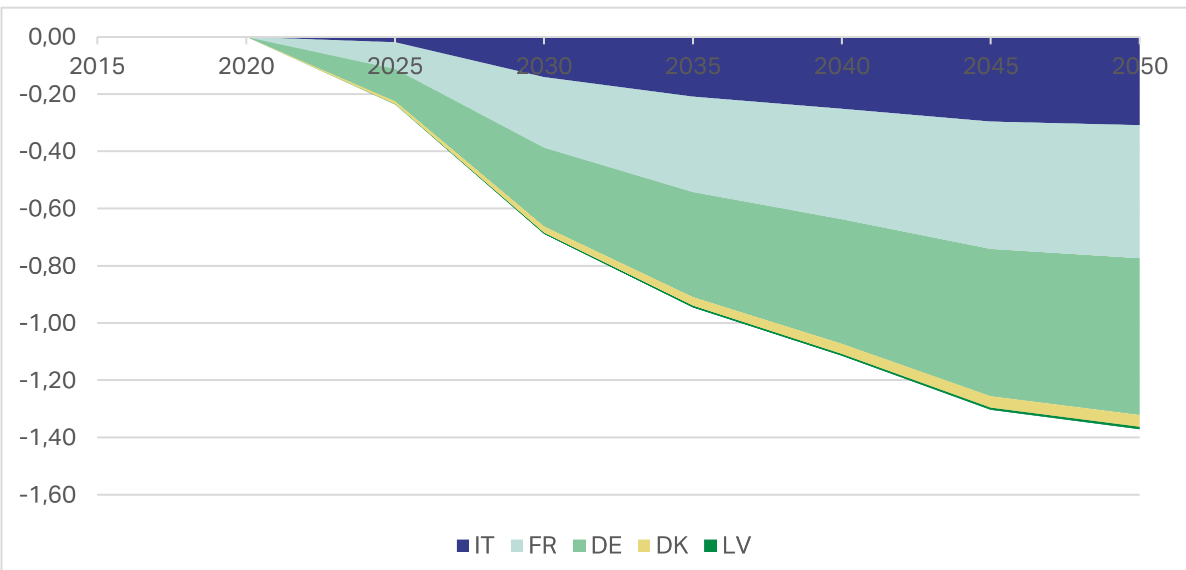


Figure 21 Absolute FEC reduction per energy carrier, for the 5 countries, for "sharing products" (TWh)

More significant impact is expected from reduced sales (and thus production) of washing machines[12]. Around 1/3 less machines would be sold in 2050, compared to the REF scenario:

[12] This quantification will be carried out in task 6.2, using input-output models.

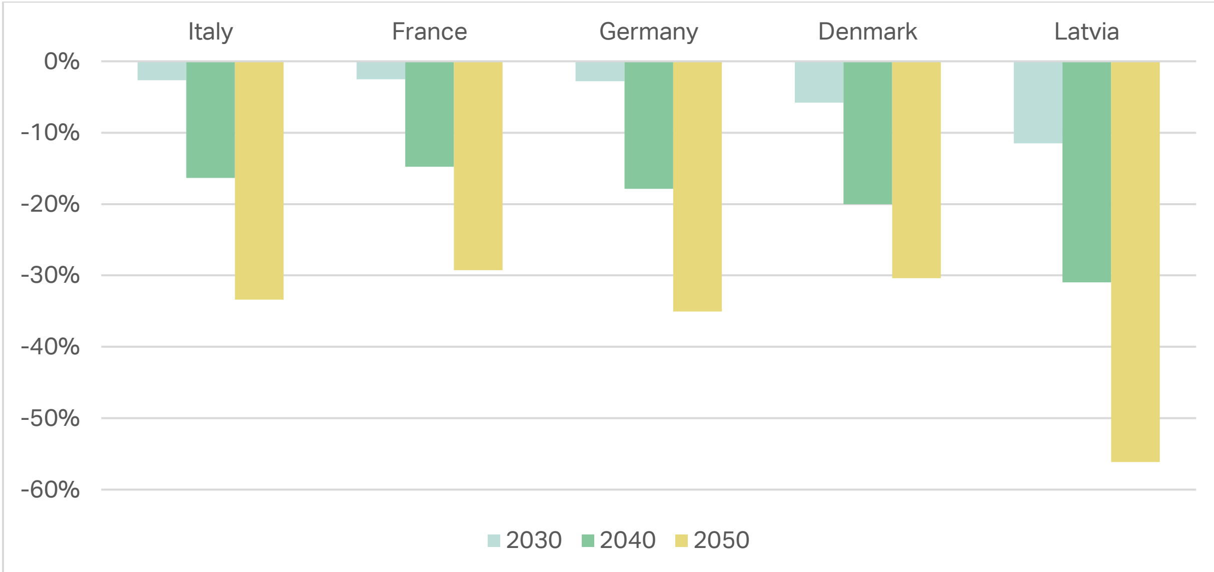


Figure 22 Sales of washing machines - relative reduction with "sharing products" scenario assumption (SUF) vs. without (REF)

The stronger reduction in washing machine sales in 2050 in Latvia (compared to the other countries) is essentially explained by Eurostat demographic projections that foresee a substantial decline in the country population and number of households. This is not related to the sharing aspects.

Discussion

The assumption that the average lifetime of washing machines follows the same trajectory in both SUF and REF scenarios may be questioned, as shared machines are used more intensively and could break earlier. However, the SUF scenario supposes the adoption of effective durability and repairability EU regulations, as well as the installation of semi-pro machines in communal laundry rooms tailored to intensive use, with a good level of maintenance services. In any case, repairing has typically a lower environmental impact than product replacement.

The model does not cover other environmental benefits such as less water and detergent consumption during cycles.

Washing machines are only one example of products that could be increasingly shared. Modelling a full sharing scenario covering all categories (cars, tools, clothes, etc.) would lead to a much higher impact.

2.4. Biking

Results from task 5.3 (integration of SSH findings in quantified sufficiency assumptions)

Task 5.3 provided trajectories with an increase in the share of daily trips made with bikes (and e-bikes), expressed in number of trips and passenger kilometres (p.km):

Table 5 Trajectories taken from task 5.3 for the "biking" scenario assumption (FULFILL, 2024)

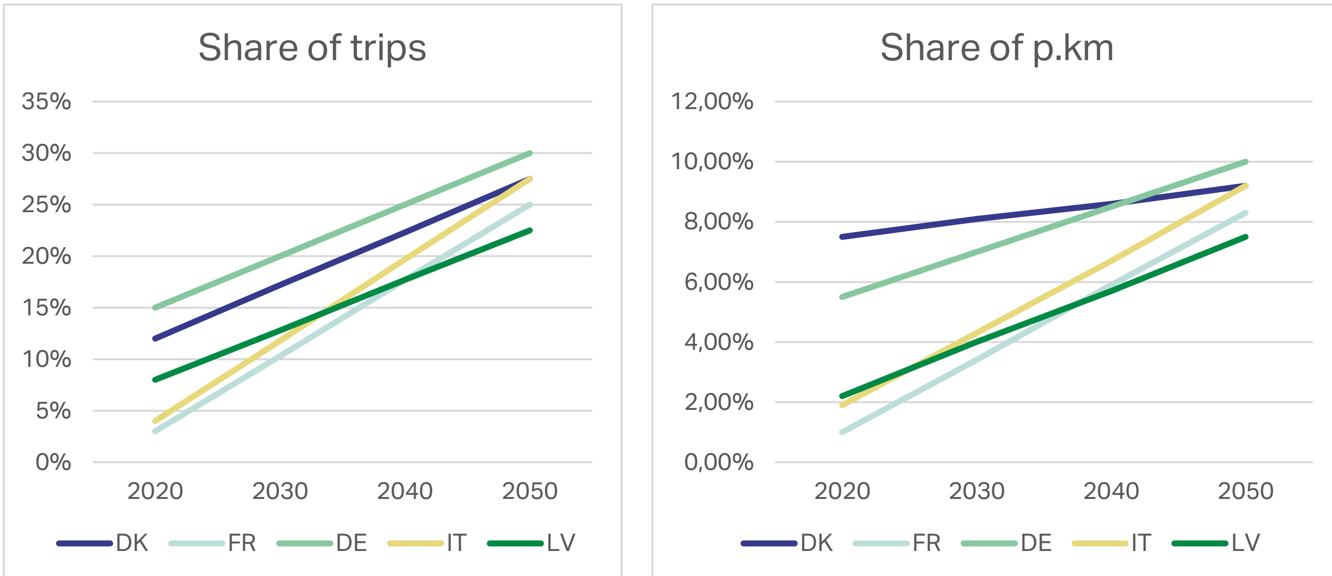


Figure 23 Trajectories taken from task 5.3 for the "biking" scenario assumption (FULFILL, 2024)

Modelling approach

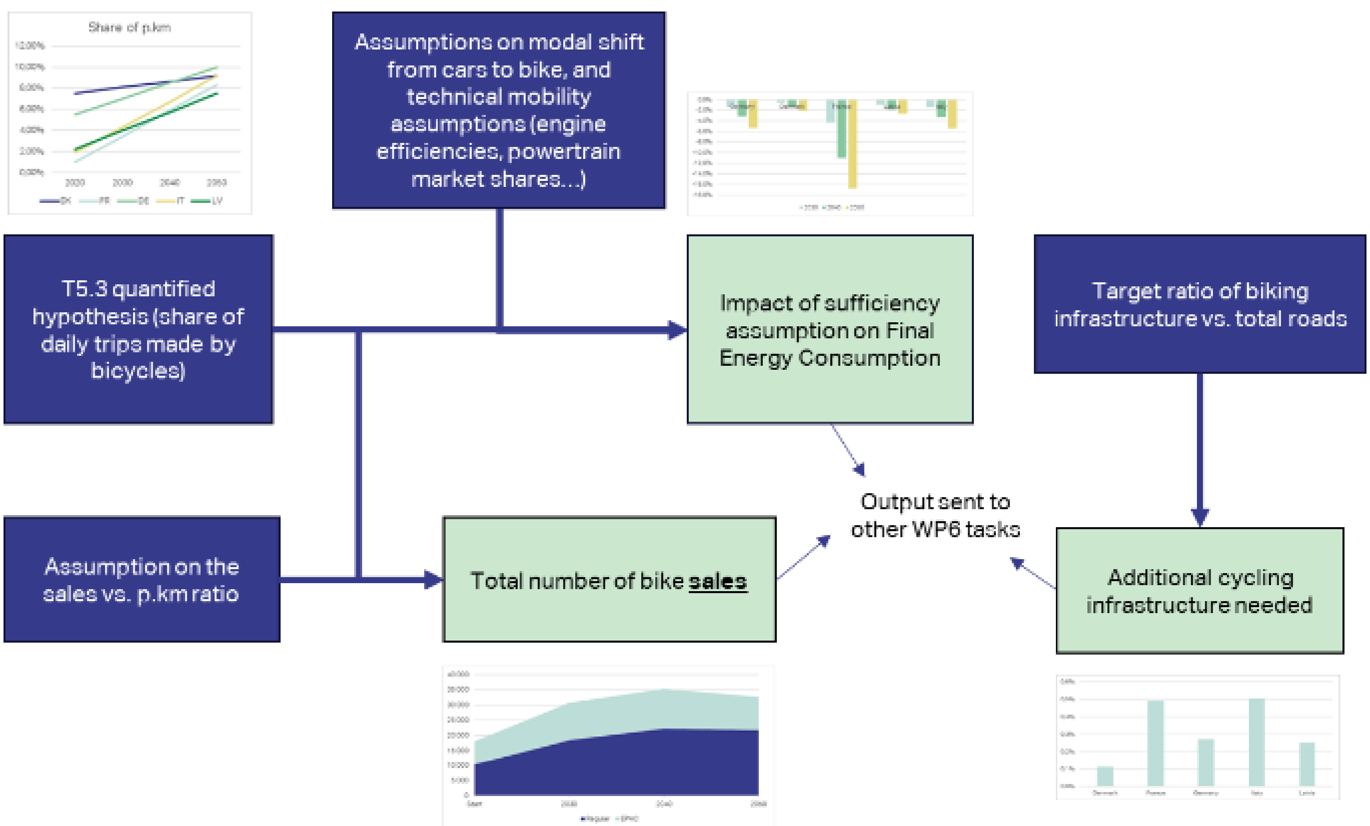


Figure 24 Overview of the modelling process for "biking"

The impact of increasing bicycle use in daily trips has been assessed on three aspects:

- Reduction of the use of cars (through modal shift from car use to bicycles)
- Need for new biking infrastructures
- Increase in bike sales

While the first item produces a direct impact on final energy consumption (from cars), analysed through a bottom-up approach (similar to the one used for the "moderate car sizing" scenario assumption, cf. 2.2), the other two will be further analysed in task 6.2 to translate them into energy consumption and emission reductions.

To assess the reduction of the use of cars, the following process was applied:

- It was assumed by default that overall daily mobility needs per capita would stay stable (although this is not necessarily consistent with the overall framework of sufficiency-oriented changes in lifestyles).

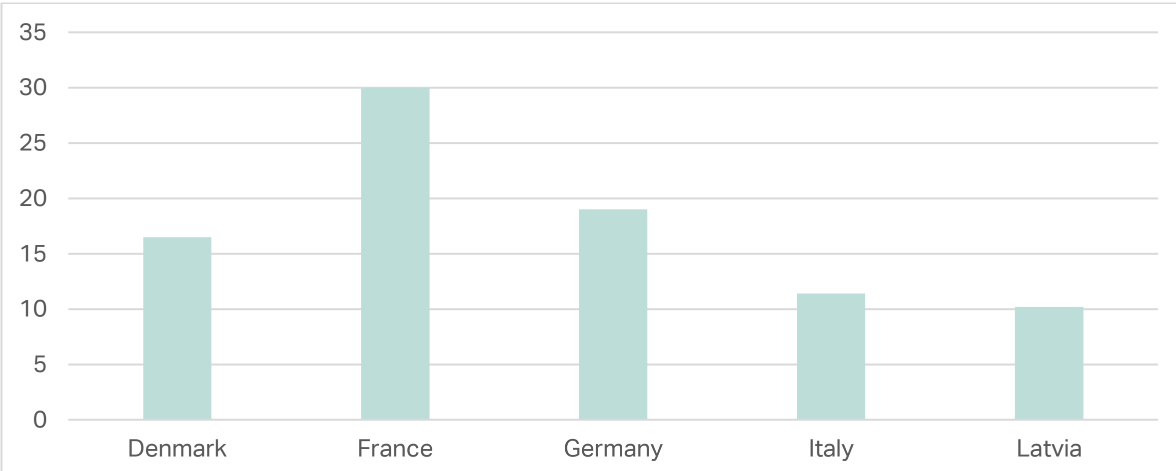


Figure 25 Average distance covered daily (km/cap), cf. annex 1 for details on sources

- This average distance covered daily through all modes has been multiplied by the modal share of bike in daily mobility (cf. results from task 5.3 shown above in Table 5) to get the average distance covered by bike per person.
- This value has then been multiplied by the number of days in a year, and the population.
- Then we made an assumption on the share of the increase in biking that directly corresponds to a decrease in car use, having in mind that it could also encompass shift e.g. from collective transports. As evidence is lacking to better inform the possible value of that ratio, which would depend on related policies (e.g. regarding collective transports) and its changes over time, we therefore estimate the potential to set it at a level of **80%** (meaning that 1 additional km by bike will result in 0.8 km less by car).
- The reduction of yearly distances covered by car thanks to shifting to bike is finally obtained by applying an average occupancy rate of car trips avoided to the overall p.km in car shifted to biking. The average occupancy rate of car trips avoided by shifting to bike has been assumed to be lower than the average occupancy rate of all car trips (as it derives from CLEVER scenario national trajectories, and ranging from 1.4 to 2.2), since it is likely that single occupant car trips are more shifted than multiple occupants' ones. The assumption used is that the average occupancy rate of car trips shifted is close to 1 in the beginning and increasing to 1.2 in 2050 as the overall rate increases.

Then distances covered by cars are converted into final energy consumption, using the same model (and trajectories) used in the "moderate car sizing" scenario assumption (cf. 2.2).

Regarding the need for new biking infrastructures, a target of "cycling infrastructure density" (ratio of segregated cycling infrastructures to main roads) has been defined for 2050, with a linear curve until then, as a key feature to reach the results in terms of shift. It takes into account a country density criterion, knowing that the Netherlands achieve 75% today, with a density of 522 person per km^2:

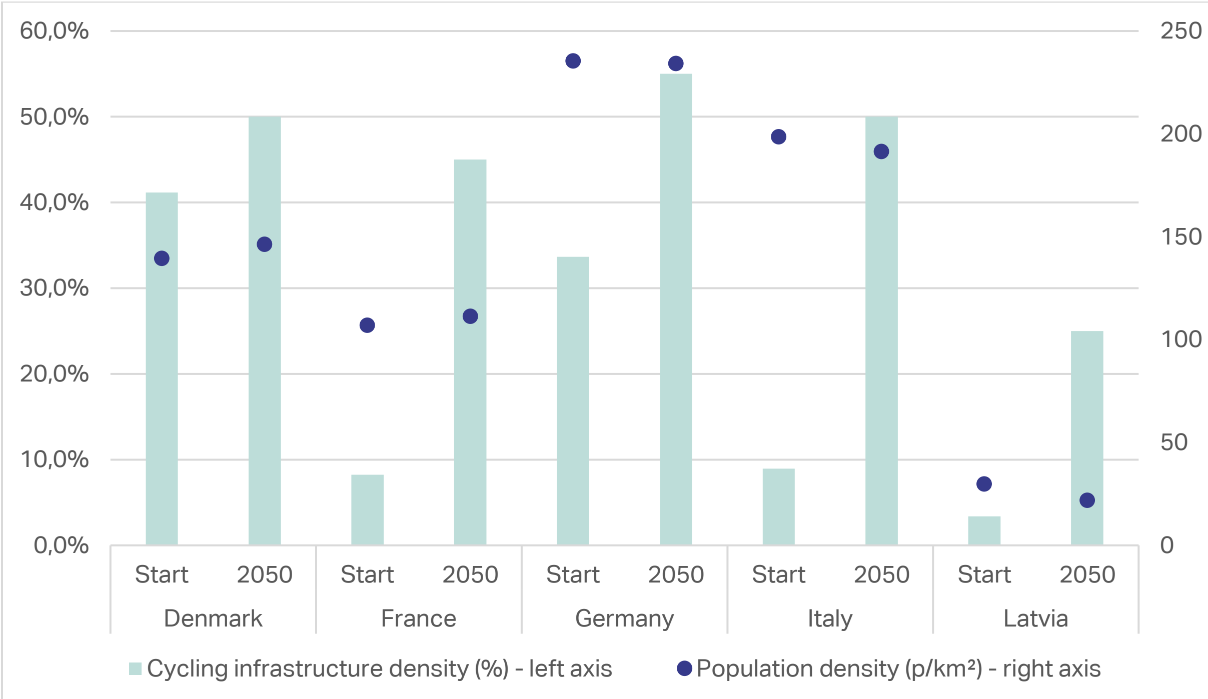


Figure 26 Cycling infrastructure density (ratio of segregated cycling infrastructures to main roads) vs. population density

To be translated into needs of new biking infrastructures, this of course needs to be combined with an assumption regarding the road system and its total length. Although this was not subject to a specific analysis, it was considered that in a global sufficiency-oriented pathway, where the modal share of car is decreasing, the default assumption that the road length is stable is conservative.

Finally, the impact on bike sales has been assessed with a simplified approach, as it has not been deemed necessary to implement a sophisticated stock model (contrary to what has been done for "moderate car sizing" and "sharing product" scenario assumptions). Bicycles have indeed slightly shorter lifespans than cars, and are less capital-intensive, therefore assuming sales are mostly proportional to mobility needs over the covered period appears a sensible assumption. Moreover, as this ratio is depending on the average level of use of bikes, it has been assumed that the number of sales per 10,000 p.km would converge for all countries towards a value of 1.5 in 2050, close to the one observed today in countries where the modal share of bikes in daily mobility is already important. Besides, we distinguished electric pedal-assisted cycles (EPAC) from regular bikes. The share of EPAC in global sales of bicycles is supposed to increase and reach an homogenous 50% by 2050 in all countries.

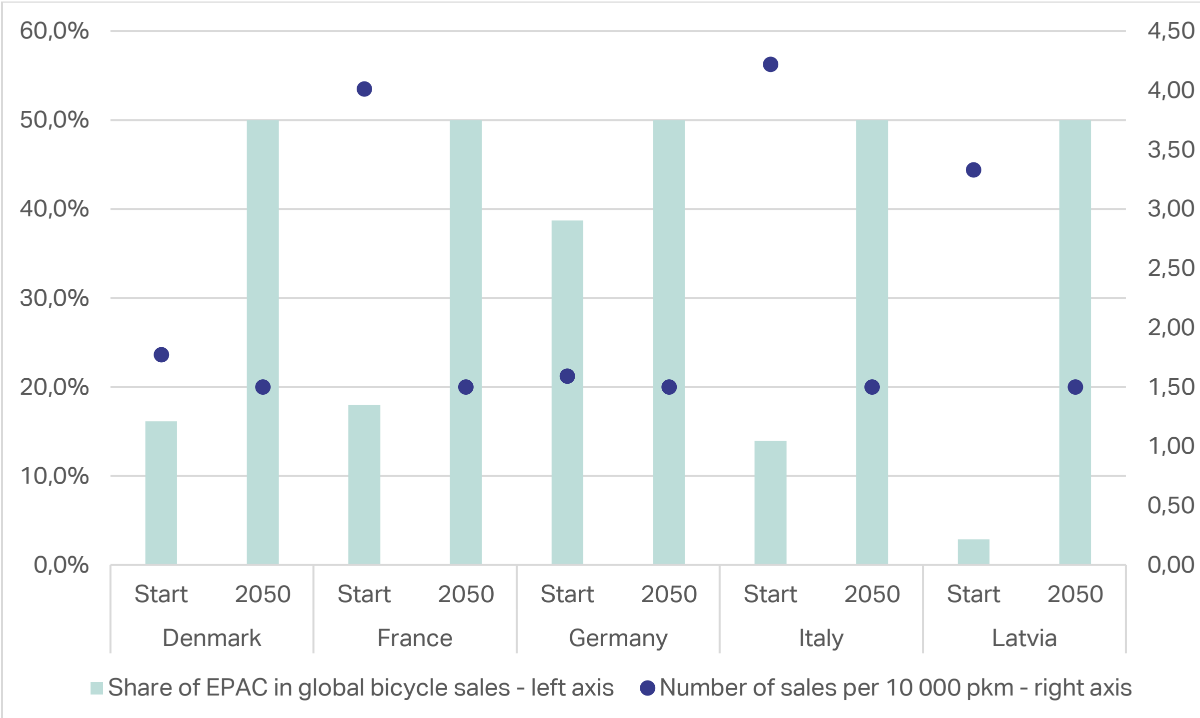


Figure 27 Evolution of share of EPAC in global bicycle sales, and ratio of number of sales per 10,000 p.km

Table 6 Main characteristics of sufficiency (SUF) and reference (REF) scenarios for "biking"

Sufficiency scenario (SUF)	Reference scenario (REF)
Increased bicycle use in daily trips	Status quo
Partial modal shift from cars to bicycles for daily trips (80% of additional distances made with bicycles used to be travelled by car)	Status quo
Increased efficiency of cars (partly through moderation in sizing, switch to electricity, lower speed limits etc.) and progressive switch to electric powertrains	Same as SUF

Results

The overall impact on final energy consumption associated with car use is rather different from one country to another, depending on its current level of bicycle use, and its room for improvement. For Denmark, only 2% of energy may be saved on car use in 2050, while in France it goes up to almost 17%. In some countries like France, this lever may be seen as a crucial one, in order to reach ambitious reduction targets for car use (and its negative externalities).

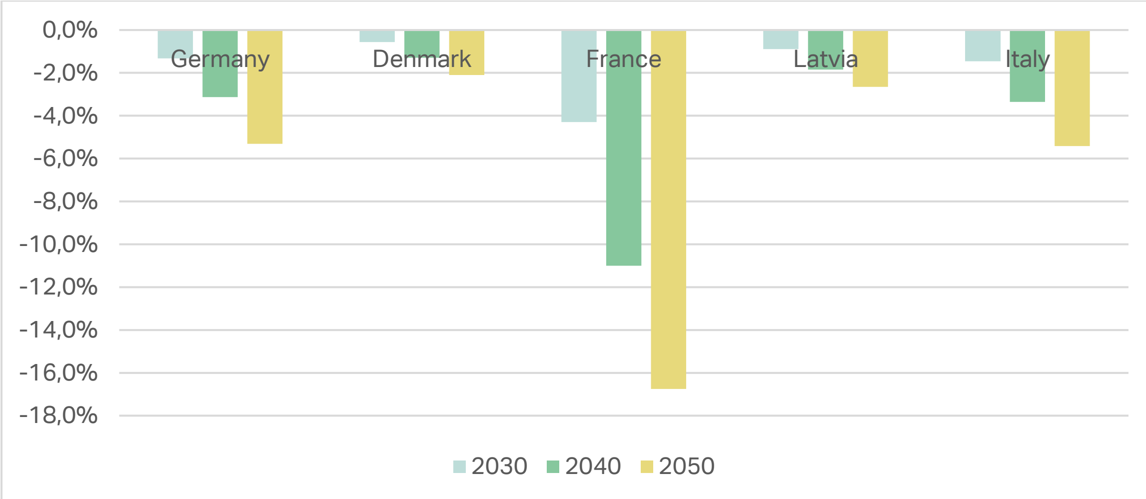


Figure 28 Relative FEC reduction for car use[13] for each country, for the SUF scenario (vs. REF scenario)

However, these are relative reductions in percentage. Since car use undergoes an overall decrease in our CLEVER project inspired trajectories, the absolute reduction in TWh actually remains rather stable from 2030 onwards, with a progressive shift to electricity in the energy mix:

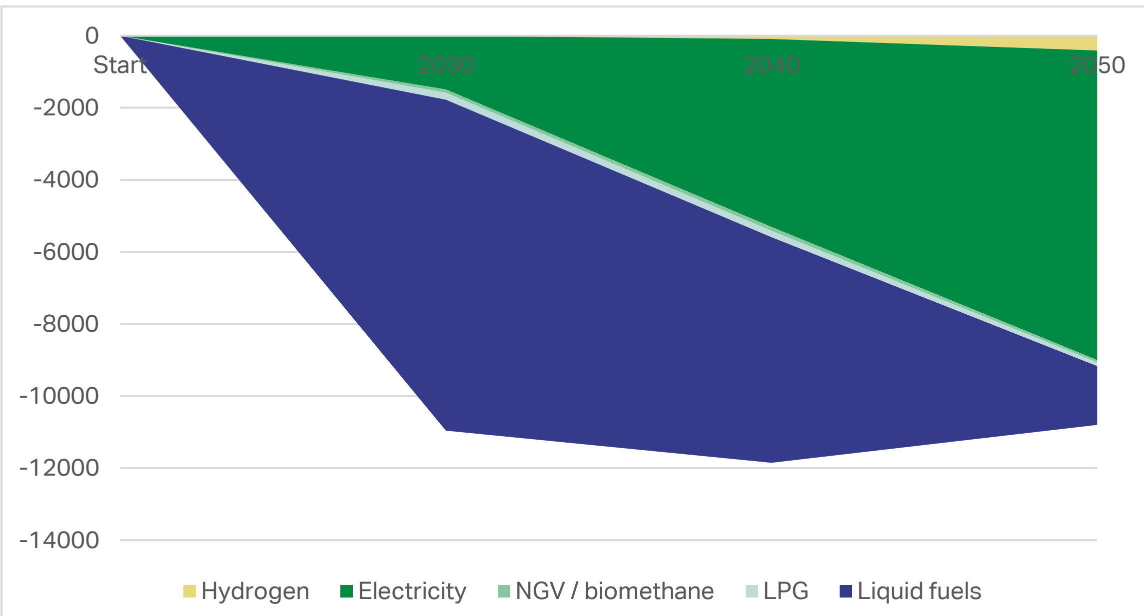


Figure 29 Absolute FEC reduction per energy carrier, for the 5 countries, for "biking" (GWh)

Unsurprisingly, the effort on dedicated bicycle infrastructure is also very different across countries:

[13] The perimeter includes here non-daily trips.

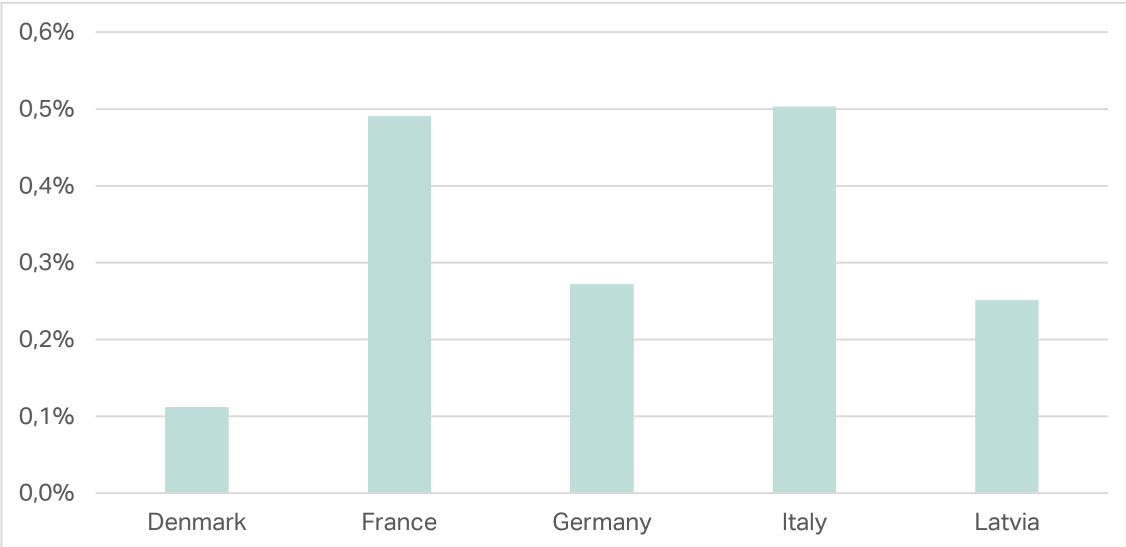


Figure 30 Yearly added length of segregated cycling infra (in % of the length of public roads in 2024)

Likewise, the bike industry would undergo a significant increase (more than twice) of its sales, and a progressive shift towards electric-powered bikes:

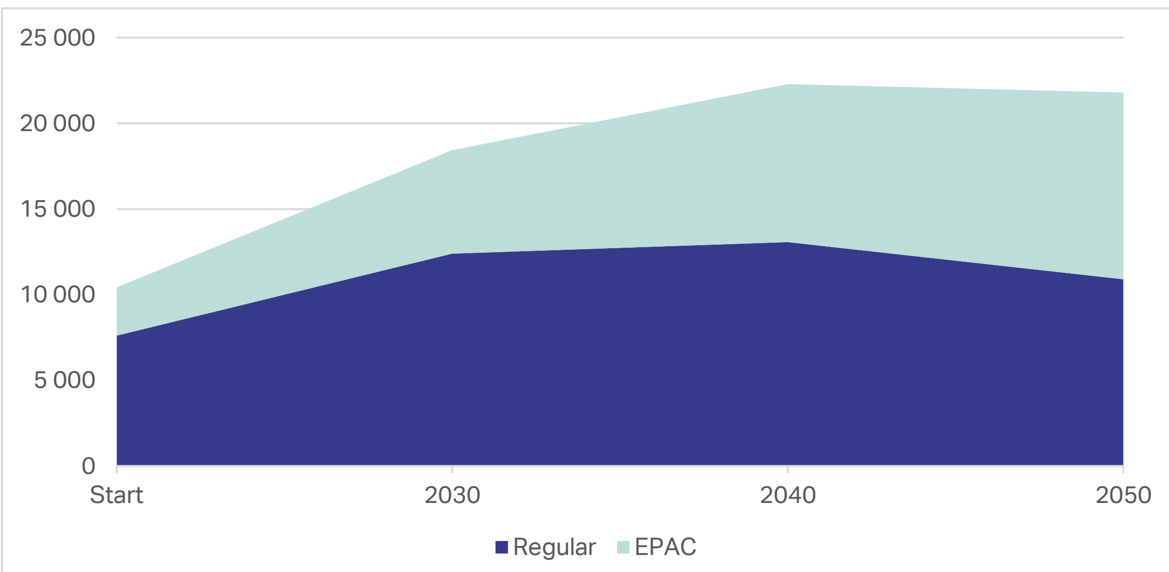


Figure 31 Total yearly sales of bikes over the 5 countries (thousands)

Discussion

Regarding the assumption of stable daily mobility needs, this is obviously a simplified approach, in the absence of more in-depth work on daily mobility needs, which would be well beyond the scope of works carried out in this task.

Likewise, a ratio of 80% of modal shift from cars to bikes was adopted (1 additional km by bike results in 0.8 km less by car). To get a more precise and sourced estimate, one would again need a very comprehensive scenario on mobility needs and its changes over time, including public transports etc. We may however say that this ratio has a direct proportional impact on the results in terms of FEC reduction (a ratio of 40% would thus divide impact by 2).

In the impact assessment of the sufficiency assumption on bike sales, it was considered that the majority of bike sales is linked to daily mobility needs. This is not necessarily the case in countries where this use is less developed, as there are a certain number of bikes sold for other (leisure) uses. One may thus think of a correction factor to take this into account. However, it is expected that, with the development of biking for mobility needs, this share of leisure bikes would decrease significantly. Another modelling approach was to consider mobility needs are directly proportional to sales, again this may not be the case in countries where the existing stock is not fully constituted. More research would be needed to assess the relevance of implementing a stock model for this kind of scenario assumption, with the challenge of data access and quality, usually lower than for other means of transport.

The assumption of stable length of the road network may seem conservative, but the impact of such assumption is nevertheless limited on results as it is again directly proportional (e.g. a 10% increase in total road would translate into a 10% in dedicated biking roads). This needs to be compared to the large uncertainty on the target ratio of biking roads vs. total roads.

Finally, the assumption on the development of EPAC bikes would need to be further discussed. The challenge with such emerging technology, in the absence of dedicated regulation[14], is that we lack past or existing examples to have accurate projections. One may even argue that some new light means of transport would be developed alongside biking.

2.5. Flying less

Results from task 5.3 (integration of SSH findings in quantified sufficiency assumptions)

For this scenario assumption, most of the quantification work has been carried out in task 5.3. The main outputs are reduced mobility needs (p.km) for planes (both domestic and international), and a partial shift towards train. Contrary to other scenario assumptions, the quantification has been carried out for all European countries, as data was mostly coming from Eurostat, and calculations could therefore be easily applied to all countries (not only the 5 countries covered in FULFILL).

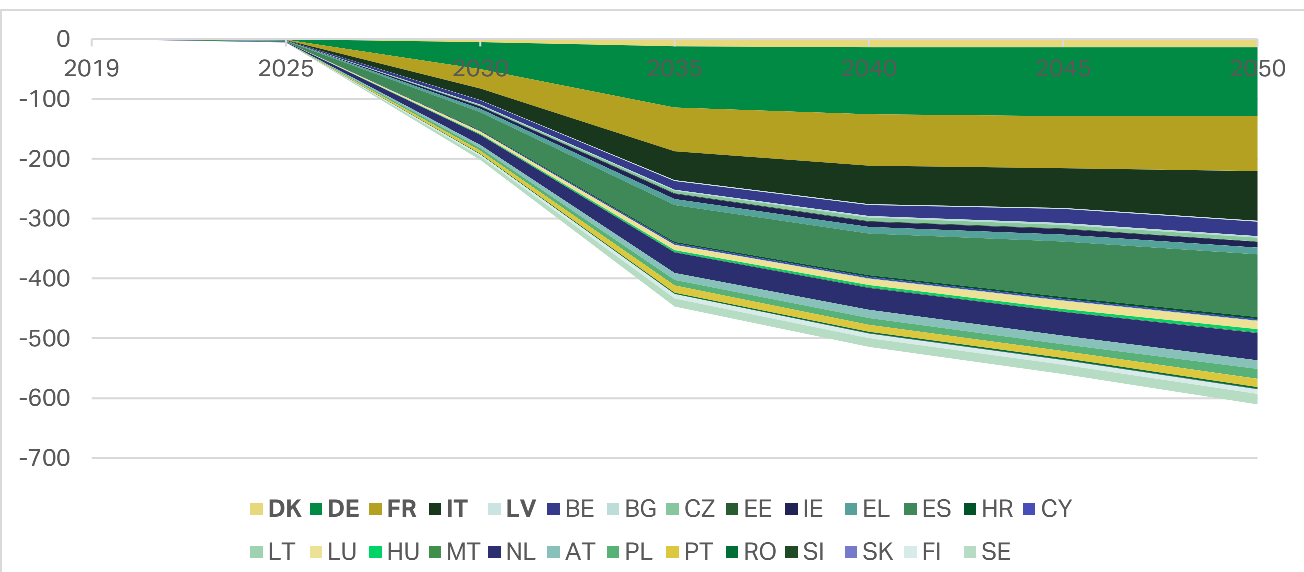


Figure 32 Trajectories for plane mobility needs (billion p.km) taken from task 5.3 for the "flying less" scenario assumption (FULFILL, 2024)

[14] E.g. cars do have a European regulatory target of phasing out ICE by 2035.

Modelling approach

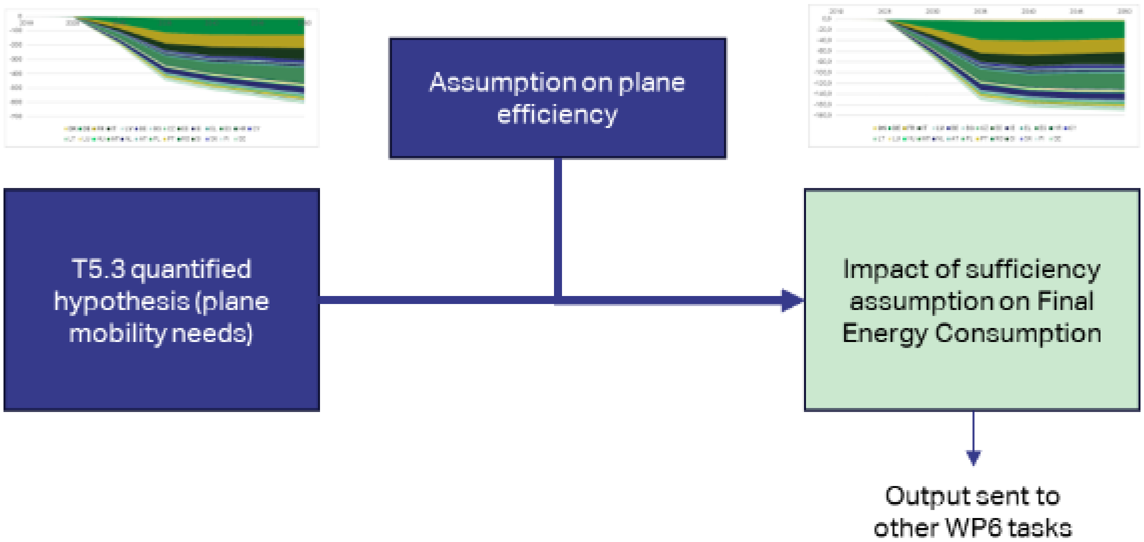


Figure 33 Overview of the modelling process for "flying less"

The main activity of task 6.1 on this scenario assumption consists in translating this mobility need reduction into jet fuel consumption reduction. Therefore, a trajectory for the specific energy consumption (kWh/p.km) of planes had to be determined.

The CLEVER project had defined a trajectory for this indicator, with an overall reduction of 30% in 2050 compared to 2015. This scenario assumption combines technical plane efficiency improvements, and increased occupancy rates.

However, the starting points (historical data) have been readjusted to better match Eurostat's figures. In 2019, the specific consumption has been set at 0.40 kWh/p.km, as calculated by dividing the total final consumption from planes, by the total mobility needs, on the EU27 perimeter, according to Eurostat. Then the relative reduction assumed in CLEVER has been applied, resulting in the following trajectory:

Table 7 Specific energy consumption of planes (kWh/p.km)

2019	2025	2030	2035	2040	2045	2050
0.401	0.378	0.358	0.339	0.320	0.300	0.281

In this scenario assumption, the historical trends for mobility needs have not been projected, except for the increase in population (i.e. we assumed fixed plane mobility needs per capita). This assumption does not seem out of place, considering the dynamics of the last decade:

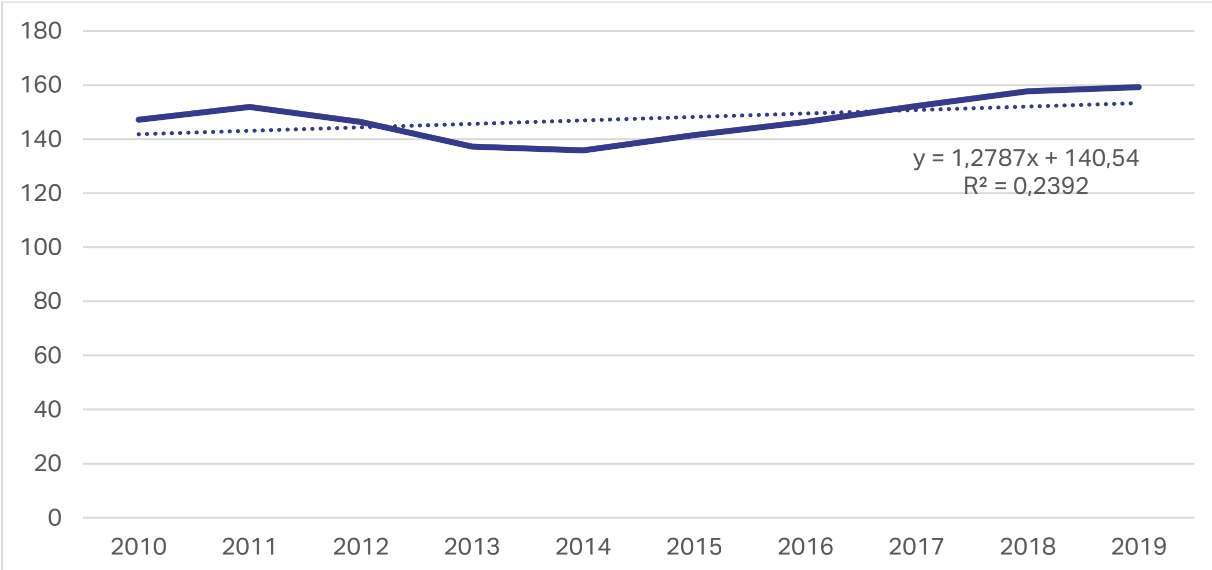


Figure 34 Evolution of per capita plane mobility on the EU27 perimeter (p.km/cap) for the 2010-2019 period, according to Eurostat

Table 8 Main characteristics of sufficiency (SUF) and reference (REF) scenarios for "flying less"

Sufficiency scenario (SUF)	Reference scenario (REF)
Decreased plane mobility needs - in line with the assumptions made in task 5.3,	Same per capita plane mobility needs (p.km/cap) as in 2019
Increased plane efficiency and occupancy rates as described in Table 2	Same as in SUF

Results

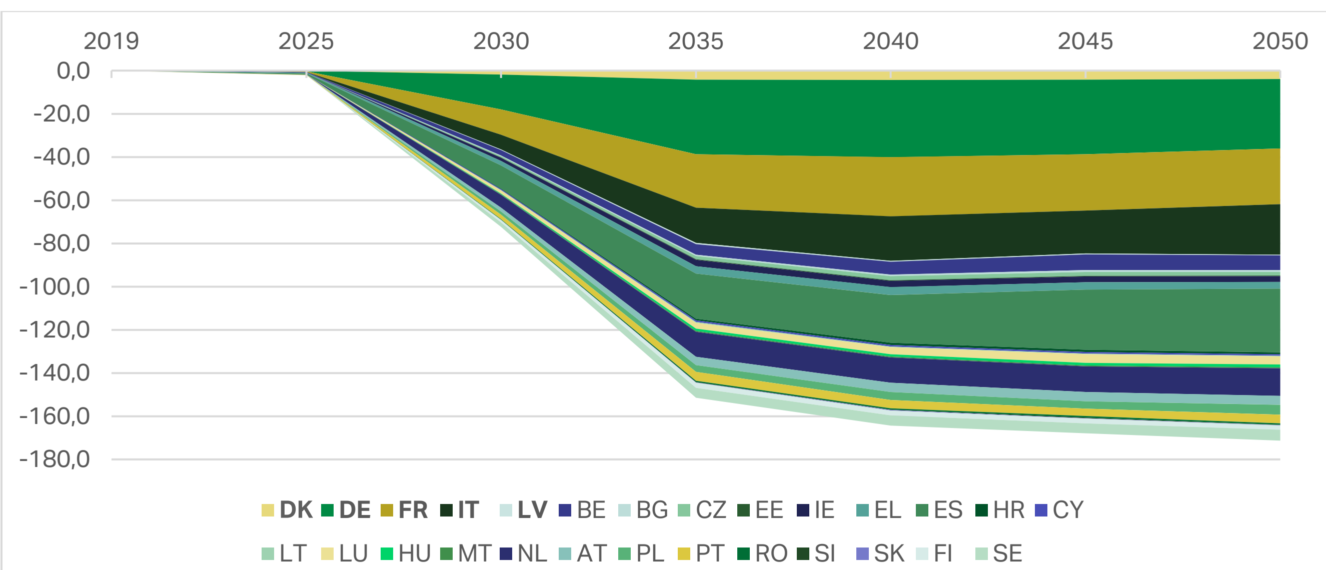


Figure 35 Absolute FEC reduction for all EU countries, for "flying less" (TWh)

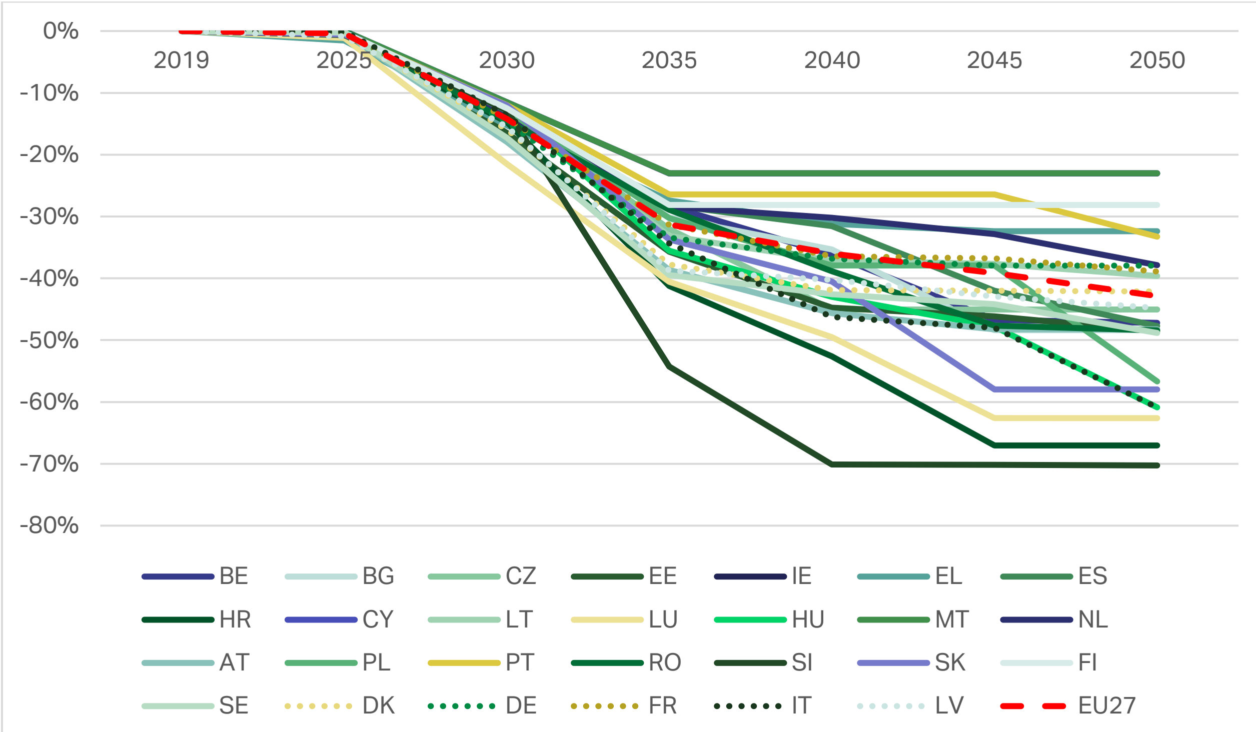


Figure 36 Relative FEC reduction for planes for each country, for the "flying less" SUF scenario (vs. REF scenario)

Energy savings on the consumption of planes are rather high in most countries, 43% on average, and up to 70% in 2050 for some countries (compared to REF scenario).

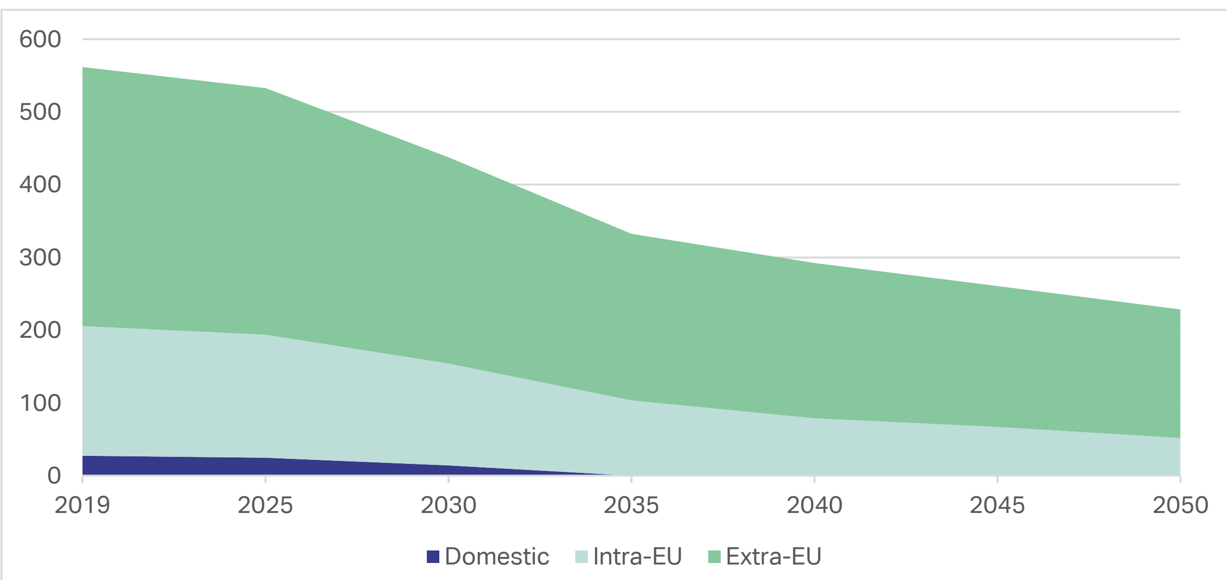


Figure 37 Evolution of the total FEC of planes on the EU27 perimeter, broken down by distance (domestic, intra-EU, extra-EU) in the SUF scenario (TWh)

As shown on the above graph, the main contributor to energy consumption (and emissions) are international flights, especially those outside the EU. In the SUF scenario, consumption of extra-EU flights is reduced by 50%[15], intra-EU by 71%, and domestic flights are phased out totally by 2035. Details on these assumptions are available in deliverable 5.3 (FULFILL, 2024).

[15] NB: international aviation bunkers are not accounted for in the European EED directive, in spite of its significant contribution to overall (fossil) energy demand.

Discussion

We did not assess the increased consumption caused by a modal shift to train (or other means of transport). To quantify it, we would need to know the market share of the different energy carriers used by trains, for which accurate data seems difficult to get, and their evolution in line with the geographical development of new train lines. While not negligible, this added energy consumption would not compensate reductions from jet fuel consumption, as trains are more efficient[16]. Besides, not all avoided plane flights would be replaced by trains or other transportation means. Moreover trains are mostly powered by electricity, which is easier to decarbonize than jet fuel. Still, it would be interesting to be more accurate on this aspect.

Another assumption made was that planes would not switch to hydrogen of electricity energy carriers., and would stick to liquid fuels[17]. This is to remain consistent with the approach followed in other scenario assumptions, we did not bet on low maturity alternative fuel technologies. In terms of modelling, this would have changed the final energy consumption mix, and possibly the average specific consumption as well.

Finally, taking into account the slight historical trend towards increased plane use would further increase the evaluated impact of the measure.

[16] Estimates from the CLEVER project give a ratio of ¼ to ⅓ for train consumption (in kWh/p.km) vs. plane consumption.

[17] These liquid fuels could possibly be progressively replaced by e-fuels and/or biofuels as described in the CLEVER project, but the upstream energy transformations (until the final liquid fuel) were beyond the scope of this task.

3. Discussion

In this section, we highlight some of the questions and challenges faced in task 6.1, as a supplement to more specific comments already provided on each scenario assumption (cf. previous chapter). Some comments are also linked to items mentioned in the “Research contributions and limits” chapter of deliverable 5.3 (FULFILL, 2024).

3.1. From *ad hoc* models to an integrated sufficiency scenario tool?

Bottom-up quantification approaches have the advantage of being very flexible and were thus a good tool to work with the heterogeneous nature of quantified results provided by task 5.3. However, the downside of this flexibility, is that each scenario assumption required creating *ad hoc* models and tools, which would not be easily transposed to other kinds of scenario assumptions.

In some cases (e.g. the “flying less” assumption), it was relatively straightforward to translate task 5.3 data into inputs for our “in-store” bottom-up models[18]. But in most cases, indicators produced in task 5.3 were either focusing on a too narrow perimeter (cf. the target population category for “sharing space”, or the washing machines for “sharing products”), or had an “unusual” disaggregation level (e.g. breakdown of cars by segment, on top of the usual breakdown by powertrain, for “moderate car sizing”), to be processed without substantial additional modelling and data.

This model design and development is time consuming - it involves defining calculation models articulating proper indicators, with the best compromise in terms of data availability, accurate representation of the sufficiency assumption and model complexity.

Therefore, it appears rather likely that extending the same kind of detailed modelling approach to all (or the most significant) sufficiency scenario assumptions, to produce a full-fledged sufficiency scenario, would require very significant human resources. A trade-off would need to be found between accuracy and feasibility, as already explained in (FULFILL, 2024).

Beyond this resource constraint, one may also find limitations in terms of model complexity, as combining too many indicators and scenario assumptions in a single integrated tool can make the whole calculation method and tool hard to develop and maintain. Trying to overcome this limitation by separating the model into smaller independent blocks could be a partial solution, with obvious drawbacks related to iterative readjustments (cf. chapter below on “target-based” approach – what happens if we need to strengthen the overall emission reductions?) and the interconnectedness of some assumptions.

Finally, data was one of the big challenges of task 5.3, but it has also been one for task 6.1 as well, although to a lesser extent. Indeed, as explained above, additional data had to be mobilised to bridge the gap between the data provided by task 5.3, and what our bottom-up models could handle. Thankfully, this kind of data is relatively aggregated compared to the needs of task 5.3 and is now made more and more available through open data from either public (e.g. Eurostat) or private (professional bodies, consultancies, NGOs, think tanks…) sources. The paradox, however, is that more data also means more discrepancies between the different sources, and this implies additional time for data compilation and reconciliation. Besides, the data quality is rather heterogenous from one country to another, and in some cases “secreted” by statistical bodies. This underlines again the challenge of extending this approach from a few sufficiency assumptions to a whole sufficiency scenario.

Therefore, one could rather think of such an SSH-inspired and very detailed approach as a way to strengthen/validate some key sufficiency assumptions and messages of a given energy transition scenario, instead of a way to build a totally SSH-based quantified trajectory.

[18] As explained in the methodology, some elements of calculation models and tools, developed by négaWatt as part of other projects (négaWatt and CLEVER scenarios) have been reused and adapted to the needs of this task.

3.2. Sufficiency impact in a changing world

An interesting methodological challenge experienced in task 5.3 also has some relevance for task 6.1: “how much should we factor in historical trends in our REF scenario (and the parts of the SUF scenario not concerned by the sufficiency assumption)” (FULFILL, 2024)?

As in task 5.3, a kind of balance has been sought between (linear) projections from the past and a simple *status quo*, depending on the type of indicator and historical trend observed. An ideal solution would have been to run several sensitivity analyses on relevant variables, to assess the role of such choices in the impact assessment. This however would have required more time than we had and could not be properly implemented in this research work.

Besides this issue of historical trends, there is most importantly the fact that single-lever effects cannot be simply added up, as we also need to consider cross-lever effects such as:

- Sufficiency combined with other sufficiency scenario assumptions (e.g. “shared space” and temperature setpoint reduction)
- Sufficiency combined with energy efficiency (e.g. “shared space” and building insulation)
- Sufficiency combined with energy mix changes (e.g. “shared space” and shift to wood stoves, heat pumps and biogas boilers)

As explained in chapter 1, we chose a simple and conservative approach in our impact assessment: our sufficiency assumptions are evaluated **once** all other levers are applied. But the literature offers a few alternative methods (Shapley, Logarithmic Mean Divisia Index…), which would certainly produce higher estimates for the impact of a given sufficiency assumption.

3.3. Compatibility with top-down models

One of the methodological challenges experienced in task 6.1 has been to ensure the consistency and compatibility of its results, with the way they are meant to be processed in further FULFILL activities (i.e. tasks 6.2 and 6.3, cf. chapter 1.5). This work was interesting in itself, as input-output and more generally “top-down” models are widespread and the question of their compatibility and consistence with bottom-up models is often raised.

Through technical exchanges within the project team, we did find a proper *modus operandi*, to connect these models of very different nature. However, some specific challenges need to be highlighted in view of generalising such kind of work:

Input-output models rely heavily on statistical databases following a certain nomenclature / breakdown of economic activities. The choice of categories for this nomenclature is usually made from an economic activity perspective and is not necessarily consistent with the main areas of concern for energy transition scenarios and their externalities (also see the key areas for sufficiency lifestyles identified in (FULFILL, 2022). To be more specific, some categories may not be disaggregated enough[19], requiring some custom adaptations. Experience from task 6.2 will tell if this work has been easy or cumbersome, and thus to what extent such work could be extended to a wide range of sufficiency scenario assumptions and/or replicated on other input-output models and databases.

- These databases, which are primarily built out of economic statistical accounts, may not be accurate when it comes to evaluating externalities such as energy consumption or GHG emissions, especially for the long-term perspective. In the case of task 6.2, the chosen input-output database was a hybrid monetary-physical unit one, which partially addresses this issue.

[19] E.g. there is a single category for “motor vehicles, trailers and semi-trailers”, as well as for “electrical machinery and apparatus”.

3.4. Feeding an iterative target-based approach

As suggested in deliverable 5.3 (FULFILL, 2024), it would have been interesting to use some feedback from the impact assessment carried out in task 6.1 and more generally work package 6, to possibly adjust assumptions made in upstream (work package 5) activities. Unfortunately, time was lacking to implement such an iterative process between activities from different work packages.

Two aspects in particular may need ex-post corrections:

- Are our sufficiency scenario assumptions compliant with a 1.5°-compatible ambition? This criterion is actually rather difficult to enforce, as there are many different ways to allocate remaining global carbon budgets to a given territory (e.g. the EU), and most importantly our sufficiency assumptions are only a fraction of the many levers to activate in order to reach this target. Nevertheless, one may try to compare reduction levels from a given sufficiency assumption, with what is suggested in comprehensive 1.5°-compatible energy transition scenarios. The challenge is to find the relevant perimeter, and sufficiently disaggregated data from such scenarios, allowing a proper comparison. Besides, this usually requires access to data beyond what is officially published by such scenarios.
- Another consistency check, which does not require having the full picture, is to look at the effort sharing across countries in terms of per capita consumption levels. As shown in chapter 2.1 on the "sharing spaces in housing" scenario assumption, following a corridor approach such as the one from the CLEVER project (targeting a convergence on several indicators, such as m²/cap) may produce very different results in some countries, which may call for some readjustments of initial sufficiency scenario assumptions. This is necessarily an iterative endeavour, as the comparison with the CLEVER project could not be done in task 5.3: some additional calculations had indeed to be performed in task 6.1 to end up with a comparable perimeter between both trajectories (average m²/cap for the whole population).

4. Overall impact of sufficiency

To go beyond the detailed assessment on 5 scenario assumptions presented above, we carried out a meta-analysis of several scenarios, to have a broader perspective on the impact of sufficiency. This is meant as a supplement, to feed recommendations on NDCs and NECPs further developed in task 6.5.

It would have been interesting to compare results from the quantification work on the 5 scenario assumptions, with what these different scenarios suggest. But as explained in chapter 3.4, we lack sufficiently disaggregated data from these scenarios.

4.1. Halving FEC while allowing decent living for all is possible

When possible, the perimeter of the FEC figures provided was corrected to fit the European Energy Efficiency Directive. This means it includes the following sectors: buildings, agriculture, industry, domestic transport and international aviation. It excludes ambient heat (heat extracted from the environment by heat pumps) and non-energy consumption (e.g. feedstocks).

Scenarios halving FEC: from a global to a national perspective

World scenarios: possible reduction of FEC by 45-55% in Global North

We analysed scenarios from the "AR6 Scenario Explorer and Database hosted by IIASA"[20], and in particular the C1 scenarios, which are the most ambitious scenarios of the AR6 and which have a 50% chance of limiting global warming to 1.5°C with no or limited overshoot.

Among global scenarios, we focused on two illustrative mitigation pathways from IPCC[21] from the C1 category:

- Low demand (IMP-LD): "efficient resource use and shifts in consumption patterns, leading to low demand for resources, while ensuring a high level of services", which seems close to the LED scenario from Grubler et al (2018)
- Shifting pathways (IMP-SP): "how shifting global pathways towards sustainable development, including by reducing inequality, can lead to mitigation"

IMP-LD and IMP-SP[22] estimate a FEC reduction higher than 45% (53% and 48% respectively) for Global North[23] countries between 2015 and 2050.

What are the results on the FEC reduction for Europe in such scenarios and more broadly in global 1.5 compatible scenarios?

The EU perspective in 1.5 compatible World scenarios

Among the IPCC scenarios from the C1 category (50% chance of limiting climate change to 1.5° with no or limited overshoot), 71 (over 96) are detailed at the EU28 level and **7 of them reach a FEC reduction of 45% to 55% of FEC/cap between 2015 and 2050 for the EU28[24].**

[20] "This scenario explorer presents an ensemble of quantitative climate change mitigation pathways underpinning the Sixth Assessment Report (AR6) of Working Group III, *Climate Change 2022: Mitigation of Climate Change*, published by the Intergovernmental Panel on Climate Change (IPCC) in 2022."
[21] IPCC (2022), p. 309
[22] To determine these figures it was assumed that IMP-LD and IMP-SP were named respectively "LowEnergyDemand_1.3_IPCC (version 1)" and "SusDev_SDP-PkBudg1000" in the workspace https://data.ece.iiasa.ac.at/ar6/#/workspaces/23
[23] Ibid, Global North is "OECD90 and EU" from the R5 classification of regions.
[24] négaWatt analysis based on the AR6 Scenario Explorer available under: https://data.ece.iiasa.ac.at/ar6/#/workspaces/1461.

Besides, in order to inform the process of defining climate targets for 2040 in the European Union (EU27), ESABCC (2023) defined illustrative pathways for the EU based on pathways limiting global warming to the 1.5°C objective which comply with feasibility criteria (environmental risks, technological and socio-cultural challenges). Among them, the ESABCC selected 3 illustrative pathways and **two of them reach about 52% and 46% reduction of FEC over 2019-2050** (respectively "Demand side focus" and "High renewable energy")[25].

We have seen that a top-down approach from global scenarios demonstrates the possibility to reduce FEC by at least 45% over 2019-2050 in EU27 and EU28. We will see that more bottom-up approaches focusing on the EU or national scale reach even higher reductions.

European scenarios halving FEC

At the European level, **several scenarios converge on the possibility of reducing by at least 45%** the FEC over 2019-2050 in the EU, for example:

- **-55%** in the CLEVER scenario[26], a collaborative scenario coordinated by négaWatt
- **-60%** in the scenario PAC2.0 from CAN Europe[27]
- **-47%** for the variant "-90%" of Strategic Perspectives (2023)[28]
- **-57% and -60%** in the variants "Shared effort" and "demand focus" of ECF scenarios "Net Zero by 2050: From whether to how" (2018)[29]

In addition, a closer look at the reductions per sector over a panel of 12 scenarios[30] (see Figure 38 below) suggests even higher possible reductions than looking only at total FEC reduction. Indeed, ambitious sectoral reductions of FEC are confirmed by more scenarios than total FEC reduction.

4 scenarios reach a FEC reduction of 50% to 61%, and 6 a reduction higher than 45%.

A 50% total reduction could also be reached assuming a combination of possible sectoral reduction confirmed by at least 6 scenarios: 63% in transports (8 scenarios), 45% in buildings (6 scenarios) and 41% in industry (6 scenarios).

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[25] ESABCC (2023), p.58
[26] négaWatt association (2023)
[27] Interactive platform, consulted on March 2024 (a technical summary is due to be published soon)
[28] Data extracted from the Pathways explorer on September 2023
[29] Figures extracted from (JRC, 2020)
[30] The scenarios included are the ones presented right before, plus a selection of scenarios from "Towards net-zero emissions in the EU energy system by 2050" (JRC, 2020) and the TYNDP2022 scenario (distributed energy variant).

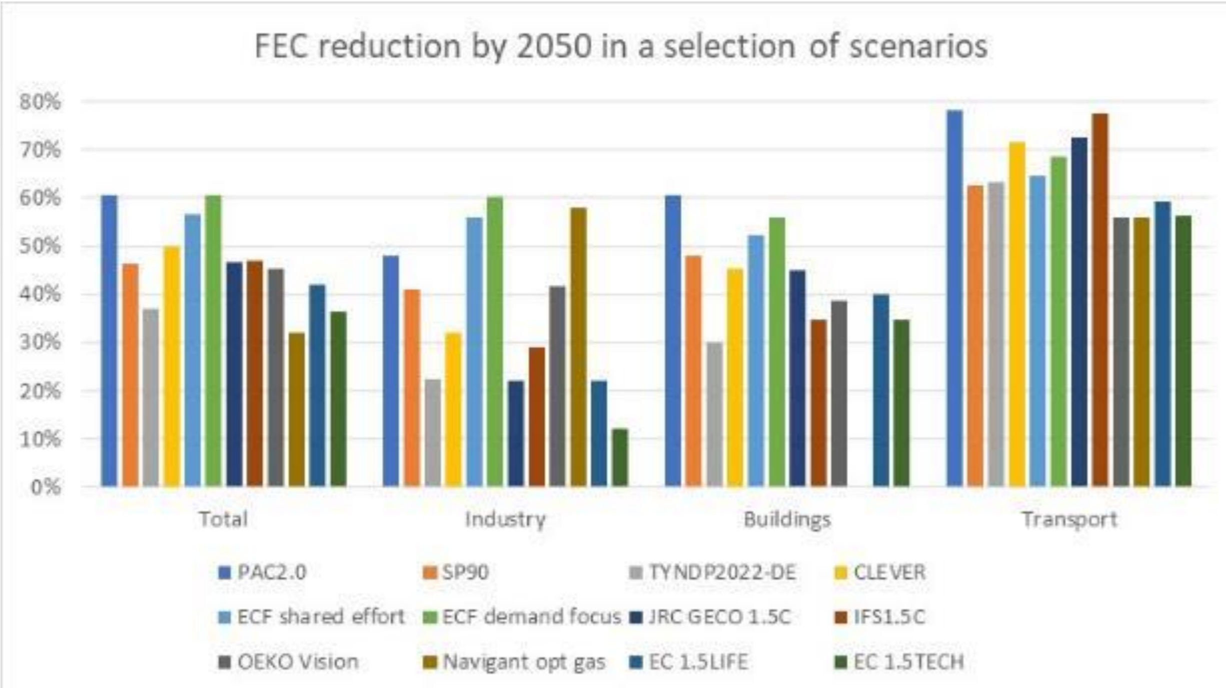

Figure 38 FEC reduction over 2019-2050 in a selection of scenarios.

This analysis of EU scenarios confirms the possibility of reducing the FEC in the EU by at least 50%. Such an ambition is also confirmed by analysis at a national scale, as detailed in the next section.

National scenarios in Europe halving FEC

In several countries, scenarios were developed that confirmed the possibility of reaching 50% (and up to 60%) of FEC reduction by 2050:

- United Kingdom:
    - -60% reduction in "Zero Carbon Britain, Centre for Alternative Technology (CAT), 2019
    - -52% in the "Transform" variant of "The role of energy demand reduction in achieving net-zero in the UK", CREDS, 2021
- France:
    - -55% in the scenario from négaWatt (2021)
    - -50% and -55% in the variants S1 and S2 of "Transitions 2050", ADEME, 2021, p.649
- Germany:
    - -50% in the GreenSupreme variant of "Resource-Efficient Pathways towards Greenhouse-Gas-Neutrality – RESCUE", Umwelt Bundesamt, 2019

We could also mention the national scenarios elaborated by the CLEVER network's partners and integrated in the CLEVER scenario. Most of these scenarios (BE, FR, DE, ES, IT) reach a FEC reduction of at least -50%, while DK reaches -45% and SE only -39%.

Compatibility with a decent living for all

We will see in the following sections that sufficiency levers are essential to reach such an ambition in terms of FEC reduction. However, it is important to note that sufficiency aims to minimise energy demand while providing decent living for all. Therefore, we can consider that scenarios integrate sufficiency only if they also achieve an energy demand compatible with minimum energy requirements for decent living.

Minimum energy requirements for decent living

For the evaluation of minimum final energy requirements to provide decent living, we analysed two publications:

- "Providing decent living with minimum energy: A global scenario", Millward-Hopkins et al. (2020)
- "A Societal Transformation Scenario for Staying Below 1.5°C", Kai Kuhnhenn et al (2020)

Millward-Hopkins et al (2020) estimate a "*minimal threshold for the final energy consumption required to provide decent material livings to the entire global population*". This threshold is called Decent living energy (DLE). 3 variants are also developed from the DLE by assuming higher "activity" levels (i.e. higher demand for energy services) and/or higher energy intensity: Higher demand (HD), less advanced technology (LAT) and Higher demand and less advanced technology (HD-LAT). **The FEC varies from 4.2 to 7.2MWh/cap. in 2050 in DLE, HD and LAT and reaches 11.1MWh/cap. for HD-LAT[31].**

Kuhnhenn et al (2020) focus on the potential energy reduction through more sufficient lifestyles. The scenario differentiates between results for "Annex 1 countries" and "Non-Annex 1 countries", referred to as North and South in the following pages. **The scenario results in 2050 in a FEC of 5.8, 7.4 and 6.1MWh/cap. respectively for South, North and the World.[32]** Most of the differences between the 3 regions seem related to FEC in industry and buildings.

We then consider that 7MWh/cap. could be a minimum that allows a decent living for all. This minimum assesses that decent living can be provided to anyone from the energy perspective with a certain margin from minimum evaluations[33]. But measures tackling inequalities remain essential to ensure a decent living for all with this amount of energy.

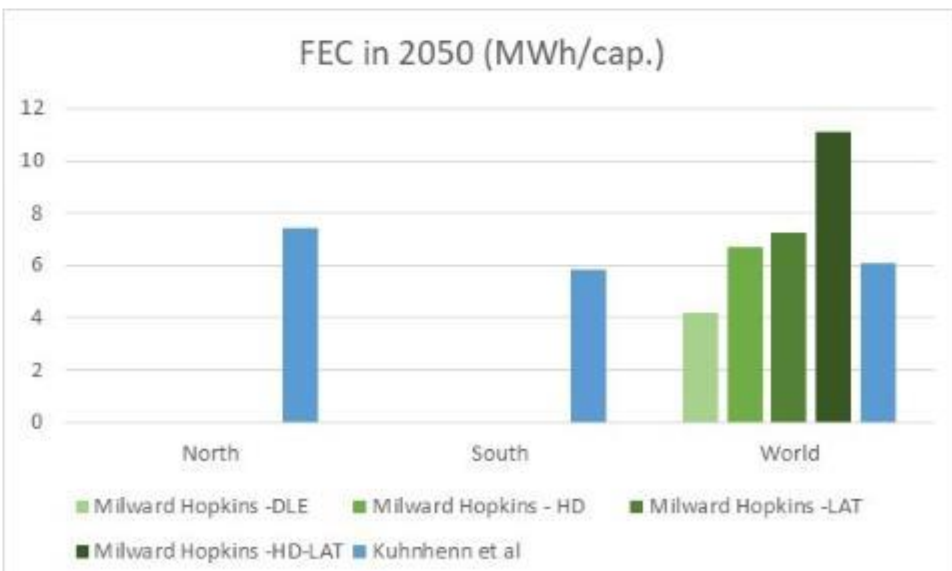

Figure 39 FEC per inhabitant in 2050 for Millward-Hopkins et al (2020) and Kuhnhenn et al (2020)

Can a 45% reduction of FEC be compatible with decent living for all?

In 2050, the IMP-SP has a higher FEC at global scale (98.5PWh vs 67.5PWh in 2050) than the IMP-LD, but the FEC/cap. in Global North is only 5% higher while FEC/cap. for Global South is 70% higher, leaving more room to provide a decent living for all. This is probably related to its narrative: "how shifting global pathways towards sustainable development, including by reducing inequality, can lead to mitigation".

[31] Millward-Hopkins et al (2020), p.8

[32] Kuhnhenn et al (2020), p. 57, 61 and 65 for population, FEC by sector and total FEC

[33] This margin allows for less advanced technologies or higher demand (as in Milward-Hopkins (2019) and/or some remaining inequalities albeit at a much lower level than today.

Then the IMP-SP reaches a 45% reduction while complying with the minimum that allows a decent living for all (7MWh/cap.).

Scenarios at EU and national scale mentioned before reach FEC per inhabitant much higher than the global minimum energy requirements of 7MWh/cap. For example, the CLEVER scenario forecasts 11MWh/cap. in EU28 in 2050 (with -55% FEC over 2019-2050 for EU27), which is close to the level of the IMP-SP for EU28 (12.4MWh/cap.).

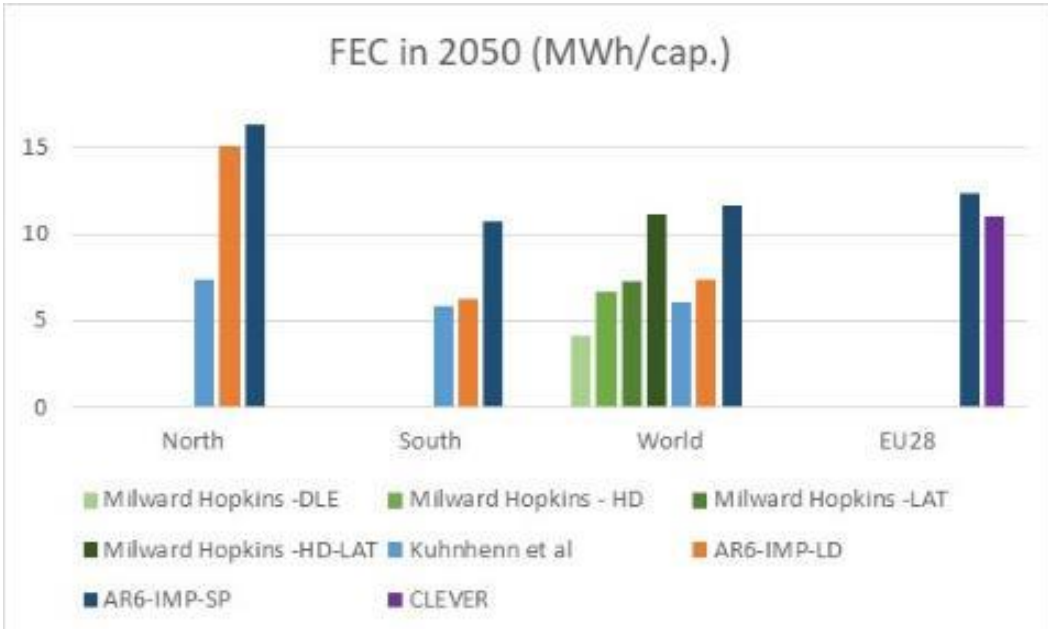

Figure 40 FEC per inhabitant (MWh/cap.) in 2050 in a selection of studies and scenarios

Conclusion

Several scenarios at the global, EU and national scales confirm the possibility of reaching at least a 45% FEC reduction in the EU by 2050 while allowing a decent living for all.

We will show in the next section that EU and national scenarios reaching such a reduction include sufficiency levers and how much reduction is driven by sufficiency.

4.2. Sufficiency as an indispensable lever to reach such ambition

What are sufficiency levers?

By "sufficiency levers" we understand "changes in habits, activities and services, that contribute to less energy and GHG-intensive lifestyles" as defined in deliverable 2.3 (FULFILL, 2022). They can be found in all key areas and sectors; for example, increasing public transport, reducing living space sizes or reducing meat consumption are considered sufficiency levers. Sufficiency levers are associated with drivers, which are defined as "modifications brought to infrastructures and societal frameworks, such as policy measures, that support and enable the sufficiency levers" (FULFILL, 2022). Examples of sufficiency drivers are facilitated traffic conditions for public transport, development of a more compact and frugal architecture or change in the promotion of meat products. In addition, the following categorisation of sufficiency levers was proposed in deliverable 2.1 (FULFILL, 2023a):

- Sufficiency habits: sufficiency measures taken by individuals due to permanent lifestyle changes
- Sufficiency infrastructures: physical and non-physical infrastructures enabling Sufficiency habits

Sufficiency societal framework: institutions, legislation and norms enabling Sufficiency habits

National and EU scenarios ambitious on FEC reduction do integrate sufficiency levers

In the 5 national studies mentioned previously (section "National scenarios in Europe halving FEC"), sufficiency levers are indispensable to reach a FEC reduction of at least 50%, even if the word "sufficiency" is not always mentioned. For example:

- CAT: Sufficiency levers are mentioned in the main drivers of FEC reduction[34], for example "improving internal temperature control", "reducing how much we travel" changing how we travel – with more use of public transport, walking, cycling"
- CREDS estimates that "Avoid/shift" (which can be assimilated to sufficiency) measures reduce FEC by 28% (or represent 54% of the total FEC reduction of 52%) in the Transform scenario.
- négaWatt estimates that sufficiency measures reduce FEC by 23% (or represent 42% of the total FEC reduction of 55%)

S1 and S2 scenarios from ADEME (2021) mention many sufficiency levers, for example: reduction of total passenger mobility (p.km/cap./year), increase of soft mobility, "more people living together and adapting the size of dwellings to the size of households", "industrial production as close as possible to needs"[35] …

- In the GreenSupreme variant from Umwelt Bundesamt (2019), many parameters which can be counted in the category of sufficiency parameters are activated: evolution of residential floor area (from 49.4 to 41.2m2/pers.)[36], change in individual mobility behaviour "By choosing the mode of transportation, the size of the vehicle as well as the place of work and residence"[37]

The national scenarios that achieve a FEC reduction of 50% or more do integrate sufficiency levers as essential drivers of the FEC decrease. Then EU scenarios that achieve a FEC reduction of 45% to 55% have probably integrated sufficiency levers

Indeed, in the selection of EU scenarios mentioned above, those that forecast a FEC reduction higher than 45% and that we have been able to analyse (PAC2.0, CLEVER, Strategic perspectives and the 2 ECF scenarios) do integrate many similar sufficiency levers in the modelling.

Assessment of the role of sufficiency in FEC reduction

Scenarios that reach an ambitious FEC reduction (-52% to -58% by 2050) and that evaluate the impact of sufficiency estimate it can reduce FEC **by 23-28% in comparison to today's level** (see Table 9).

According to its authors, a first estimate of the impact of **only the most important sufficiency levers** in the CLEVER scenario for residential, passenger mobility, freight and industry sectors evaluated that sufficiency can **reduce by at least 19%** the FEC in these 4 sectors between 2019 and 2050.

Table 9 Reduction of FEC by sufficiency between a reference year (2015 or 2019) and 2050

<table>
<tr><th></th><th></th><th>TOTAL</th><th>Tertiary</th><th>Residential</th><th>Transport</th><th>Industry</th><th>Methodology</th></tr>
<tr><td>UK</td><td>CREDS - transform</td><td>28%</td><td>22%</td><td>25%</td><td>36%</td><td>21%</td><td>LMDI *</td></tr>
<tr><td>FR</td><td>ADEME - S2</td><td>24%</td><td>19%</td><td>7%</td><td>34%</td><td>36%</td><td>LMDI *</td></tr>
<tr><td>FR</td><td>négaWatt 2022</td><td>23%</td><td colspan="2">14%</td><td>34%</td><td>20%</td><td>SDA**</td></tr>
<tr><td>EU28</td><td>ECF - shared effort</td><td>26%</td><td colspan="2">13%</td><td>42%</td><td>35%</td><td>Comparison to BAU***</td></tr>
</table>

**LMDI: log mean divisia index additive method. Comparison to a BAU scenario to estimate the effect of sufficiency ("Ignore" for CREDS in which FEC decreases by 5%)*

[34] CAT (2019), p.13
[35] ADEME (2021), p.9
[36] Umwelt Bundesamt (2019), p.34
[37] Umwelt Bundesamt (2019), p.41

*** "SDA": Input-output structural decomposition analysis*[38]

**** "Share of the energy reduction in the Shared efforts scenario w.r.t. EU-REF16 in 2050" (p.23) The groups of levers "Social patterns" and "Societal organisation" have been considered as sufficiency-related drivers*

4.3. Benefits of sufficiency beyond energy

Sufficiency is indispensable to reach ambitious energy demand reduction. It can then bring an important contribution to GHG reduction.

But it can also bring major benefits beyond energy and climate: contribute to sustainable development goals, mitigate material-related environmental impacts, provide more resilience to exogenous risks, reduce health, environmental and socio-economic impacts and reduce the energy system costs.

GHG emissions can be reduced by 25-35% through sufficiency

The IPCC evaluates the effects of different categories of levers (socio-cultural factors, infrastructure use, end-use technologies) on emissions reduction by comparison to a BAU[39]. The two categories "socio-cultural factors" and "infrastructure use" can be assimilated to sufficiency given the drivers it refers to in Figure 5.7[40] of IPCC (2022) (reproduced in Figure 41) and in Table 5.SM.2 of the associated supplementary material.

As a result, **GHG emissions can be reduced by 29% through sufficiency** and 17% through efficiency in comparison to a BAU scenario[41].

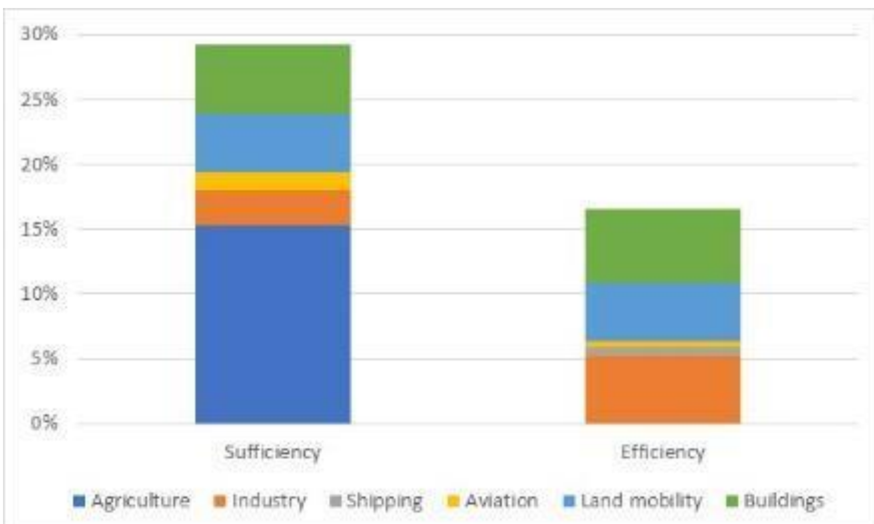

Figure 41 Percentage of GHG reduction by comparison to a BAU attributed to sufficiency and efficiency. négaWatt analysis based on figure 5.7 of IPCC (2022) and related supplementary material

[38] De Boer P. (2009)
[39] IPCC (2022), chapter 5, p.530 ; p.42 of the related supplementary material
[40] https://www.ipcc.ch/report/ar6/wg3/figures/chapter-5/figure-5-7
[41] négaWatt analysis based on Creutzig et al (2022) (supplementary material of chapter 5 of WG3 of AR6, p.42) and figure 5.7 of the WGII of the AR6 (IPCC(2022))

At the EU level, 2 scenarios (PAC2.0 and Strategic perspectives (2023)[42]) evaluated that **sufficiency[43] can reduce GHG emissions by 33-35% by 2040** in comparison to a "reference scenario" (this reduction represents 24-25% of 2015 emissions)

At the national level in France, in the S2 scenario from ADEME, sufficiency reduces about 20% of 2015 emissions[44].

Sustainable development goals (SDGs): sufficiency brings co-benefits and possibly few trade-offs

Demand-side measures potentially offer more synergies and fewer trade-offs than supply-side ones

The analysis of the ESABCC shows that **considering SDGs, demand-side measures should be prioritised over supply-side measures.**

Demand-side measures can contribute to most of SDGs (13 out of 17) and present relatively few trade-offs*"*[45;46]*.* Supply-side measures also contain multiple synergies with SDGs, but in comparison to demand-side measures, they have a lower potential of contribution to SDGs and higher risks of bringing negative impacts on SDGs.

The tables below analyse potential synergies and trade-offs with SDGs for demand-side measures and supply-side measures in the three iconic pathways of ESABCC (2023) complying with GHG budgets and achieving -90%GHG/1990 for the European Union.

"The Demand-side focus and High renewable energy pathways have greater deployment of such demand-side measures compared to the Mixed options pathway, suggesting greater potential to support the achievement of the SDGs"

Figure 40 Potential SDG synergies and trade-offs from demand-side mitigation measures in Iconic pathways

[42] p. 7 of the report: https://strategicperspectives.eu/wp-content/uploads/2024/01/StrategicPerpectives_Choices-for-a-more-Strategic-Europe.pdf

[43] The categories "lifestyle changes" in PAC2.0 and "Behaviours" in Strategic perspectives have been assimilated to sufficiency.

[44] Transitions 2050, Sobriété : Quelle place dans la réduction des consommations d'énergie et d'émissions à 2050, ADEME, 2024, https://librairie.ademe.fr/cadic/8387/feuilleton-sobriete-transitions2050-ademe.pdf

[45] ESABCC (2023), p.86

[46] Further details of synergies/trade-offs by type of measures can be found in ESABCC (2023), figure 39 p.85

Figure 41 Potential SDG synergies and trade-offs from supply-side mitigation measures in Iconic pathways

Note: The SDGs listed are 1 – No poverty, 2 – Zero hunger, 3 – Good health and well-bering,4 – Quality education, 5 – Gender equality, 10 – Reduced inequalities, 16 – Peace, justice and strong institutions, 6 – Clean water and sanitation, 12 – Sustainable production and consumption, 14 – Life below water, 15 – Life on land, 7 – Affordable and clean energy, 8 – decent work and economic growth, 9 – Industry, innovation and infrastructure, 11 – Sustainable cities and communities.

Figure 42 Potential SDG synergies and trade-offs from demand-side and supply-side measures in Iconic Pathways of ESABCC (2023). The 2 figures, respectively for demand-side measures and supply-side measures, have been copied from ESABCC (2023)

The sufficiency measures studied in the IPCC's AR6 report offer even more synergies and fewer trade-offs

Sufficiency measures evaluated in the light of SDGs in the IPCC's AR6 report bring important co-benefits and very few potential trade-offs. Where sufficiency measures could bring trade-offs[47], they could also provide synergies for the same SDGs.

The following sufficiency measures, listed in Figure SPM.8 of the summary for policy makers (SPM) of the WGIII of the AR6[48], were analysed:

- "Shift to balanced, sustainable healthy diets"
- "Demand-side management" in buildings
- "Shift to public transport"
- "Shift to bikes, e-bikes and non-motorised transport"
- "Material efficiency and demand reduction"

A deeper analysis has been carried out in the chapter related to buildings[49]. It shows that "enhancement of sufficiency measures" in this sector could bring trade-offs to a small extent only to SDG8 (Decent work and economic growth) and SDG9 (Industry, innovation and infrastructure), but also co-benefits on these SDGs. **Besides, sufficiency strongly contributes to 9 SDGs:** 1-No Poverty, 3-Good health and well-being, 6-Clean water and sanitation, 7-Affordable and clean energy, 8-Decent work and economic growth, 9-Industry, innovation and infrastructure, 11-Sustainable cities and communities, 13-climate action and 15-Life on land.

[47] **SDG1 (No poverty)** for diets; **SDG3 (Good health and wellbeing)** for shifts to soft modes; **SDG8 (Decent work and economic growth)** for demand-side in buildings and "material efficiency and demand reduction"; **SDG9 (Industry, innovation and infrastructure)** for diets, demand-side in buildings and public transports

[48] Summary for policy makers of IPCC (2022)

[49] IPCC (2022), Table 9.5 of the chapter 9.8 of the WGIII of the AR6

Other cobenefits from sufficiency and demand-side measures

Limitation of materials' consumption and related impacts

Several studies[50;51;52;53] demonstrate how sufficiency and, more broadly, demand reduction assumptions lead to a reduction in the consumption of various materials[54] on a global, European and national scale.

This reduction in demand mitigates material-related pressures, resulting in a reduction of environmental impacts integrated into other planetary boundaries than climate change, including land system change, freshwater change and biosphere integrity. This is particularly relevant for metals, as shown by the International Resource Panel (2019)[55], where increased production, due to reduced grades, leads to an increase in mining impacts according to the OECD[56].

Resilience to risks and minimisation of impacts

The French Environment Agency (ADEME) analysed for their 4 transition scenarios (S1, S2, S3 and S4) how resilient they could be to geopolitical, natural and technological exogenous risks and how much health, environment and socio-economic impacts they could create[57]. They conclude that "only S1 and S2 [scenarios which integrate sufficiency[58]] have limited risks or impacts, which shows that **sufficiency is a factor in mitigating risks and impacts**, without and impacts, although it does not provide complete insurance"[59].

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[50] Rauzier, Toulouse (2022)
[51] Cabeza, L. et al (2022); chapter 9 of the WGIII of the AR6
[52] RTE (2022); chapter 12.3.8, p.715
[53] Transport & Environment (2023): Clean and lean: Battery metals demand from electrifying passenger transport. https://www.transportenvironment.org/wp-content/uploads/2023/07/Battery-metals-demand-from-electrifying-passenger-transport-2.pdf
[54] These include wood, foodstuffs, textiles, non-metallic ores for construction and metal products, including critical raw materials such as lithium and copper.
[55] International Resource Panel (2019)
[56] OECD (2018)
[57] ADEME (2024), p.42-43
[58] Ibid. Some insights on how sufficiency is integrated in these 2 visions on page 70
[59] ibid, p.42, translated from French

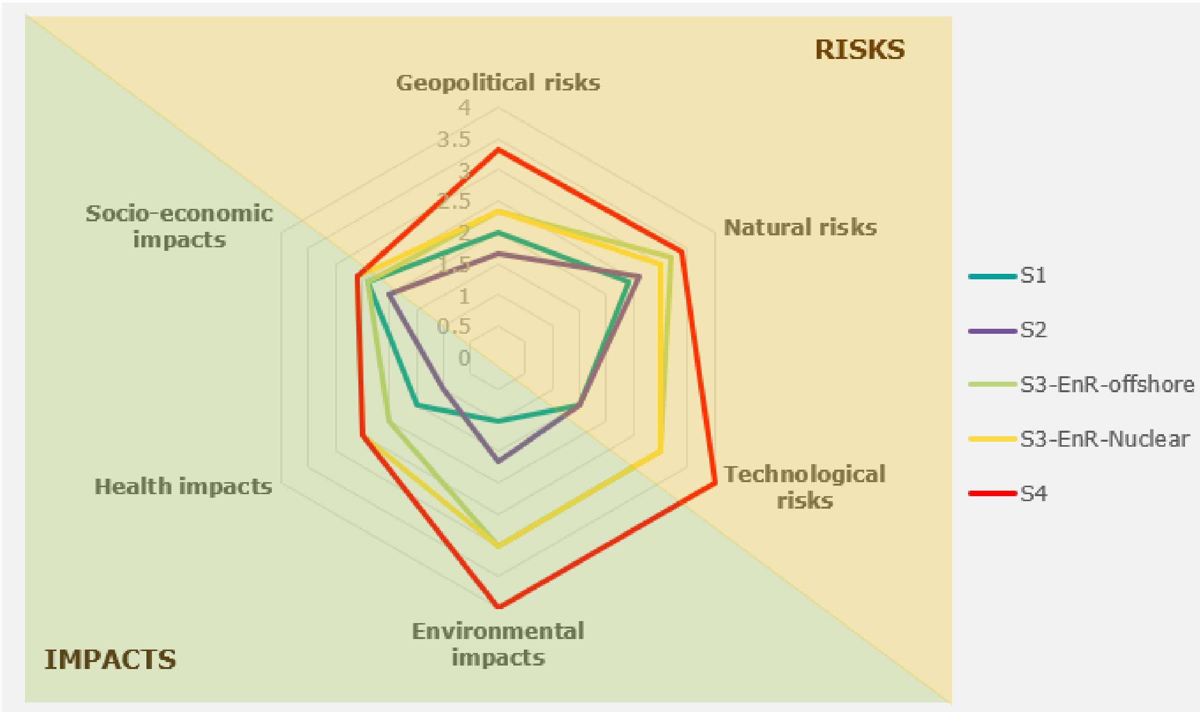


Figure 43 Risk and impact ratings by sub-category in the 4 scenarios of ADEME (2021). This figure has been extracted from page 43 ADEME(2024)[60]*, translated and reproduced*

Improved energy security

According to Bento et al (2024), "***Demand-side policies offer clear advantages for energy security*** *improvement across many dimensions, including continuity, affordability, and sustainability. They also have advantages in terms of flexibility. Demand-side policies give more opportunities.*"

In addition, **scenarios that do integrate sufficiency at an ambitious level tend to have lower energy imports** (which is only one aspect of energy security). For example, in Figure 44, the scenarios CLEVER and PAC2.0 (which integrate sufficiency) have much lower imports in 2040 and 2050 than scenarios with low levels of sufficiency - S3 from the European Commission (EC-S3) and Global ambition from TYNDP2022 (TYNDP22-GA). However, it is important to note that the level of sufficiency and energy savings is just one of the factors that can influence the level of imports.

[60] ibid

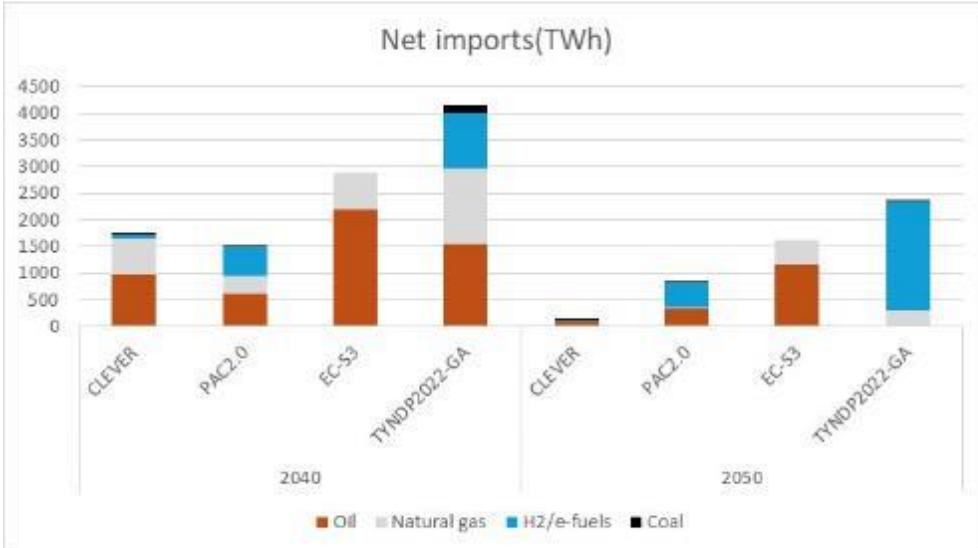


Figure 44 Net imports (TWh) in 2040 and 2050 in EU27 for a selection of scenarios

Lower costs and investments

In the "Analysis of the European Commission's 2040 climate target proposals and scenario comparison"[61] négaWatt highlights reports that show how sufficiency can reduce investments and energy system costs.

In the impact assessment accompanying the European Commission's communication for a 2040 climate target for the EU[62], the LIFE scenario (which integrates more sufficiency measures[63]) reduces total investments over 2031-2050 by 8-8.5%[64] in comparison to S1, S2 and S3 scenarios and energy system costs by 1.4%, 2.9% and 3.6%[65] in comparison to S1, S2 and S3. Then, in comparison to S1, the LIFE scenario brings similar energy system costs for a higher climate ambition than S1 (-93%GHG in 2040 LIFE vs -78% in S1).

This confirms the positive effects of sufficiency on costs already highlighted by other studies like RoadtoNetZero[66] estimating that sufficiency can avoid 200 billion euros of imports (which corresponds to 8% of energy system costs in scenarios S1 and LIFE of the EU Commission).

4.4. Conclusion

Global scenarios among the most ambitious[67] have demonstrated the **possibilities to reduce FEC by at least 45%** (and up to 55%) over 2019-2050 in countries from the Global North and in the EU.

Several scenarios at the national and EU levels also demonstrate the **possibility of halving FEC over 2019-2050**. All the national and EU scenarios that achieve high demand reduction (at least -45%) and that we were able to analyse integrate many sufficiency levers into their modelling. At the same time we did not identify any scenarios that reach such an ambition on FEC reduction without sufficiency. Then, **sufficiency seems essential to reach a FEC reduction of at least 45%** over 2019-2050 in the EU. By itself, **sufficiency can reduce energy consumption by 23-28% over 2019-2050,** according to the few studies that evaluate its impact on energy demand reduction.

[61] négaWatt (2024)
[62] European Commission (2024)
[63] European Commission (2024), Table 4 on p.33 of Part 1
[64] European Commission (2024), Table 16 on p.57 of Part1, table 26 on p. 160 of Part3
[65] European Commission (2024), p.62 of Part1, Table 34 on p.185 of Part3
[66] Institut Rousseau (2024)
[67] C1 category from IPPC's AR6 report

Given that sufficiency aims at **minimising energy demand while providing decent living for all**, scenarios can be considered as integrating sufficiency only if they reach energy demand compatible with minimum energy requirements for decent living. For example, at a global scale, t**he IMP-SP[68] scenario reaches a FEC of 12.4MWh/cap. in 2050 for Global South, which is much higher than minimum energy requirements (7MWh/cap), allowing a decent living for all**. At the European level, the CLEVER scenario forecasts 11MWh/cap. for EU28 in 2050 (-55% FEC over 2019-2050 for EU27), which is close to the level of IMP-SP for EU28 (12.4MWh/cap.) and much higher than global minimum energy requirements. Then a FEC reduction of 55% in the EU is compatible with the 1.5°C objective and a vision of sustainable development allowing decent living for all.

Beyond energy, sufficiency can also contribute to reducing GHG by 20% to 35% over 2015-2050 and bring important co-benefits: contribute to sustainable development goals, mitigate material-related environmental impacts, provide more resilience to exogenous risks, reduce health, environment and socio-economic impacts and reduce the energy system costs.

[68] An illustrative mitigation pathway from the IPCC AR6 called "Shifting pathways" and described as "how shifting global pathways towards sustainable development, including by reducing inequality, can lead to mitigation" see p. 309 of IPCC (2022)

5. Conclusions

The work presented in this report is meant to be an intermediary step between quantification work performed in task 5.3, and further impact assessment work carried out in tasks 6.2 and 6.3. The methodology and main results have been presented, along with a few interesting methodological issues and areas for future research.

Although the impact will be further refined through the following activities in work package 6, some interesting outcomes can already be pointed out. The assessed impact in FEC reduction of selected sufficiency assumptions is far from negligible for most of the studied scenario assumptions, as illustrated in Table 10, even when focusing on a narrow population category (cf. "sharing spaces in housing"), thereby highlighting both **the positive role sufficiency can play** and the relevancy of the sufficiency scenario assumptions retained.

Table 10 Overview of absolute and relative FEC reductions (SUF vs. REF scenario) for the 5 sufficiency scenario assumptions in 2050

Scenario assumption	**Absolute FEC reduction in 2050 for the 5 selected countries (TWh – total for the 5 countries)**	**Relative FEC reduction in 2050 (% - range for the 5 countries)**
Sharing spaces in housing	18.2	3.4%-5.1% of residential energy consumption (except specific electricity)
Moderate car sizing	22.4	11%-20% of energy consumption from cars
Sharing products	1.4	18%-21% of electricity consumption from washing machines
Biking	10.8	2.1%-16.7% of energy consumption from cars
Flying less[69]	85.6	38%-61% of energy consumption from planes

NB: The figures shown above are direct reductions, some additional indirect (e.g. product manufacturing) effects will be modelled in task 6.2.

Moreover, our additional work on the broader impact of sufficiency allowed us to go beyond these very specific levers and further supports the idea that **sufficiency is key in decarbonisation pathways**. From this meta-analysis, we find converging evidence that:

- **Halving final energy consumption** (in 2050, compared to current levels) i**s feasible, while still leaving room for fair access to energy (decent living for all)**
- Among scenarios having this level of ambition, **sufficiency is necessarily part of the solution**. To be more specific, the contribution of sufficiency to overall energy consumption reduction ranges from 23% to 28% in these scenarios, thus **representing roughly half of the final energy consumption reduction**. Impact on GHG abatement is of the same order of magnitude, **with many additional co-benefits on other externalities**.

[69] Although results have been calculated in this task for all EU countries, only values for the 5 selected countries are shown here, to be consistent with other scenario assumptions shown in this table.

References

ADEME (2021): Transitions 2050. Available under: https://librairie.ademe.fr/ged/6531/transitions2050-rapport-compresse2.pdf

ADEME (2024): "Transitions 2050, Synthèse, Nouvelle édition 2024". Available under: https://librairie.ademe.fr/ged/6529/transitions2050-synthese-mars2024.pdf

AR6 Scenario Explorer and Database hosted by IIASA, "This scenario explorer presents an ensemble of quantitative climate change mitigation pathways underpinning the Sixth Assessment Report (AR6) of Working Group III, *Climate Change 2022: Mitigation of Climate"* Available at: https://data.ece.iiasa.ac.at/ar6/#/workspaces

Bento N., Grubler A., Boza-Kiss B., De Stercke S., Krey V., McCollum D., Zimm C., Alves T. (2024): Leverage demand-side policies for energy security

Cabeza, L. F., Q. Bai, P. Bertoldi, J.M. Kihila, A.F.P. Lucena, É. Mata, S. Mirasgedis, A. Novikova, Y. Saheb, 2022: Buildings. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter09.pdf

Center for Alternative Technology (CAT) (2019): "Zero Carbon Britain"

CREDS (2021): "The role of energy demand reduction in achieving net-zero in the UK"

Creutzig, F., J. Roy, P. Devine-Wright, J. Díaz-José, F.W. Geels, A. Grubler, N. Maïzi, E. Masanet, Y. Mulugetta, C.D. Onyige, P.E. Perkins, A. Sanches-Pereira, E.U. Weber, 2022: Demand, services and social aspects of mitigation Supplementary Material. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Available from https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter05_SM.pdf

De Boer P. (2009): Generalized Fisher index or Siegel–Shapley decomposition?

European Commission (2024): COMMISSION STAFF WORKING DOCUMENT IMPACT ASSESSMENT REPORT Part 1 Accompanying the document COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Securing our future Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society. Available under: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52024SC0063

European scientific advisory board (2023): Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050 Available under: https://climate-advisory-board.europa.eu/reports-and-publications/scientific-advice-for-the-determination-of-an-eu-wide-2040/scientific-advice-for-the-determination-of-an-eu-wide-2040-climate-target-and-a-greenhouse-gas-budget-for-2030-2050.pdf/@@display-file/file

FULFILL (2022). Refinement of research design. FULFILL Deliverable D 2.3. Karlsruhe, Paris. https://fulfill-sufficiency.eu/wp-content/uploads/2022/08/FULFILL_Research_Design_202208_submitted.pdf

FULFILL (2023a). Literature review for analysis of lifestyle changes. FULFILL Deliverable D 2.1. Milan. https://fulfill-sufficiency.eu/wp-content/uploads/2023/10/D2.1-Literature-review-revised-version.pdf

FULFILL (2023b). Operative definition and indicators for energy sufficiency. FULFILL Deliverable D 2.2. Milan. https://fulfill-sufficiency.eu/wp-content/uploads/2023/07/D2.2-revised-version-31-July-2023-final.pdf

FULFILL (2023c). Report on the first survey and identification of the sufficiency groups. FULFILL Deliverable D 3.1. Karlsruhe. https://fulfill-sufficiency.eu/wp-content/uploads/2023/10/D3.1-Report-on-the-first-survey-and-identfication-of-the-suficiency-groups.pdf

FULFILL (2023d). In-depth analysis of highly sufficient lifestyles. FULFILL Deliverable D 3.2. Valence. https://fulfill-sufficiency.eu/wp-content/uploads/2023/07/D3.2_interviews-micro.pdf

FULFILL (2023e). From pioneering sufficiency lifestyles to a sufficiency society. FULFILL Deliverable D 5.1. Valence. https://fulfill-sufficiency.eu/wp-content/uploads/2023/07/D5.1_Lifestyles-macro-dynamics-2.pdf

FULFILL (2024). Integration of SSH findings in quantified sufficiency assumptions for decarbonisation pathways. FULFILL Deliverable D 5.3. Valence.

Grubler, A., Wilson, C., Bento, N. *et al.* (2018): A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nat Energy* **3**, 515–527. https://doi.org/10.1038/s41560-018-0172-6

I4CE (2021): "Bonus-malus automobile : la nécessaire évaluation. https://www.i4ce.org/publication/bonus-malus-automobile-evaluation-climat/ "

ICCT (2019): "European Vehicle Market Statistics 2018/19 Pocketbook". Resources available under : https://theicct.org/sites/default/files/publications/ICCT_Pocketbook_2018_Final_20190408.pdf

ICCT (2023): "European Vehicle Market Statistics 2022/23 Pocketbook". Resources available under : https://theicct.org/publication/european-vehicle-market-statistics-2022-23/

ICCT (2024): "European Vehicle Market Statistics 2023/24 Pocketbook". Resources available under : https://eupocketbook.org

IEA (2019): "Fuel economy in major car markets: technology and policy drivers, 2005-2017". https://theicct.org/publication/fuel-economy-in-major-car-markets-technology-and-policy-drivers-2005-2017/

Institut Rousseau (2024), Road to Net Zero: Bridging the green investment gap. Available at: https://institut-rousseau.fr/road-2-net-zero-en/

IPCC (2022): Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Available at: https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_FullReport.pdf

International Resource Panel (2019): "Global Resources Outlook 2019: Natural Resources for the Future We Want. A Report of the International Resource Panel". United Nations Environment Programme. Nairobi, Kenya. Available under: https://wedocs.unep.org/handle/20.500.11822/27517

JRC (2020): Towards net-zero emissions in the EU energy system by 2050

Kuhnhenn K., Costa L., Mahnke E., Schneider L., Lange S. (2020): A Societal Transformation Scenario for Staying Below 1.5°C

Millward-Hopkins J., Steinberger J. K., Rao N. D., Oswald Y. (2020): Providing decent living with minimum energy: A global scenario

négaWatt Association (2021): "Scénario négaWatt 2022". Resources available under: https://négaWatt.org/Scenario-négaWatt-2022#ressources

négaWatt Association (2023): Collaborative low energy vision for he European Union (CLEVER). Final report and data available under: https://clever-energy-scenario.eu/#clever-major-publications

négaWatt Association (2024): Choosing climate ambition, resilience and savings: Analysis of the European Commission's 2040 climate target proposals and scenario comparison. Available under: https://www.négaWatt.org/IMG/pdf/240228_choosing_ambition_resilience_and_savings.pdf

OECD (2018): Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences, OECD Publishing, Paris. Available under: https://doi.org/10.1787/9789264307452-en

Rauzier E., Toulouse E. (2022): The material impacts of an energy transition based on sufficiency, efficiency, and renewables. ECEEE SUMMER STUDY PROCEEDINGS. Available under: https://www.négaWatt.org/IMG/pdf/220608_ecee_the-material-impacts-of-an-energy-transition-based-on-sufficiency-efficiency-and-renewables.pdf

RTE (2022): Futurs énergétiques 2050. Available under: https://www.rte-france.com/media-url/11456

Strategic Perspectives (2023): Choices for a more Strategic Europe. Available under : https://strategicperspectives.eu/wp-content/uploads/2024/01/StrategicPerpectives_Choices-for-a-more-Strategic-Europe.pdf

Transport & Environment (2023): "Clean and lean: Battery metals demand from electrifying passenger transport"

Um-welt Bundesamt (2019) "Resource-Efficient Pathways towards Greenhouse-Gas-Neutrality – RESCUE"

Annex 1 – Additional information on historical data and projections

A1.1 Sharing spaces in housing

Note on overall m²/cap calibration

The housing surface per capita (m²/cap) combines data on **total building surface** and population (cap).

Population has been taken from ESTAT data & projections (except France from INSEE, to restrict to its metropolitan area).

However, housing surface is more challenging in terms of data accuracy:

- Not all m² are occupied (main house, secondary house, vacant)
- Not all m² are heated or even accounted (garage, cellar, walls etc.)
- CLEVER figures have been chosen, as they have been cross-checked with local partners and most importantly are **consistent with the energy intensities** in kWh/m² retained for this work (to make sure we end up with figures of final energy consumption consistent with Eurostat statistical data).

The Hotmaps project database has also been analysed, as consistency check. Some gaps have been identified (especially in Italy), but they are hard to explain, therefore we kept our CLEVER & ESTAT values.

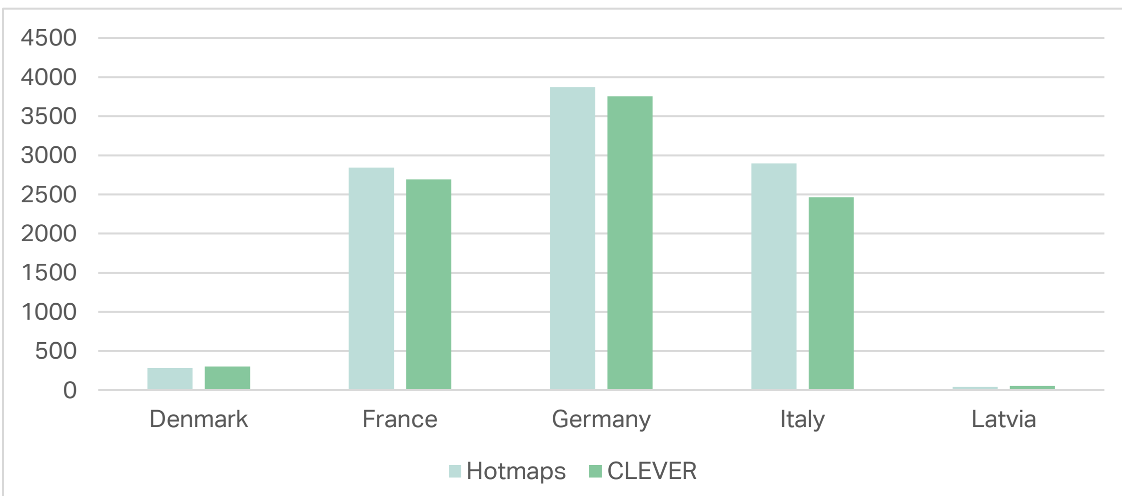


Figure 45 Total floor area in Mm² in 2016, comparison CLEVER/FULFILL vs. Hotmaps project

As shown in the following chart, there is a rather consistent gap across countries, between values calculated above, and data coming from the task 3.1 survey (used in task 5.3). This may come from a survey bias, i.e. people tend to overestimate their surface area. Therefore, we had to apply a correction to task 5.3 figures.

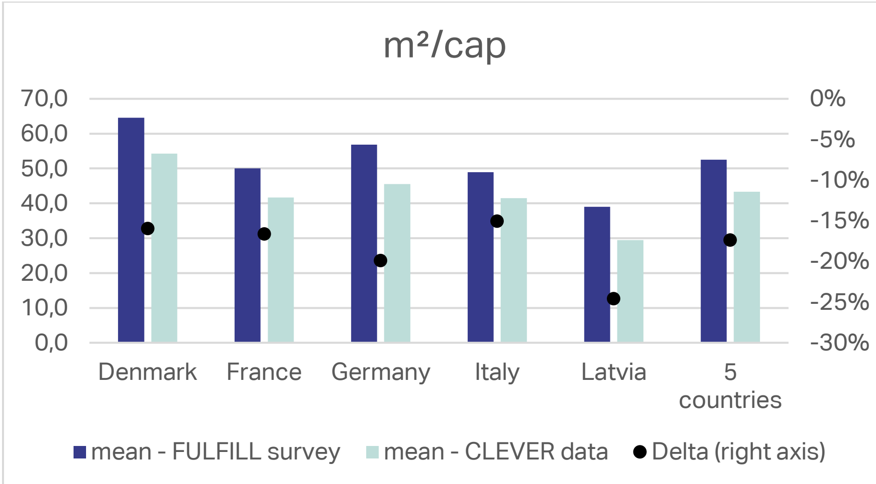


Figure 46 Comparison of m²/cap for the whole population in 2019, between data from the FULFILL task 3.1 survey and the CLEVER scenario

Note on kWh/m²

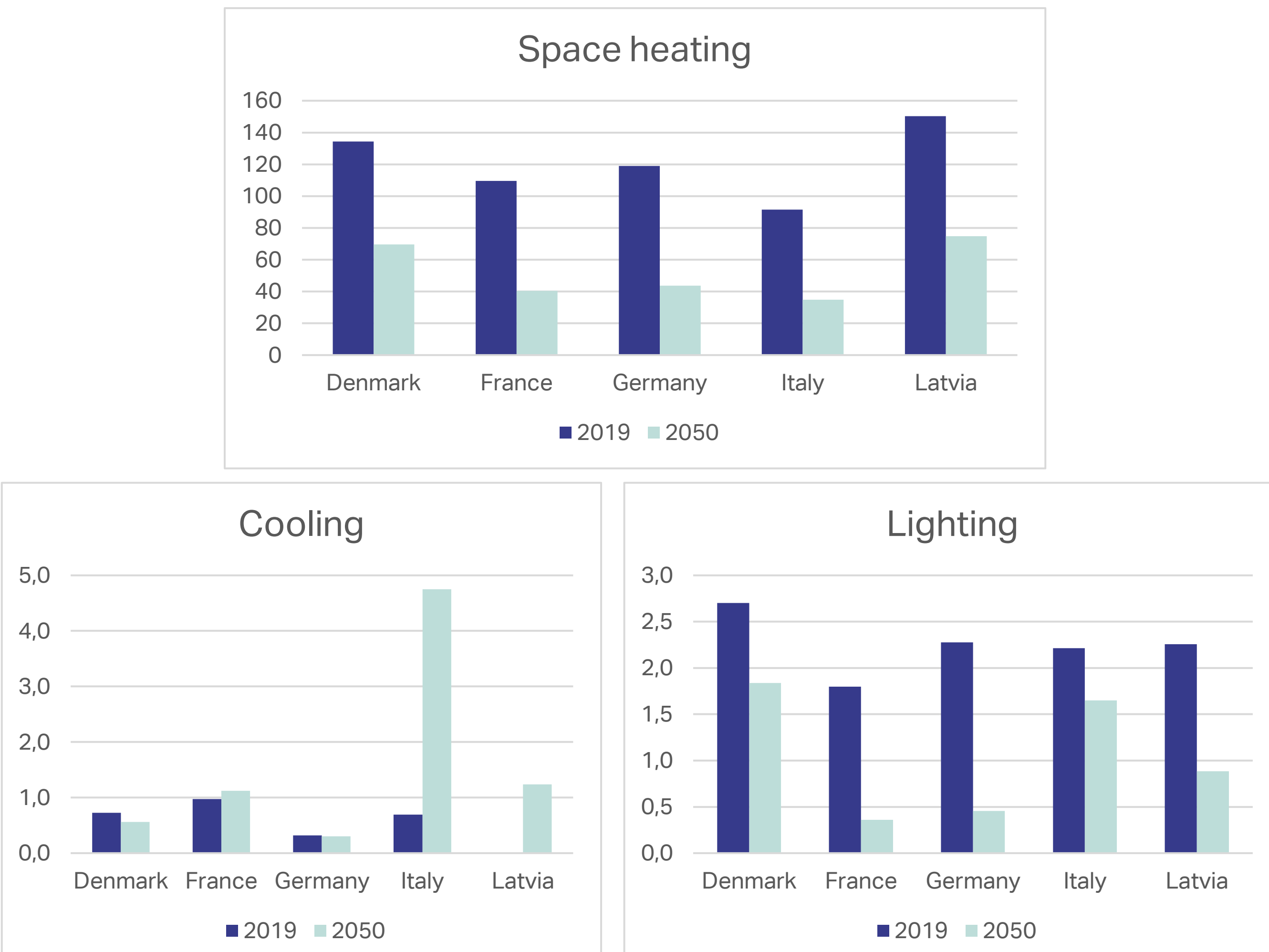


Figure 47 Final energy consumption intensities (kWh FEC/m²) in the residential sector, per use and for each of the 5 countries

As shown in Figure 47, the main contributor to FEC is space heating, even when taking into account progressive reduction of space heating intensity (through better insulation and some sufficiency on setpoint temperature) and slightly increasing cooling needs.

Heating appliance efficiency

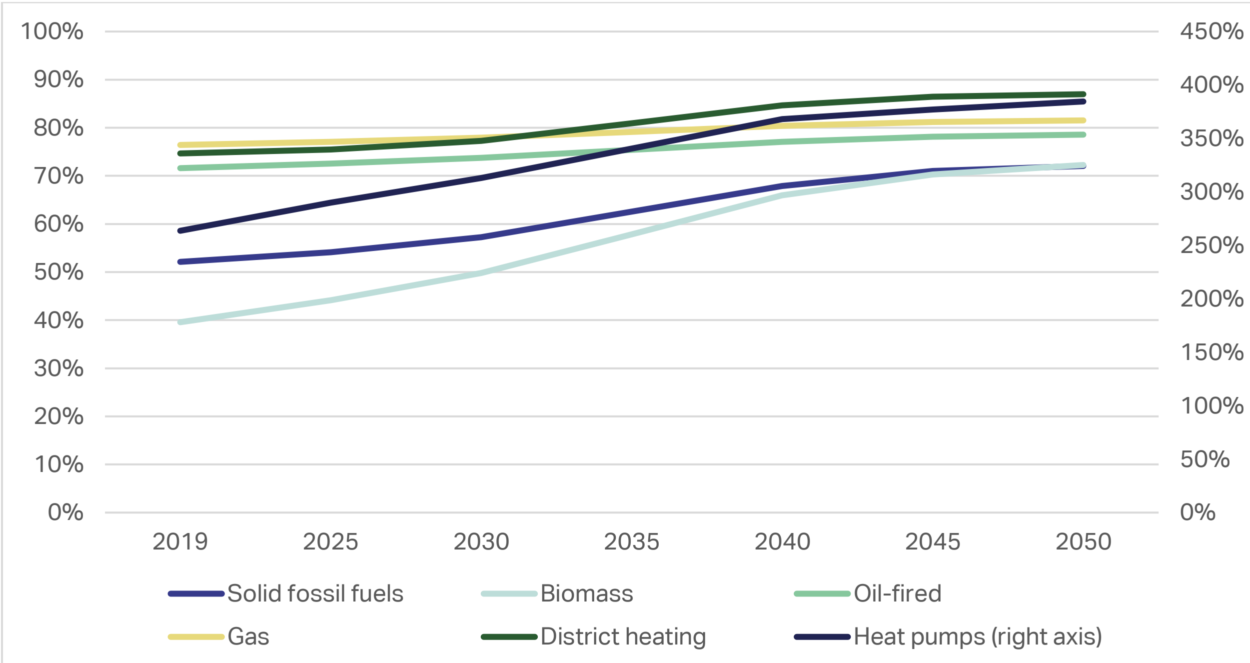
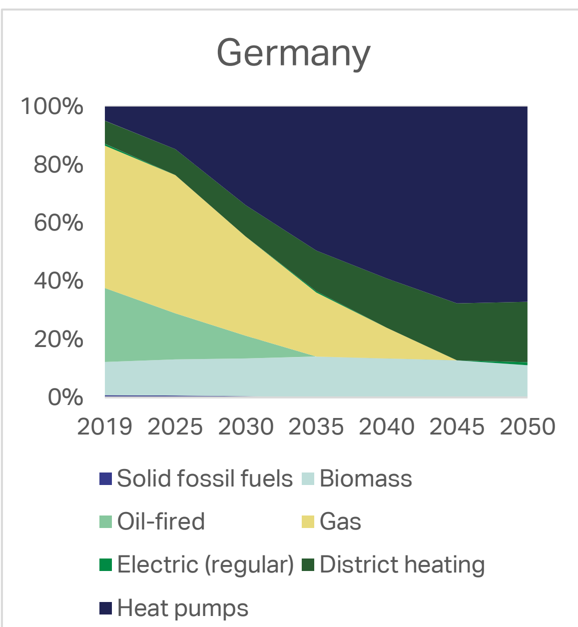
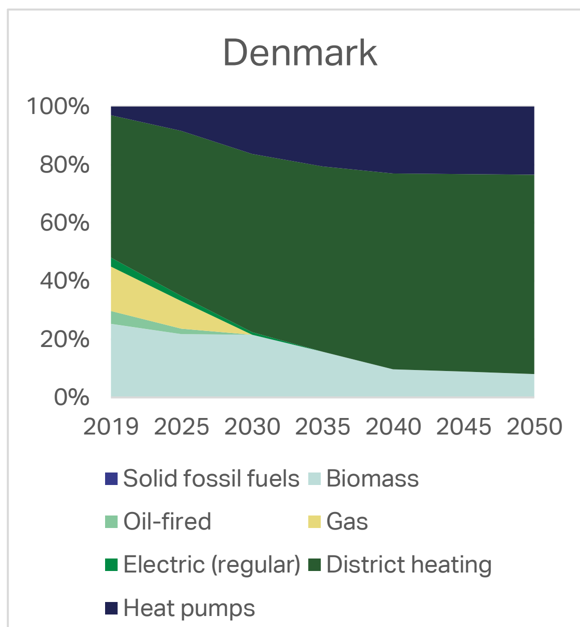
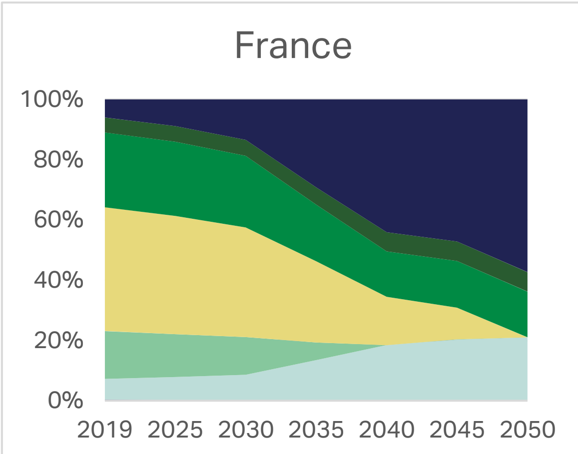


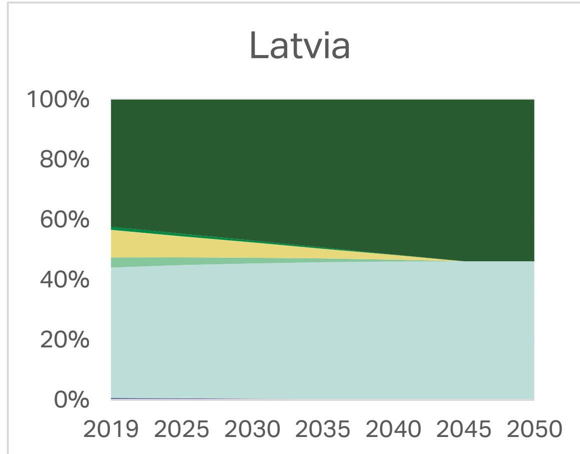
Figure 48 Heating appliance efficiencies, average for the 5 countries (%), taken from the CLEVER project

Heating appliance market shares









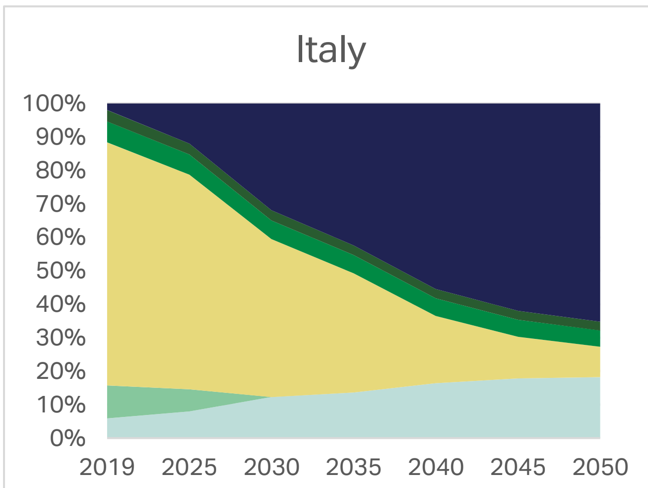


Figure 49 Trajectories for the market shares of heating appliances, taken from the CLEVER project

A1.2 Moderate car sizing

Note on kerb weights

Average kerb weights in 2020 have been taken from European averages calculated in (ICCT, 2023):

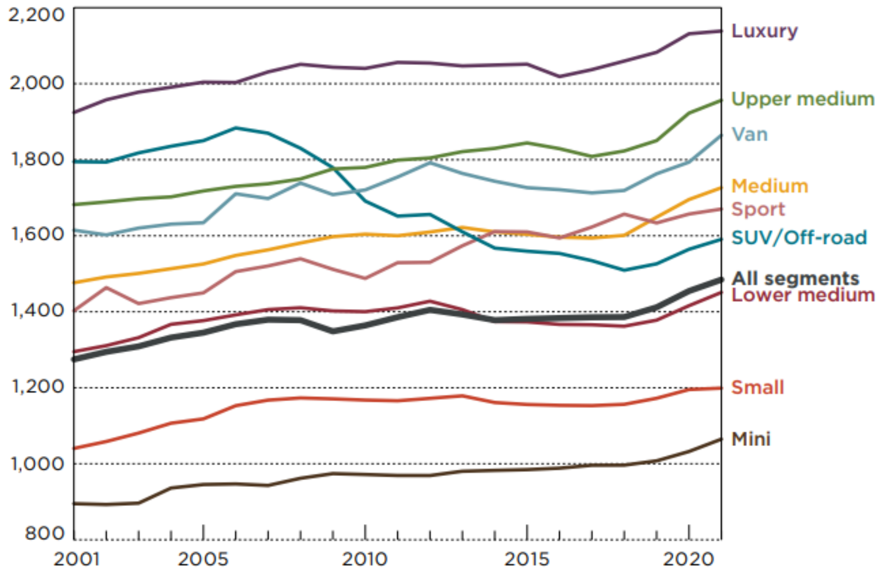


Figure 50 Passenger cars: vehicle mass in running order by segment (kg), source (ICCT, 2023)

Table 11 Kerb weight (and battery capacity) assumptions in 2020

Segment	Kerb weight for ICE (kg)	Kerb weight for battery electric (kg)	Battery capacity assumption (kWh)
Micro	350	458	15
Mini Cars	1041	1257	30
Small Cars	1212	1464	35
Medium Cars	1445	1805	50
Large Cars	1731	2163	60
Executive Cars	1976	2480	70
Luxury Cars	2189	2765	80
SUVs	1601	1961	50
Minivans	1845	2277	60
Sports Cars	1689	2265	80

It has been assumed that these vehicles were mostly ICE (not battery-powered electric vehicles). Additional battery weights have been assumed on each segment, using assumptions on battery capacities (kWh) and current battery material content (7.2 kg/kWh).

As the "micro" car segment is not available in ICCT data, an assumption of 350 kg has been taken, consistent with the existing models of "Aixam City" and "Twizy cars".

These figures have been cross-checked with some specific car examples on each segment. Results were usually close to these averages, except for SUVs, which happen to have surprisingly low values in ICCT data (close to the overall average). This probably illustrates the fact that this segment now encompasses a very diverse range of cars.

These ICCT figures are nevertheless consistent with data from Eurostat in the different countries, when comparing the average weight of car sold calculated from:

- ICCT segment weights and market shares provided by task 5.3
- Eurostat data on number of cars sold by weight ranges (<1000 kg, 1000-1249 kg, 1250-1499 kg, >1500 kg)

In the REF scenario, we made the scenario assumption that past trends on increasing car weights (beyond changes in car segments) would continue. We therefore did a simple linear regression (a logarithmic regression would have a very similar outcome), with approximately 9kg added every year:

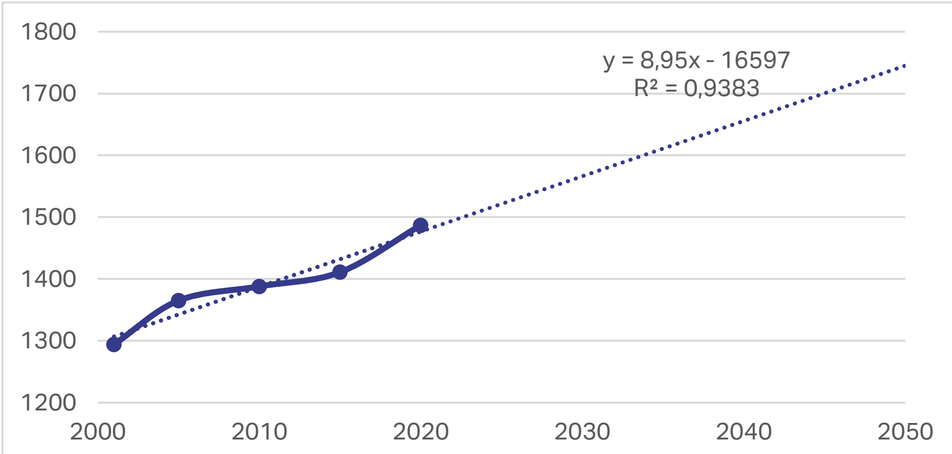


Figure 51 Trajectory of the average car weight in Europe (kg). Historical data from ICCT (2023) and linear regression for the future.

Note on stock model calibration

The BAMASI stock model requires a certain number of indicators to run, with both historical data and prospective assumptions (cf. annex 2):

- Total sales (units/year)
- Total stock (units)
- Mobility needs (p.km)
- Traffic (v.km)
- Average use (km/v/year)
- Occupancy rate (cap/v)
- Vehicle lifetime (km)

Main historical data sources used have been:

- Eurostat
- Odyssée-MURE
- Local/national data from the CLEVER project (when possible, as Latvia was not among the countries were local partners were active in building the national trajectories)

When possible, preference has been given to Eurostat, but in some cases, we had to supplement with the other two sources:

- **Sales & mobility needs (p.km)**: data from Odyssée has been used to fill the gaps for "secreted" years in Eurostat data (otherwise Odyssée & Eurostat are rather consistent on these indicators, except for Latvia on sales). Sales were required at least from 2000 onwards, to have a proper modelling of the current stock of cars.

- **Stock**: data from Odyssée & Eurostat has been used for values before 2012. After this year, both sources are relatively consistent, except for France and Latvia (values in Odyssée are slightly lower than Eurostat, pointing at a possible perimeter issue, e.g. with LCVs).
- **Use (km/v/year)**: Eurostat does not directly provide this indicator, but it can be simply reconstructed by dividing car traffic (v.km) by the stock. Odyssée is anyway required for figures before 2012 (considering that Eurostat does not provide stock values over this period). Otherwise, Eurostat and Odyssée are consistent, except for Latvia.
- **Occupancy rate (cap/v)**: this indicator is slightly harder to get than the others. National data has been taken for France (SDES) and Denmark (DST). For the other countries, the indicator has been calculated from mobility needs, average use and stock:

$$occupancy = \frac{mobility\ needs}{use \times stock}$$

Vehicle lifetime is modelled with a survival law expressed in km/v. Its average is a calculated parameter (different for each country), adjusted to make the cumulated historical sales match the starting point (2019) of the car stock. The result of this calibration is as follows:

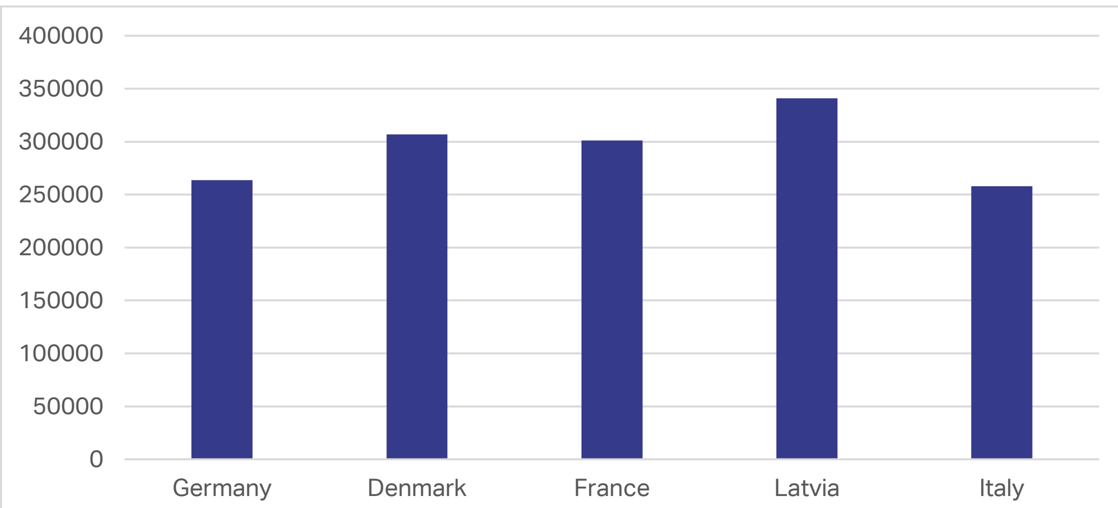


Figure 52 Car lifetimes used in the stock model, expressed in km after which 90% of cars are destroyed.

NB: it has been assumed as a simplifying assumption that the different car segments and powertrains would not have different lifetimes.

For prospective trajectories, three indicators have been adjusted:

- **Occupancy rate (cap/v) and mobility needs (p.km)**: trajectories have been taken from the CLEVER project, except for Latvia. For this country, occupancy follows the German trajectory (having the same starting point), and mobility needs follow CLEVER's default trajectory for road mobility (not disaggregated by road transport means). These trajectories converge towards similar per capita values in 2050 for mobility, as shown in Figure 53 :

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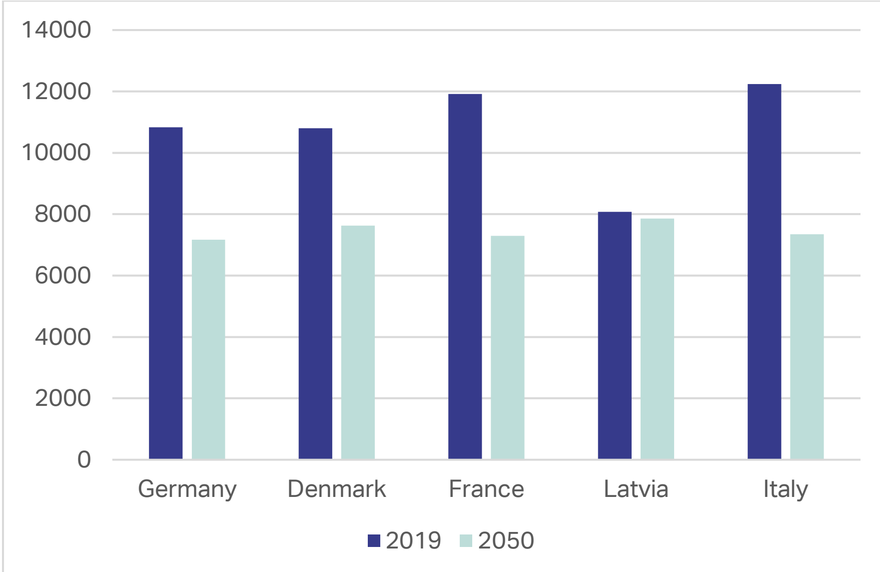


Figure 53 Evolution of mobility needs per capita (km/cap/year) per country

- **Sales**: a 2050 sales target has been defined in order to reach similar car ownership levels (vehicle per capita) across countries, and most importantly, reasonable car usage levels (km per vehicle per year). Setting excessively high or low sale targets could indeed end up with underused cars (which is unrealistic, considering their capital-intensive nature, and not desirable from a climate perspective) or overused cars / too low car ownership levels (which is unrealistic as well, if we want to match the service levels required for some remote parts of the territory). Sales trajectories are as follows:

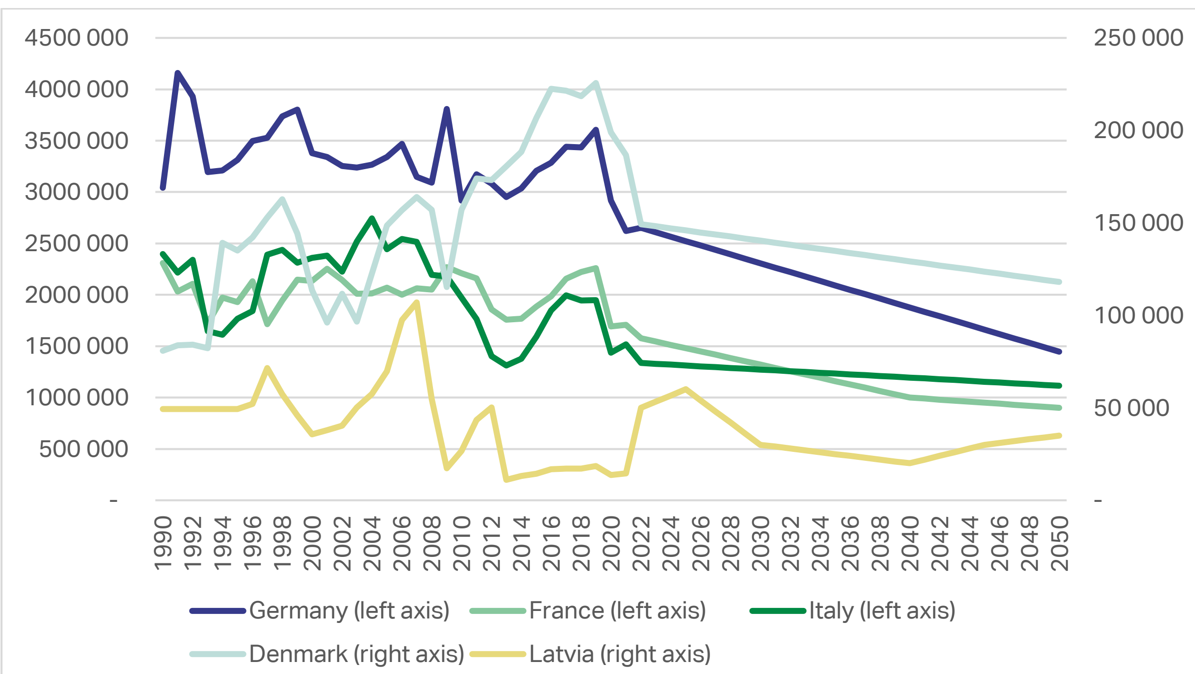


Figure 54 Number of cars sold since 1990 and up to 2050 (according to our assumptions from 2023 onwards)

Their consequence in terms of car ownership and car use are shown below:

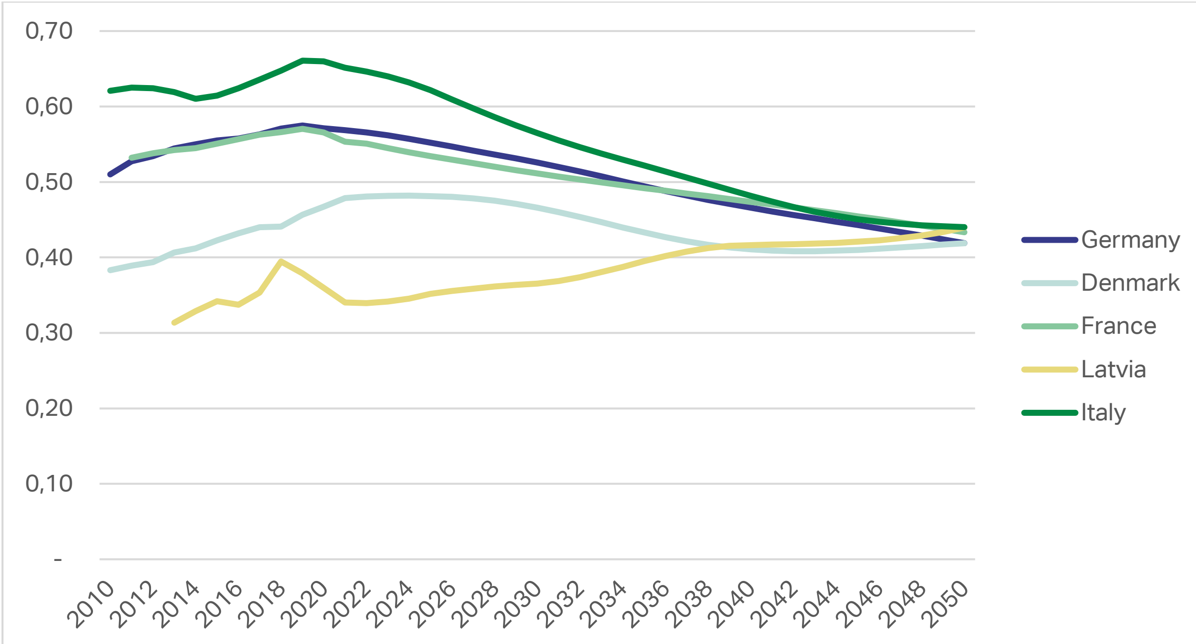


Figure 55 Car ownership trajectories (vehicle per capita), for each country

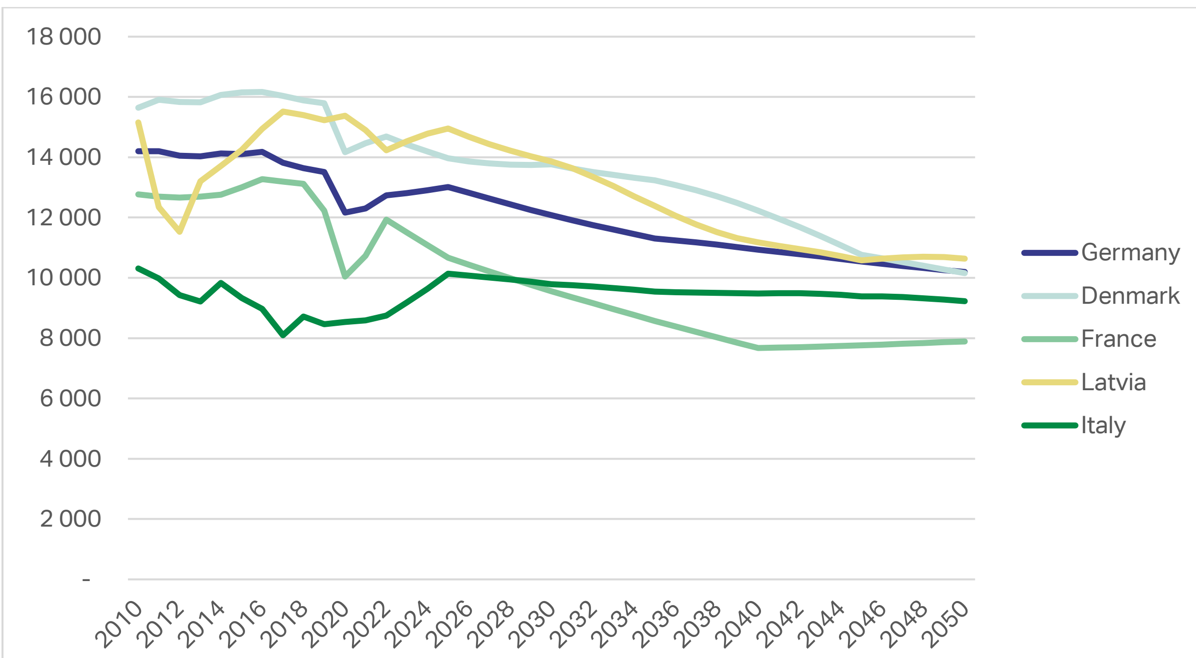


Figure 56 Average vehicle use (km per vehicle per year)

Note on powertrains and their efficiencies

Regarding powertrains, we strived to comply with:

- The current ban on ICE in 2035, assuming that cars sold at this stage will be exclusively battery electric cars initially, and to a much smaller extent hydrogen cars later on
- Trajectories defined by local partners as part of the CLEVER project, as far as possible (sometimes, small differences remain, since our stock model was not available at the time, and some trajectories were not totally realistic with regards to the stock inertia)
- Recent past dynamics in terms of battery electric and hybrid car sales

This translates into the following penetration rate for battery electric cars:

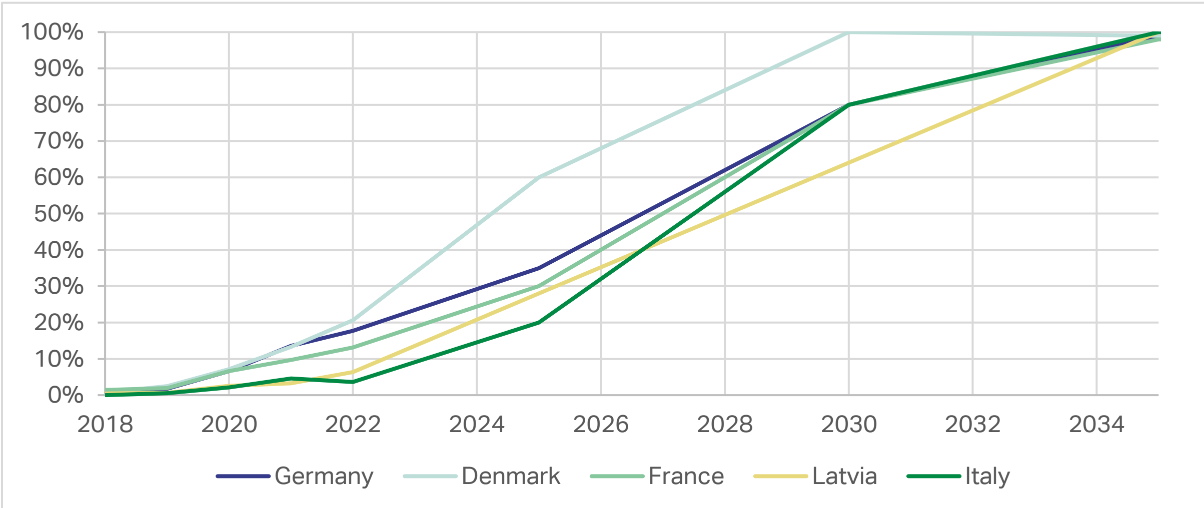
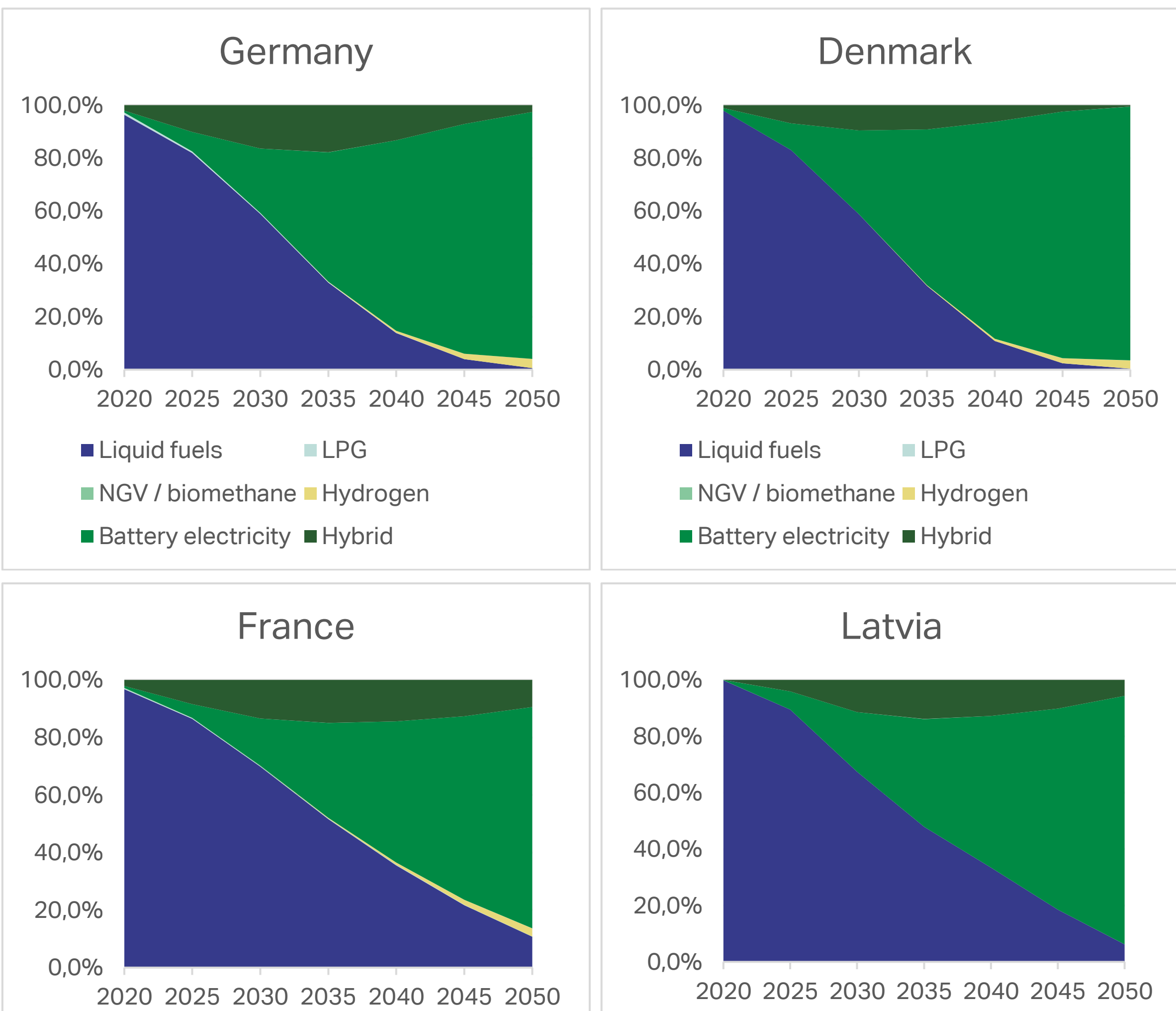


Figure 57 Share of battery electric in car sales (%). Data until 2022 comes from Eurostat.

Results are as follows in terms of share of stock, after running our stock model:



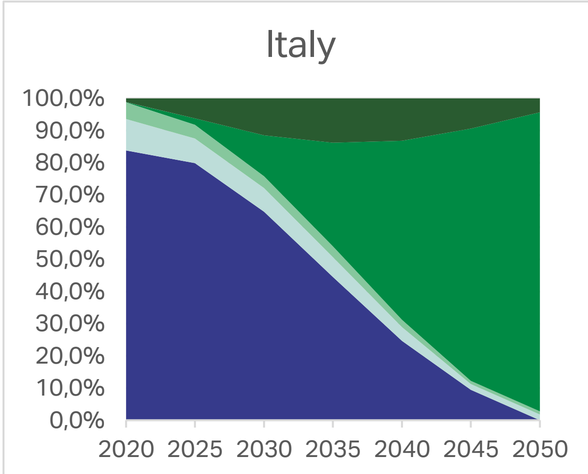


Figure 58 Breakdown of car stock, by powertrain, for each country

Hydrogen remains rather marginal, LPG and NGV / biomethane occur mostly in Italy[70].

Specific consumption of each powertrain (kWh or L/km) have been taken from CLEVER trajectories, cf. Figure 59. Their improvement over time comprises assumptions on reduced speed limits, improved driving behaviour (eco-driving), technical improvements etc.

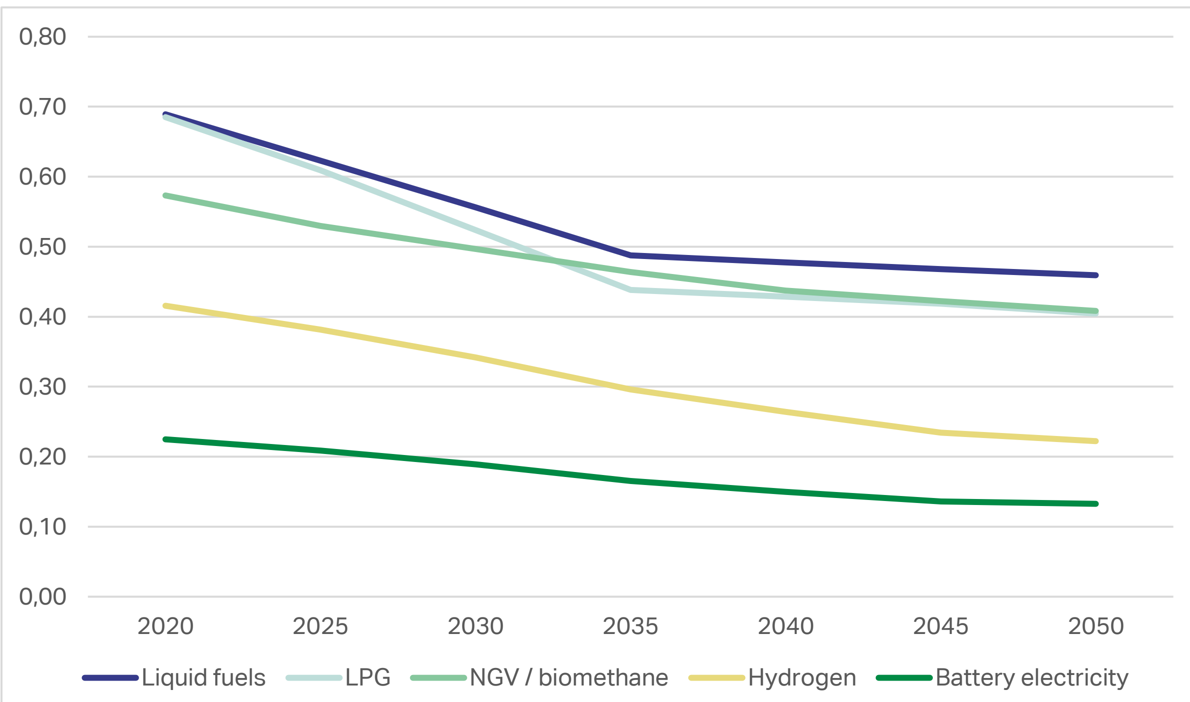


Figure 59 Specific consumption of cars, average for the 5 countries (kWh/km)

Note on the impact of car weight on energy consumption

Most sources identified dealing with the impact of car weight on their consumption focus on internal combustion engines, and usually deal with car emissions rather than their consumption (ICCT 2019, 2023, 2024, IEA 2019). Most values encountered range from 3 to 5 additional kWh/100km, every additional 100kg of car kerb weight. An average of several values has been taken, at **4.13** kWh/100km increase, every 100kg of car kerb weight for ICE cars.

[70] CLEVER trajectories do have a share of NGV for other types of (heavy duty) vehicles.

We assumed here a linear relationship between weight and consumption, but it's likely that reality is slightly more complex, especially for battery powered cars as shown by data analysis performed on 2019 data from EEA open databases:

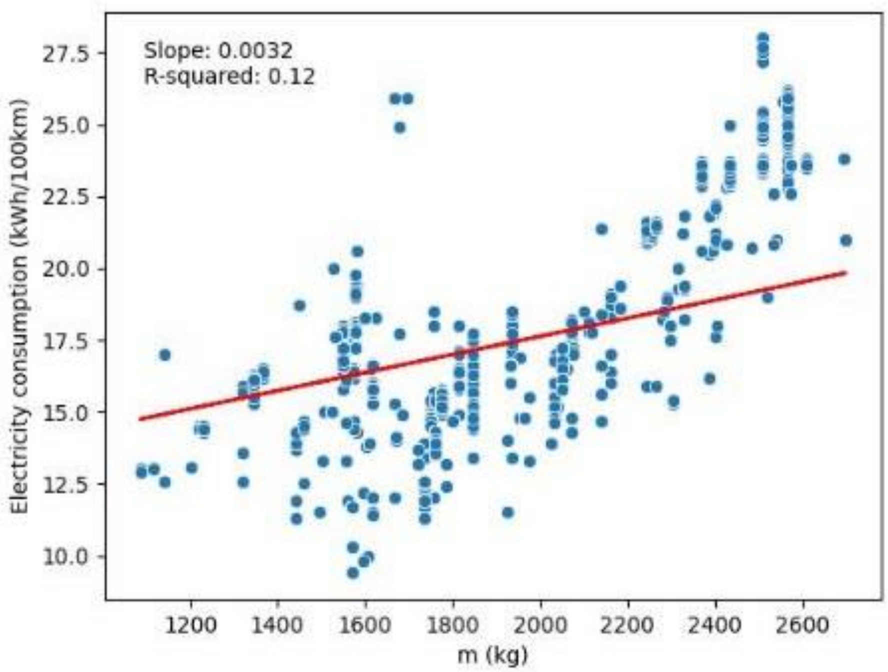


Figure 60 Analysis of manufacturer-declared electricity consumption (kWh/100) vs. kerb weight (m) in 2019, according to EEA[71]

The above graph shows a slope of 0.3 kWh/100km every 100kg of car weight, but the correlation is rather poor. Another figure, from a French parliamentary note gives a value of **0.6** for battery powered cars, which we retained. This is much lower than the value for ICE cars, because battery powered cars have a better overall tank-to-wheel efficiency, and also probably because regenerative braking slightly reduces correlation between consumption and weight (heavier cars means more energy is retrieved when braking).

A1.3 Sharing products

- The historical data and trends for population are based on Eurostat mean population projections.
- The historical data for ownership rates are based on national statistics.
- The historical data for annual sales in units, size and energy class for France, Germany and Italy is based on a market monitoring study by French Environmental Agency ADEME (the study data stops in 2019, but we could have access to a draft update including data until 2022, however it is not published and cannot be cited yet).
- The historical data for annual sales in units for Denmark is based on APPLiA Denmark data submitted by INFORSE - the sales by energy classes is assumed to be similar to Italy (rough assumption based on this source).
- The historical data for annual sales in units for Latvia is reconstructed from custom data submitted by Zala Briviba (very rough and uncertain calculations) - the sales by energy classes are assumed to be similar to France (very rough assumption).

[71] Database available at https://co2cars.apps.eea.europa.eu/

- The annual number of cycles is based on a 2021 French measurement campaign in a representative sample of 100 households, and it is assumed that all countries have a similar number (this is a rough assumption but no better data could be found for the other countries).
- The impact of washing temperatures on the energy use of the washing cycles has been modelled using data from a survey by Electrolux (2001), "The truth about laundry".

A1.4 Biking – Note on the starting points

- Daily mobility needs: average distance covered in daily mobility in **2017** (DE, LV) or **2019** (DK, FR, IT) are based on surveys on personal mobility compiled by Eurostat in **2020** (DK, DE, IT, LV), and a specific survey by the French Government in **2019** (FR).
- Ratio of segregated cycling infrastructures to main roads comes from the European Cycling Federation (QECIO 2.1) of January 2024[72] - see
- Population density per country has been taken in 2022 from Eurostat 2023. NB: data on density is not fully consistent with data on population and surfaces, with respective discrepancies of -2,9% (DK), 11,1% (FR), -1,3% (DE), 0,5% IT) and -0,9% (LV). They could be in part explained by differences in years and roundings, apart from the gap for France which probably relates to ultramarine territories being counted/not accounted for in population vs. surface
- Number of bicycles sales by country in 2020 are taken from the Confederation of the bicycle European industry[73]

[72] https://ecf.com/quantifying-europe-cycling-infrastructure-using-openstreetmap-qecio-2
[73] https://www.conebi.eu/wp-content/uploads/2023/08/2021_BIMP_with_2020_data.pdf

Annex 2 – BAMASI tool documentation

This annex aims at providing an overview of the BAMASI tool calculation methodology. The BAMASI tool differs in particular from other stock models such as those used by the International Energy Agency (IEA) and the French Environment and Energy Management Agency (ADEME). Unlike these models, BAMASI adopts a stock model in which vehicle lifetimes are defined in kilometers (e.g. 195,000 km for a passenger car) rather than years. This difference is intended to reflect more accurately the sufficiency scenario assumptions in the mobility and freight sectors, which lead to a reduction in the annual distance travelled by vehicles.

Abbreviations

- B_t : Vehicle traffic, here defined as mobility or freight needs in passenger.km (p.km) or ton.km (t.km).
- B_{mot} : Vehicle traffic for a specific powertrain[74]
- IMB_{mot} : Battery material composition for a specific powertrain (%)
- IMV_{mot} : Vehicle material composition for a specific powertrain (%)
- NCC_t : Total vehicle sales
- NCC_{mot} : Vehicle sales for a specific powertrain
- NHU_t : End-of-life (EOL) vehicles
- NHU_{mot} : End-of-life (EOL) vehicles for a specific powertrain
- P_t : Vehicle stock
- P_{mot} : Vehicle stock for a specific powertrain
- TM_t : Occupancy rate define as persons per vehicle or tons per vehicle
- TM_{mot} : Occupancy rate for a specific powertrain
- u_t : Vehicle use corresponding to the yearly kilometers travelled by the vehicle
- u_{mot} : Vehicle use for a specific powertrain

[74] Here powertrain may be substituted by “segments”, the model has been used twice, with both powertrain and segment breakdowns.

Model description

As part of this model, the determination of historical lifetime in kilometers is instituted to ensure rigorous alignment with historical data on vehicle stock, new sales and end-of-life vehicles provided by statistical sources (see annex 1 for details).

Input parameters:

	Historical	Prospective
Traffic (p/t.km)	B_{t_n}	$B_{t_{n+1}}$
Stock	P_{mot_n}	
Occupancy	TM_{t_n}	$TM_{t_{n+1}}$
Veh. use (km)	u_{mot_n}	
Veh. EOL	NHU_{mot_n}	
Veh. sales	NNC_{mot_n}	$NNC_{mot_{n+1}}$
Veh. material composition (%)	IMV_{mot_n}	$IMV_{mot_{n+1}}$
Bat. material composition (kg/kWh)	IMB_{mot_n}	$IMB_{mot_{n+1}}$

Calculation Steps

1. $u_{t_{n+1}} = \frac{B_{t_{n+1}}}{P_{t_n} \times TM_{t_{n+1}}}$
2. $u_{mot_{n+1}} = u_{t_{n+1}} \times \frac{u_{mot_n}}{u_{t_n}}$
3. $P_{mot_{n+1}} = f(u_{mot_{n+1}}, NNC_{mot_{n+1}}, U_{\max})$
4. $P_{t_{n+1}} = \sum_{\text{mot}}(P_{mot_{n+1}})$
5. $NHU_{mot_{n+1}} = P_{mot_n} - P_{mot_{n+1}} + NNC_{mot_{n+1}}$
6. $B_{mot_{n+1}} = \frac{u_{mot_{n+1}} \times P_{mot_{n+1}} \times TM_{mot_{n+1}}}{\sum_{\text{mot}}(u_{mot_{n+1}} \times P_{mot_{n+1}} \times TM_{mot_{n+1}})} \times B_{t_{n+1}}$

Output parameters:

- $NHU_{mot_{n+1}}$: end-of-life vehicles (useful to assess recycling potential)
- $P_{mot_{n+1}}$: share of stock for the different powertrains
- $B_{mot_{n+1}}$: share of mobility needs met by the different powertrains
- $u_{t_{n+1}}$: total use
- $u_{mot_{n+1}}$: use by powertrain

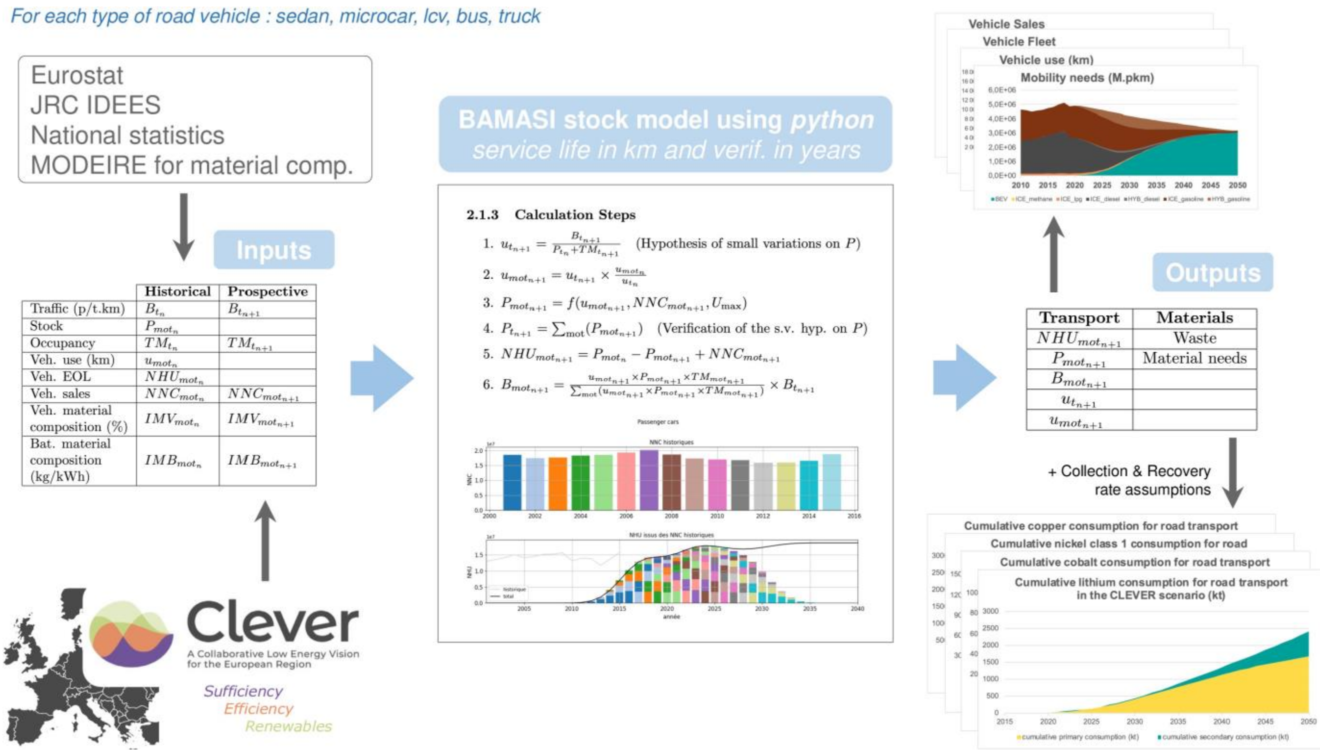


Figure 61 Overview of the BAMASI tool calculation process

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